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Adapted two-equation turbulence closures for actuator disk RANS simulations of wind & tidal turbine wakes

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ABSTRACT

Reliable methods for modelling wake recovery within a farm of wind or tidal turbines are critical for obtaining accurate estimates of annual energy production, and for detailed farm layout optimization. These are important objectives for maximizing energy yield while minimizing costs. Computational fluid dynamics (CFD) simulation is rapidly being adopted as a tool for flow modelling in wind and tidal farms, gaining favour over more traditional and simpler empirically-determined wake models. The most practical methodology for CFD simulations of turbine farms uses an actuator disk (AD) representation for each rotor, which imposes the rotor forces by adding source terms to the governing equations rather than explicitly resolving the flow over the turbine blades. It is well understood that when using the AD approach, standard turbulence models tend to predict faster wake recovery than is observed in real flows. Thus, the standard CFD turbulence models must be adapted for use with the AD methodology. Additionally, because of the manner in which the AD approach distributes the rotor forces, it cannot resolve the system of discrete vortices trailed from the blade tips.

This article presents two contributions to improving AD simulations of wind/tidal turbine wakes. The first is identifying that the well-established k-ω SST turbulence model is appropriate for AD simulations because it mitigates the problem of over-predicting the initial wake recovery rate. The second contribution is a method to include the typically un-modelled production of turbulent kinetic energy due to the breakdown of trailed vortices. This method was tuned to minimize the wake error for three experimental test cases with different rotors and different ambient turbulence intensities {3,10,15}%. The new model was validated and compared to existing turbulence methods for the wake of a second rotor in a tandem array configuration with different separation distances and ambient turbulence intensities. The different models were assessed using an error metric designed to estimate the error in predicting the power production of a turbine array. The reduction of this error by the new model varied from case to case, but was on the order of 3.5–10%, compared to the standard k-ε model.

1. Introduction

This article explores turbulence modelling options for Reynolds-averaged Navier Stokes (RANS) simulations of wind or tidal turbine farms. For simulating an entire turbine farm, it is not computationally feasible to explicitly model each rotor geometry, so the influence of the rotor on the flow is often represented by adding momentum source terms to the governing equations. As summarized by Refs. [1,2], there are several approaches to how the source terms are distributed within the flow domain. The actuator-line (AL) approach concentrates the blade forces near the turbine blades and requires time-resolved simulations. The actuator-disk (AD) approach applies time-averaged forces over the swept area, allowing for steady-state simulations and reducing computational expense.

For turbine farm simulations the AD approach strikes a reasonable balance between accuracy and computation cost. This method is well established and predicts turbine performance with high accuracy for isolated rotors (e.g. Ref. [3]) and for rotors in flume tanks with high blockage [4]. However, a problem with the AD approach is that when using standard turbulence models, the wake recovers too quickly and hence interactions with downstream rotors are not well predicted. The primary problem is that the eddy viscosity is over estimated in the high-shear flow near the actuator

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disk region, resulting in overly fast mixing of the wake. Despite this, the AD approach remains a popular option due to its low cost and relative ease of implementation.

Several studies, reviewed in §2, have presented turbulence model modifications to improve wake recovery predictions by limiting the eddy viscosity. In this article, the eddy viscosity limiter of the two-equation SST turbulence model [5] is shown to provide good initial wake recovery predictions.

A secondary shortcoming of the AD approach is that it does not resolve the helical vortex system in the wake. A real wake is composed of a discrete system of vortices trailed from the blades, with the strongest vortices coming from the blade tips. The vortices are coherent immediately downstream of the rotor, but quickly become unstable and decay into small-scale turbulence. The timescale for this decay process is fastest when the ambient flow is highly turbulent. Since the vortices are not resolved in the AD method, it cannot resolve the production of turbulence resulting from the breakdown process. Therefore, this production must be modelled to obtain good predictions of wake turbulence. This article presents a model to account for this production which improved the match to experimental profiles of velocity and turbulence intensity.

2. Literature review

Many studies dating back to 1985 [6–15] have noted that the AD approach, combined with either the k-ε [16] or the k-ω [17] turbulence closure, overestimates the initial recovery rate by a wide margin. With both of these two-equation closures the primary interaction between the momentum equations and turbulence model is through the eddy viscosity μ_t. Thus the primary goal of the turbulence model is to accurately predict μ_t.

There have been many studies presenting modified turbulence closures to improve wake recovery predictions. Most have employed a limited set of field experiments at small wind-farms for validation. Field experiments of the following turbines/farms have been employed: the NASA/DOE Mod-0A [100]kW turbine [18]; the Nibe A and B turbines [19,20]; four Danwin [180]kW turbines [21]; eighteen [310]kW turbines at the Sexbierum farm [22]; five [2.5] MW turbines at the ECN test farm [23]; and three turbines at the Risø campus of DTU [15].

