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M. Singer, J. Mirocha, J. Lundquist, J. Cleve

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Implementation and assessment of turbine wake models in the Weather Research and Forecasting model for both mesoscale and large-eddy simulation

Michael A. Singer[a], Jeffrey D. Mirocha[b], Julie K. Lundquist[c], Jochen Cleve[d]

[a]*Lawrence Livermore National Laboratory, Livermore, CA, USA, msinger@llnl.gov*
[b]*Lawrence Livermore National Laboratory, Livermore, CA, USA, mirocha2@llnl.gov*
[c]*University of Colorado, Boulder, CO, USA, julie.lundquist@colorado.edu*
[d]*Siemens Energy, Inc., Denmark, jochen.cleve@siemens.com*

ABSTRACT: Flow dynamics in large wind projects are influenced by the turbines located within. The turbine wakes, regions characterized by lower wind speeds and higher levels of turbulence than the surrounding free stream flow, can extend several rotor diameters downstream, and may meander and widen with increasing distance from the turbine. Turbine wakes can also reduce the power generated by downstream turbines and accelerate fatigue and damage to turbine components. An improved understanding of wake formation and transport within wind parks is essential for maximizing power output and increasing turbine lifespan. Moreover, the influence of wakes from large wind projects on neighboring wind farms, agricultural activities, and local climate are all areas of concern that can likewise be addressed by wake modeling. This work describes the formulation and application of an actuator disk model for studying flow dynamics of both individual turbines and arrays of turbines within wind projects. The actuator disk model is implemented in the Weather Research and Forecasting (WRF) model, which is an open-source atmospheric simulation code applicable to a wide range of scales, from mesoscale to large-eddy simulation. Preliminary results demonstrate the applicability of the actuator disk model within WRF to a moderately high-resolution large-eddy simulation study of a small array of turbines.

1 INTRODUCTION

Wind turbine wakes can significantly impact flow dynamics both within wind parks and downstream. Regions of low-speed flow immediately behind the turbines can elevate the level of turbulence for considerable distances downstream, due both to vorticity that is shed from the blade surfaces and to strong shear layers that develop between the wake and the free stream flow. These turbulent stresses may increase turbine loading and accelerate component fatigue, thereby decreasing machine reliability, lifespan, and operating time, while increasing maintenance costs. In addition, low speed flow in the wake of one turbine may reduce the inflow wind speed of downstream turbines. Power output scales as the cube of the inflow velocity and therefore lower speeds means significantly lower power production. Turbine wakes may also impact flow conditions for surrounding wind parks, reducing their power output and increasing their fatigue loading and maintenance costs. Downstream agricultural activities may also be impacted due to the role of increased turbulence in enhancing the vertical mixing of temperature and other parameters both within the lower atmosphere and between the atmosphere and the surface. The effects of increased vertical mixing on frost and freeze occurrences and soil moisture exchanges with the atmosphere, for example, may influence regional climate. Consequently, a thorough understanding of turbine wakes and their ability to influence wind park performance is essential for maximizing power output and mitigating unwanted environmental effects.

Large wind parks support a multitude of flow phenomena that occur over a large range of spatial scales, which complicates modeling of their effects. In a typical offshore park, for example, individual turbines may be separated by 500-1000 m, and the entire park may occupy 20-30 km^2. Hence, understanding the impact of wakes on flow throughout the entire park and the surrounding area is well-suited for mesoscale modeling, which typically resolves flow features down to approximately 5 km. In contrast, the near wakes produced by the turbines, whose typical rotor diameters are around 100 m, generally extend 1-3 rotor diameters downstream of the turbine, and therefore higher resolution models, such as large-eddy simulations (LES), are required to capture the relatively small scale features of the near wake. This large disparity in length scales at which flow features occur presents numerous modeling challenges that require flexible numerical algorithms and computational models.

