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Numerical simulation of multiple interacting wind turbines on a complex terrain

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ABSTRACT

Modern wind farms are subjected to significant aerodynamic interference due to unsteady wakes of individual turbines as well as the complex terrains on which they are erected. The present study uses a new mixed basis formulation of the *Navier–Stokes* equations to numerically simulate turbines on a complex terrain. The turbines are modeled using a distribution of momentum sources. A finite-volume procedure (SIMPLER algorithm) is used to solve the incompressible *Reynolds Averaged Navier–Stokes* equations on body-fitted grids to obtain the flow-field. Three different turbulence models, the standard, RNG, and realizable $\mathcal{K} - \epsilon$ are implemented and compared. Results validating the ability of the numerical procedure to simulate flows over complex terrains and interacting wind turbines are presented. Applications providing insights into the performance and loading on wind turbines on complex terrains are studied. The evolution and interaction of the turbine wakes over the complex terrain are also analyzed.

1. Introduction

The United States Department of Energy (DOE) has set an ambitious goal of meeting 10%, 20%, and 35% of the annual energy consumption in the year 2020, 2030, and 2050, respectively, through wind energy (Lindenberg et al., 2008). To put things into perspective, only 0.5% of the total energy demand was met by wind during the year 2005. It has risen to 4.5% for the year 2013. Among other factors, the growing demand for electricity, increasing concerns over climate change, favorable economics, and the reliability of modern wind turbines are only expected to further accelerate the growth of the wind energy production. One of the challenges facing the wind energy industry is the design of the wind farm layout. Commercial wind farms have multiple wind turbines operating relatively close to each other. Owing to their proximity, the wakes of the upstream turbines interact with the downstream turbines, leading to significant aerodynamic interference. Such interference between the turbines is referred to as turbine-turbine interaction. Additionally, in the case of an onshore wind farm, the surfaces on which the turbines are erected may be complex. The terrain may have features like hills, trees, buildings, etc., and the effect from such topographical features on the wind turbines is referred to as turbine-terrain interaction. The interference from the terrain adds to the complexity of the flow-field. As a result of turbine-turbine and turbine-terrain interference, all turbines in a wind farm do not face a free-stream, leading to sub-optimal power output. The presence of terrain also causes high wind shear and turbulence, resulting in increased fatigue loads on the turbines (Røkenes, 2009). In the design of a modern wind farm, there is an increased emphasis to understand the effects of the turbine-terrain interaction. In the initial design phase, numerical models are a suitable tool for optimizing the layout of the turbines on the terrain. Such optimization will minimize the turbine-terrain interference losses and result in a better overall performance. The objective of the present research is to develop a computational tool capable of simulating a wind farm, including the aerodynamic interference of turbine-turbine and turbine-terrain interactions.

Wind turbines have been an active area of research in the past three decades. A diverse range of literature, focusing on different aspects of the current problem of interest is available. Baker and Walker (1984) used primitive kite anemometers to measure the wakes behind MOD-2 turbines at the Goodnoe Hills in Washington, USA. They found the wake profiles behind various turbines were not similar and deduced the reason to be topographical effects. Elliott and Barnard (1990) performed more extensive measurements at the same location with bi-vane anemometers to measure the wake properties and found a linear relationship between velocity deficit and downstream distance. The effects of the roughness caused by the trees upwind of the site were also studied. Subramanian et al. (2015) used an autonomous, sophisticated drone to measure the near-wake properties behind a single turbine located in the Mont Crossin wind farm in Switzerland. They observed

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the pitch between subsequent tip vortices increased in the near-wake as it evolved. Kim et al. (2015) used meteorological towers before and after construction of the Yeongheung wind farm in the mountainous island of South Korea. A significant increase in the wind shear and turbulence intensity was observed after the construction of the wind farm. The downside of field measurements in a wind farm is that they are useful for post construction analysis and not directly useful in the initial design phase. Additionally, they are often expensive, time consuming, require massive logistics, and result in turbine downtime.