Based on such field data, researchers have proposed model modifications for neutrally- and stably-stratified atmospheric boundary layers (ABL). Crespo [6] initially proposed changing the constants of the k-ε model for consistency with a neutrally-stratified ABL. Building on Crespo's suggestion, El Kasmi and Masson [7] further introduced a source term in the ε equation, applied in a region near the turbine rotor, to represent the enhanced transfer of turbulent energy from large scales to small scales caused by the presence of the rotor. The source acts to reduce μ_t near the rotor, slowing the initial wake recovery, and greatly improved results for the Mod-0A and Nibe field studies compared to Crespo's formulation. For convenience, the model introduced by El Kasmi and Masson [7] is herein referred to as the k-ε+S_ε model.

Rados et al. [9] adapted El Kasmi's correction for use in Wilcox's k-ω model [17] and compared to results for stably-stratified conditions using ECN field-data, with reasonable wake profiles at 2.5D and 3.5D downstream of the rotors. Cabezon et al. [8] tested both the k-ε+S_ε model and a seven-equation Reynolds-stress model, comparing to data from the Sexbeirum experiment for neutral stratification. Both models overestimated the velocity in the near wake, but the far wake was reasonably predicted. The turbulence intensity was grossly under predicted in the near wake, however.

In very detailed studies, Réthoré et al. [10] and Réthoré [11] compared several modified two-equation turbulence closures to the Nibe and Sexbierum experiments, and to high fidelity LES simulations. The modified closures included: the k-ε+S_ε model; an eddy-viscosity limiter accounting for adverse pressure gradients; an eddy-viscosity limiter based on *realizability* constraints; and a model adapted from forest canopy modelling. Réthoré remained unsatisfied with all of these modifications. He noted that the k-ε+S_ε model produced an unphysical increase in ε near the rotor, which persisted downstream. He found that the realizability-based eddy viscosity limiter was the most theoretically sound, but did not produce sufficient change from the original k-ε model to give a good match to experiments.

Continuing from the work of Rados et al. [9], Prospathopoulos et al. [12] tested several modifications to Wilcox's k-ω model including (among others) El Kasmi's modification (adapted for k-ω) and a μ_t limiter based on Durbin's [24] realizability constraint for stagnation-point aerodynamics. El Kasmi's model required very different tunings for the Sexbierum and Nibe experiments, bringing into question its general applicability. The μ_t limiter approach was tuning-free and improved the results compared to the baseline (Wilcox) k-ω model, but did not achieve the same fidelity as El Kasmi's approach. Because of its better generality, Prospathopoulos et al. [12] recommended the μ_t limiter method for future studies.

Very recently, van der Laan et al. [25] tested a number of non-linear eddy viscosity models, which improved model predictions but unfortunately degraded the stability of the numerical solvers employed. Van der Laan et al. [15] presented a reduced-order version of a non-linear eddy viscosity model called the k-ε-f_P model; which accounts for non-equilibrium turbulence (*i.e.* local production and dissipation rates not in balance) by limiting μ_t in regions of high strain rate. This reduces the initial wake recovery rate similar to the k-ε+S_ε model, but without artificially increasing the dissipation rate. The k-ε-f_P model compared very well to detailed large-eddy-simulation (LES) results, and gave reasonable agreement to velocity profiles from the ECN, Nibe, and DTU experiments.

In summary, many modifications have been proposed to improve simulation fidelity of two-equation turbulence models. The most widely tested is the k-ε+S_ε model of El Kasmi and Masson [7], which has shown reasonable fidelity for a wide variety of cases. However as noted by Refs. [11,12], El Kasmi's approach requires different tuning coefficients for different experimental cases. It's addition of ε near the rotor has been shown to be non-physical [11,14]. It achieves a good match to the near-wake velocity by artificially increasing ε, which causes the wake turbulence to decay too quickly, thus resulting in too slow recovery further downstream. Despite these deficiencies it has achieved the best fidelity in matching field data so far. Most of the more recently proposed modifications involve limiting the eddy viscosity in regions of high mean strain. Proposed forms of this general strategy are based on: Durbin's limiter [12]; realizability constraints [11]; and non-equilibrium turbulence [15].

Higher-fidelity turbulence models such as LES and detached-eddy-simulation (DES) are now emerging as options for turbine-farm simulations. Recently, Troldborg et al. [26] used DES with actuator-disk, actuator-line and blade-resolved rotor representations. They showed good agreement between the three rotor representations, concluding that the actuator-disk is sufficiently accurate for wind-farm simulations. While this is a promising result, the high cost of DES simulations means that RANS simulations remain attractive for farm layout configuration and energy assessment studies. It is likely that such higher-fidelity turbulence models could be used to inform the development of future modifications to two-equation turbulence closures for RANS simulations.