The Weather Research and Forecasting (WRF) atmospheric simulation model is an ideal testbed for assessing different wake models and parameterizations. The code is open-source and is supported by a large community of users. This flexibility facilitates the formulation and implementation of wake models for use within the WRF code. In addition, the WRF model can be run at different mesh resolutions and domain sizes, from mesoscale simulations to LES, which addresses the broad range of length scales that must be considered in wake modeling. A variety of physics options (e.g., boundary layer schemes, turbulence models, radiation and surface parameterizations) as well as data assimilation techniques are readily available in the WRF model. Many such physical processes may be important to developing a thorough understanding of the formation, transport, and impact of turbine wakes, especially across the broad range of variability in weather encountered by wind projects sited in disparate locations with different climatologies. The WRF model provides a rich set of functionality that, when combined with wake models, is capable of advancing our ability to characterize and predict wakes from large wind projects, as well as their effects on neighboring physical processes and activities.

The present study focuses on the implementation of an actuator disk model in the WRF software framework to study wake effects within individual wind farms. The work is primarily geared towards capturing the flow dynamics in the far wake region (greater than 1-3 rotor diameters downstream of each turbine) and beyond, as well as predicting power generation of entire wind parks. Consequently, the actuator disk approach provides a mechanism to incorporate the presence of each turbine and the resulting disruption to the flow without requiring exceedingly high resolution of the flow field around each turbine. Instead, parameterized source terms, which account for the drag introduced into the flow by the turbine blades, are added to the momentum equations and serve as skinks of momentum that decelerate the surrounding flow. The actuator disk model is applicable to LES, which can be run with adequate spatial resolution to resolve the individual actuator disks comprising the wind project. Such an approach can facilitate a variety of studies to assess the projected performance of both single turbines and collections of turbines. In addition, LES using actuator disks can be used to develop wake effect parameterizations for mesoscale applications, which do not employ the high spatial discretizations required to resolve individual disks.

Numerous approaches to wake modeling have been developed and reviews of the different techniques are presented elsewhere (e.g., Crespo et al., 1999; Vermeer et al, 2003). In particular, several studies have employed actuator disk methods to model flow past single turbines and past large wind parks (e.g., Ivanell, 2009; Jiménez et al., 2009; Masson et al., 2001; Mikkelsen 2003; J.N. Sørensen and Myken, 1992; J.N. Sørensen et al., 1998). Some of these studies assume an axisymmetric flow field (J.N. Sørensen and Myken, 1992; J.N. Sørensen et al., 1998) while others solve the full three-dimensional equations that govern the flow (e.g., Jiménez et al., 2009). The former approach limits the incorporation of complex terrain while the later approach is often computationally expensive.

In contrast to previous methods, the actuator disk model developed here is implemented and tested within the WRF model, the benefits of which are described above. Consequently, formulation of the model is necessarily consistent with the equations and numerical methods used within the WRF software. As such, the source terms introduced into the momentum equations are terms that describe the deceleration of flow as it approaches and crosses the actuator disk. Our formulation is unique in that, like the conservation equations computed in WRF, the local mass is measured by a pressure variable (i.e., pressure is related to the amount of mass in a column of fluid) rather than the density. Therefore, our expressions that represent the drag forces due to the turbine deviate from those commonly found in codes based on solving the equations in primitive variables.

2 ACTUATOR DISK MODELS

The actuator disk model is an extension of the blade element method (BEM) in that it uses tabulated airfoil data coupled with conservation laws that describe the flow (e.g., Glauert, 1935). Unlike the BEM, which assumes annular independence of the different blade elements, however, actuator disk methods solve the Euler or Navier-Stokes equations. Hence, no physical restrictions are imposed on the kinematics of the flow, though the physical limitations of the actuator disk assumption must be remembered, e.g., infinite number of blades, inability to handle heavily loaded rotors, lift and drag coefficients for three-dimensional flow are difficult to determine. Many of the constraints of BEM-based methods are discussed in Snel (1998).