Migoya et al. (2007) numerically studied the Sotavento wind farm located in the Galicia region of Spain. The turbine wake effects were taken into account using the UPMPARK model, which is based on the UPMWAKE model proposed by Crespo et al. (1985), Crespo and Hernández (1989). The terrain was accounted using Migoya et al.'s linearized UPMORO model and the linearized WAsP model (WAsP, 2016). These linearized models were found to be suitable only for attached flows and they had to resort to non-linear Computational Fluid Dynamics (CFD) in the case of separated flows. Ivanell (2009) made use of an existing in-house CFD code, EllipSys3D, with actuator disk and actuator line turbine models to perform Large Eddy Simulations (LES) of turbine-wake interactions at the offshore Horns-Rev wind farm (with no complex terrain). An inverse relationship between the turbine wake length and the turbulence intensity was found from the numerical studies. Porté-Agel et al. (2013) found the direction of the incident wind angle had a dramatic impact on the turbine-wake interactions and a small change of 10° in the wind angle from the worst case scenario caused a 43% increase in the total power output at Horns-Rev. As a part of the Upwind WP8 (Barthelmie et al., 2011) project, Prospathopoulos et al. (2008) studied the influence of terrain on turbines using two different non-linear CFD solvers and the linearized WAsP (2016) model. The CFD solvers were body-fitted RANS solvers with various $\mathcal{K}-\epsilon$ and $\mathcal{K}-\omega$ turbulence models. A simplistic actuator disk model without the swirl effects is used to model the turbines. The actuator disk model extracted axial momentum using a single thrust coefficient (C_t) value known *a priori*. Moreover, the C_t value is an input parameter, obtained from an analytical or experimental thrust-velocity correlation for the specific turbine. This simple actuator disk model does not consider the turbine blade sectional properties or the effects of turbine-induced wake-swirl. Using these codes, flow through a turbine on a flat, quasi-3D, 3D Gaussian terrain (Prospathopoulos et al., 2008), and a complex wind farm site in Spain (Prospathopoulos et al., 2010) were simulated. Makridis and Chick (2013) used the commercial CFD software Fluent, with unstructured grids to simulate wind turbines on complex terrains. The RANS equations along with the *Reynolds* stress turbulence model are used for flow solution. The wind turbines are modeled using the Fluent's virtual blade model developed by Ruith (2005), based on the momentum source model for vertical axis wind turbines and helicopters by Rajagopalan and Fanucci (1985), Rajagopalan and Chin (1991), Rajagopalan and Mathur (1993), Zori and Rajagopalan (1995). Makridis and Chick performed simulations of flow over the Askervein Hill without turbines, single turbine on a flat terrain, and a coastal terrain wind farm site. Castellani et al. (2015) used an existing RANS solver, WindSim, with the RNG $\mathcal{K}-\epsilon$ turbulence model to study two wind farm sites located in southern Italy. The wind turbines are modeled with the actuator disk model and the swirl effect is ignored. Also in this analysis, the power estimation is based on the pressure differential across the turbine disk and not the mechanical torque on the blades. Numerical estimation of wind speed-up, wind directional shifts, turbulence intensity, and power were compared against the turbines' Supervisory Control and Data Acquisition (SCADA) data sets.

