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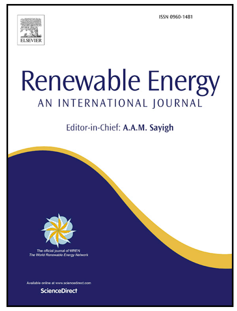

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A Novel Hybrid Free-Wake Model for Wind Turbine Performance and Wake Evolution

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Abstract

A new free-wake analysis for wind turbine aerodynamics is developed to accurately predict turbine performance and downstream wake evolution. A key feature is the Constant Circulation Contour Method (CCCM) which is a novel free-wake model for wind turbine wakes. This method characterizes a turbine wake by a number of resultant vortex filaments, avoiding the numeric artifact of a vortex lattice comprised of trailing and shedding vortices. The natural capture of wake roll-up and distortion using CCCM is illustrated and its computational complexity is demonstrated to be lower than Vortex Lattice Method (VLM). For accurate blade downwash calculation, a hybrid free-wake model is developed by combining CCCM with a VLM wake immediately behind turbine blades, which transitions to CCCM further downstream. Important properties of this hybrid wake are discussed and optimized to enhance model accuracy and efficiency. Blade static stall and unsteady effects are included. The hybrid model is validated through comparison to the wind tunnel experiments UAE Phase VI and MEXICO. Simulation examples are presented showing the utilization of this free-wake analysis to investigate wake steering, demonstrating the potential application of this method to wind farm scale wake simulations.

Keywords: wind turbine wakes, free wake method, free vortex method, Constant Circulation Contour Method, turbine wake control, turbine wake interaction

1. Introduction

Wind turbines located in wind farms operating within the influence of energy-depleted upstream turbine wakes experience substantial power loss. Measurements at the Horns Rev Wind Farm [1] show the downstream turbines can only operate at their 60% potential. One promising method to alleviate this problem, discussed in [2, 3], is to redirect the turbine wake upward so that it rises above the downstream turbine, or at least avoids full impingement. To explore the possibility of improving efficiency by controlling downwind wakes, it is crucial to obtain insights into detailed wake structures, especially behind yawed and tilted turbine rotors. Turbine wake simulation must be performed in an accurate and efficient manner to achieve this goal.

Three types of numerical models for turbine wake simulation are in common usage: the Blade Element Momentum method (BEM); the vortex based free-wake method; and Computational Fluid Dynamics (CFD). Due to its high computation efficiency and fairly accurate turbine performance calculation, BEM has been widely used in industry to solve engineering problems for individual turbines. However, the BEM’s theoretical assumptions and idealizations make it incapable of simulating turbine wake evolution and the interaction of upstream wakes with downstream turbines. A number of CFD codes, therefore, have been developed to perform wind turbine wake simulations [4, 5, 6, 7, 8, 9]. Alternatively, the utilization of CFD simulation is largely restrained by its requirement of substantial computation resources and long computation time. The free-wake method [10, 11, 12] is intermediate between BEM and CFD. It only requires moderate computer resources yet offers relatively high accuracy for turbine performance and wake simulation.

The most commonly used free-wake scheme is the Vortex Lattice Method (VLM), which characterizes the wake using a discrete lattice comprised of shedding and trailing vortex segments. These constituent segments’ endpoints are convected with local fluid resultant velocity, and their positions are updated at each time step. One concern regarding this lattice representation of the wake is its limitations in simulating wake rollup and heavy distortion, unless extremely fine lattice is used. Moreover when the wake extends far behind the turbine, the required computational resources are relatively high, leading to a computationally slow simulation.