Actuator disk models do not explicitly represent the geometry of the blades or resolve the viscous flow around the blades. Instead, the surface swept out by the blades is represented by a permeable surface normal to the free stream flow (a so-called actuator disk), on which blade forces act on the flow. The forces correspond to the period-averaged mechanical work that the rotor extracts from the flow. When flow past real turbines is computed, lift and drag coefficients are used to compute the forces; the lift and drag data are determined from experiments or from numerical computations of two-dimensional airfoils that are corrected for three-dimensional effects.

3 ACTUATOR DISK MODEL IN WRF

The WRF model's dynamic solver integrates prognostic equations for the conservation of momentum. These equations are formulated so that the conserved variable is $\mu\mathbf{u}$, where μ is the column pressure (Pa) and $\mathbf{u}$ is the velocity (m/s). Therefore, source terms that appear on the right-hand side of the momentum equations must have dimensions of kg/s^4, which is a product of the column pressure and an acceleration/deceleration. Hence, the actuator disk model that is implemented into the WRF model must prescribe the deceleration, with units of m/s^2, that a fluid particle experiences when the disk is encountered.

The deceleration used for the present work is

$$a_i = \begin{cases} -A|\sin(\theta)|(1 - d/L)^{\alpha}\, u_i^2 & \text{for } d < L \\ 0 \text{ for } d \geq L \end{cases} \qquad (1)$$

Here, i = 1, 2, 3 indicates the zonal, meridional, and vertical directions, respectively, a_i is the deceleration (due to the minus sign) of the i^{th} component of momentum, u_i is the i^{th} component of velocity, θ is the counterclockwise angle between the mean wind vector and the turbine, and A (with dimensions of inverse length, similar to the leaf area index used in canopy models) is a parameter that characterizes the amplitude of the deceleration. The perpendicular distance between a computational grid point and the actuator disk is d, and L is the perpendicular distance over which the deceleration is applied. Figure 1 is a top view of one rotor, indicated by the solid black line, and the grid points within a distance $L = 2\Delta x$, where Δx is the grid spacing in the horizontal direction. The color of the symbols indicates the distance of a given gridpoint to the rotor plane. The dimensionless parameter α controls the shape of the attenuation of the deceleration as a function of distance from the rotor plane. Hence, the term $(1 - d/L)^{\alpha}$ provides a local spreading of the deceleration over a finite number of grid points that surround the plane of the actuator disk; the deceleration is maximum at d = 0, which corresponds to the plane of the rotor, and a_i decreases with distance from the rotor until the cut-off length, L, is reached. Formulation of the deceleration in this manner avoids the introduction of a point source term in the equations, which may lead to numerical instabilities. The angular rotation term, $|\sin(\theta)|$, ensures that the deceleration is maximum when the rotor disk is perpendicular to the flow and vanishes when it is parallel to the flow. The parameters A, L, and α are unknowns and must be determined from field data.

4 RESULTS

The actuator disk model representation of a four-by-four array of wind turbines is demonstrated in a large-eddy simulation of neutral, boundary-layer flow over a flat, rough surface. The resolution of the LES is 9 m in each horizontal direction and 2.25 m in the vertical direction at the first model gridpoint above the surface, beyond which a stretching of the vertical grid spacing by approximately 5% per nodal index is applied. The simulation is forced with a uniform geostrophic wind aligned along the x-axis and having a magnitude of 10 m/s. The surface boundary condition is a standard logarithmic similarity function, with a surface roughness of 0.1 m, and periodic conditions are applied at the lateral domain boundaries. The simulation is run for six hours to provide sufficient time for a nearly steady turbulence field and rotation of the flow direction with height to develop.