The present work involves studying multiple wind turbines on a complex terrain using a new RANS-based computational tool capable of simulating turbine-turbine and turbine-terrain interactions. For proper resolution of geometry in flows involving complex terrains, there is a need to use an unstructured or a structured body-conforming grid. Within the scope of structured body-fitted grids using general curvilinear coordinates, there are a variety of methods that differ in their equation formulation (Rhie and Chow, 1983; Shyy et al., 1985; Demirdzic et al., 1987; Karki and Patankar, 1988; Yang et al., 1990; Tamamidis and Assanis, 1993; Lien and Leschziner, 1994; Sharatchandra and Rhode, 1994; Graef et al., 1997). Recently, Murali and Rajagopalan (2016), Murali (2016) proposed a new mixed basis *Navier–Stokes* formulation for simulating convection-dominated flows over complex geometry. The new mixed-basis *Navier–Stokes* formulation uses structured, general curvilinear, non-orthogonal body-fitted coordinates for accurate terrain geometry incorporation. The flow-field is solved using the full *Reynolds Averaged Navier–Stokes* equations. Three different turbulence closure models including the standard (Jones and Launder, 1972), RNG (Yakhot et al., 1992), and realizable $\mathcal{K}-\epsilon$ (Shih et al., 1995) are implemented and compared. The momentum source method of Rajagopalan and Fanucci (1985), Rajagopalan and Chin (1991), Rajagopalan and Mathur (1993), Zori and Rajagopalan (1995), Guntupalli and Rajagopalan (2010) is used to model the wind turbines. The incompressible *Navier–Stokes* equations are solved using the pressure-based SIMPLER algorithm by Patankar (1980). Results validating the ability of the current CFD solver to simulate flows over complex terrains and wind turbines are presented first. Cases exploring the turbine-wake and complex terrain interactions are studied. Results relating to the turbine performance, blade loading, and wake interactions with the terrain are also analyzed. It is noted here the present literature overview only addresses prior work relating to wind turbines on complex terrains. A more detailed overview relating to other aspects of current problem of interest, including wind flow prediction over a complex terrain and wind turbine wakes are presented in Murali (2016).

2. Governing equations and methodology

2.1. *Mixed basis* Reynolds Averaged Navier–Stokes *equations*

This section briefly introduces the equations that govern the fluid flow. The mixed basis *Reynolds* averaged mass and momentum conservation equations are given by,

$$\frac{\partial \rho}{\partial t} + \frac{1}{\sqrt{g}}\frac{\partial}{\partial x^i}\left(\frac{\rho\sqrt{g}\,g^{ij}\,v_j}{h^j}\right) = 0, \tag{1}$$

$$\frac{\partial \rho v_i}{\partial t} + \frac{1}{\sqrt{g}}\frac{\partial}{\partial x^j}\left(\frac{\sqrt{g}\,t_i^{\,j}}{h_j}\right) + h^i\frac{\partial p}{\partial x^i} + h^i\frac{\partial}{\partial x^i}\left(\frac{2}{3}\rho\mathcal{K}\right) = \left(\Gamma_{ij}^k\,h^i + \delta_{ik}\frac{\partial h^k}{\partial x^j}\right)\frac{t_k^{\,j}}{h^k h_j} + s_{i-WT}. \tag{2}$$

The mixed form representation of the convection-diffusion flux is $t_i^{\,j} = \rho v_i v^j - 2(\mu+\mu_t)s_i^{\,j}$, where the components, $s_i^{\,j}$, of the mean strain rate tensor are given by,

$$s_i^{\,j} = \frac{1}{2}\left\{h^i h_j\left(\frac{\partial(v_i/h^i)}{\partial x^k} - \frac{v_l}{h^l}\Gamma_{ik}^l\right)g^{kj} + h^j h_i\left(\frac{\partial(v_j/h^j)}{\partial x^k} - \frac{v_l}{h^l}\Gamma_{jk}^l\right)g^{ki}\right\}. \tag{3}$$

Here ρ, v_i, v^i, p, μ, μ_t, $\mathcal{K}$, and $s_{i-\mathcal{WT}}$ are the density, physical covariant velocity, physical contravariant velocity, pressure, molecular viscosity, turbulent eddy viscosity, turbulent kinetic energy per unit mass, and force per unit volume of fluid due to the presence of wind turbines, respectively. Eqs. (1), (2) and (3) also contain geometric terms like g^{ij}, Γ_{ij}^k, h_i, h^i, and g which are the components of the contravariant metric tensor, *Christoffel symbols of the second kind*, covariant scale factor, contravariant scale factor, and the determinant of the covariant metric tensor, respectively. No summation is implied on the repeated indices when used with scale factors. Additional details on the mixed-basis governing equations, formulation, and its advantages are explained in Murali and Rajagopalan (2016) and Murali