To test the implementation of the algorithm, a model problem is run with A = 0.1, $L = 2\Delta x$, and $\alpha = 2$. Figure 2 shows an instantaneous plane view of the zonal (u) velocity component at approximately 100 m above the surface. The locations of the sixteen turbines, which are oriented perpendicular to the direction of mean flow, as well as their effects on the downstream flow, are clearly demarcated by the abrupt deceleration at the rotor planes and significant reductions in flow velocity downstream. Evidence of turbulence enhancement at the wake edges, due to the large gradients in velocity that develop between the wake regions and the bounding free stream flow, is also observed. The reductions in velocity and the spatial extent of the wakes are in good qualitative agreement with data from a real wind project, which will provide the data for estimation of the unknown model parameters.

The flow results are sensitive to the model parameters, A, L, and α, and these parameters must be calibrated with wind park data. The amplitude of the deceleration, A, exhibits the strongest influence on the solution, within a range of an order of magnitude. Decreasing L or, alternatively, increasing α each have the effect of making the disk appear narrower in the alongstream direction, thereby creating narrower bands of larger-magnitude decelerations. Narrow disks with large decelerations have the effect of destabilizing the numerical solution, favoring the use of larger values of L and smaller values of α. However, while larger values of L or smaller values of α improve the stability of the solution, they do so at the expense of creating disks that are wider in the alongstream direction.

5 CONCLUSIONS

An actuator disk model for wind turbines is implemented into the WRF model to improve our understanding of the effects of turbine wakes in large wind projects. The ability of the model to qualitatively mimic the behavior of turbines in a real wind project is demonstrated in a large-eddy simulation. The reductions in velocity and increase in turbulence downstream from the turbines are in qualitative agreement with observations from a real wind project.

Future efforts will establish values for the various model parameters, thereby extending the approach to more general applications. The actuator disk model will also be used to develop a wake effect parameterization for use in mesoscale applications. Implementation of these two wake models into the WRF framework will provide a powerful tool with a variety of applications, including operational forecasting, assessment of optimal siting strategies, and quantification of downstream effects on neighboring wind projects and other activities.

6 ACKNOWLEDGEMENTS

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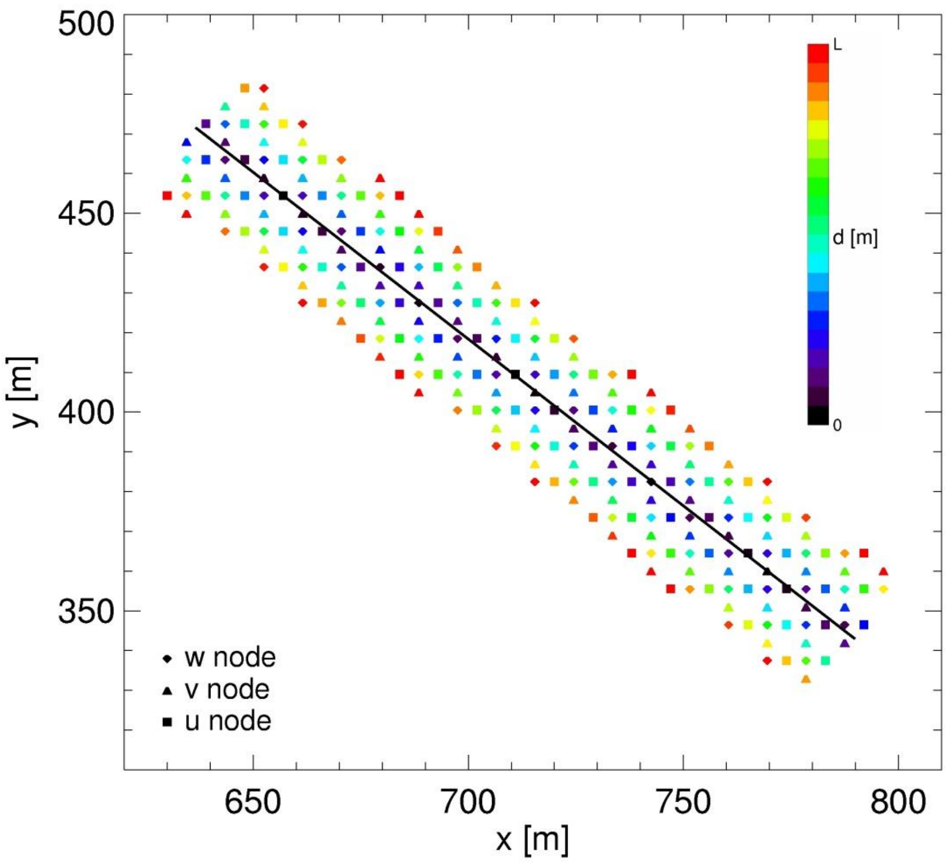

Figure 1, Top view of the actuator disk overlaid upon the computational grid. The black line represents the actuator disk, and the colors indicate the distance, d, from the disk. Note that the deceleration term (Eq. 1) is applied only at grid points with $d \leq L$. The grid points at which u, v, and w components of velocity are computed are denoted by squares, triangles, and circles, respectively.

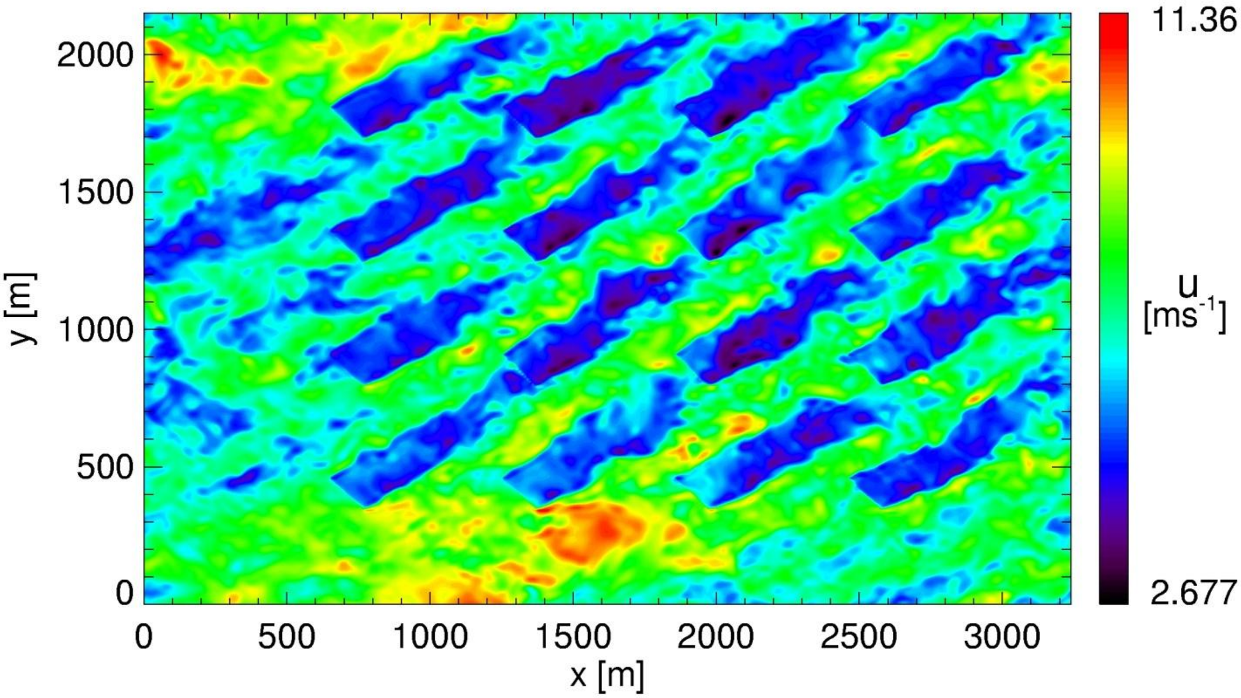

Figure 2, Instantaneous plane view of the zonal (u) velocity component at approximately 100 m above the surface. The wake behind each disk in the four-by-four array of actuator disks is indicated in blue, which corresponds to low speed flow.