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Sensitivity Analysis of Inflow Conditions and Turbulence Models on Wind Turbine Wake Simulation Using an AD/RANS Approach

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Abstract. This work is devoted to perform systematic sensitivity analysis of different turbulence models and various incoming wind conditions in predicting the wake flow behind a horizontal-axis wind turbine represented by an actuator disc (AD). The tested turbulence models are the standard $k-\epsilon$ model and the Reynolds Stress Model (RSM). Employing each turbulence model, the wind turbine immersed in four inflow conditions, including both uniform and non-uniform ones, is numerically studied. Simulation results are validated against Sexbierum field experimental data. Comparisons show that $k-\epsilon$ model is much more sensitive to the employed inflow conditions, with simulated wake velocity and turbulence profiles strongly differ from one condition to another; among them, a uniform TI & Length scale condition delivers the most accurate predictions. By contrast, comparisons identify that RSM is less sensitive to the inflow condition implemented, the results under all inflow conditions are consistently in fair match with the measurements; the RSM is found to be more robust for capturing wake behavior reliably when using the AD/RANS approach.

AMS subject classifications: 34H05, 45L05, 47F05, 76G25

Key words: Wind turbine wake, Actuator disc method, Inflow boundary condition, $k-\epsilon$ turbulence model, Reynolds Stress Model (RSM), atmospheric boundary layer.

1 Introduction

When the wind passing through a wind turbine, wake effect will be observed in the following downstream field. Wakes not only induce velocity deficit but also cause increased

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turbulence level, which will further lead to reduced power production and structural fatigue issues for turbines that located in the downstream area. Hence, it is quite necessary to study the wake development, in order to gain the highest possible efficiency from the wind and ultimately achieve maximum economic benefit for a wind energy project. With computational power increasing, numerous researchers [1–6] have employed computational fluid dynamics (CFD) to study the wake effect. However, as modelling the wake aerodynamics is a complicated and challenging process, there still remain three important challenges to face with: one is the accurate description of incoming wind condition, another is the accurate representation of rotor blades and the last one is the choice of suitable turbulence model to model the atmospheric and wake turbulence.

Wind turbines actually operate in the lower part of the atmospheric boundary layer (ABL), accurate modelling of this ABL wind is a prerequisite for reliable wake simulations. Just as Richards et al. [7] and AbdelSalam et al. [8] pointed out in their work, the incoming wind condition plays an important role in the wind turbine behavior and the wake characteristic. However, it has been found that different expressions of wind conditions exist in the literatures; for a wind engineering study, one of the difficulties that has not been treated satisfactorily is the choice of approximate input parameters to define the ABL flow [9]. More specifically, on one hand, due to economic concerns, the wind speed and its fluctions are measured only at hub height. With these data, a uniform inflow condition is obtained and then is employed in wake studies [10, 11]. Besides, in order to compare fairly with wind tunnel experiments that are conducted in uniform flow, some work [4] assumed the incoming wind was ideal and uniform. On the other hand, as considering the presence of wind shear effect in the ABL flow, a set of non-uniform profiles were theoretically proposed [7, 12], which have been widely used in computational wind engineering (CWE) projects. In addition, with the development of measuring instruments, vertical profiles of flow quantities can be obtained, then a non-uniform inflow condition would be derived accordingly. Under various uniform and non-uniform conditions, the authors in refs. [13, 14] discovered that their predictions varied significantly from one to another. All these facts raise a scientific question: how sensitive the predicted wind turbine wake filed when different sets of inflow conditions are input for the simulation setups.

The actuator disc (AD) model is the most widely used one for modelling the turbine rotor. The basic idea of the AD technique is representing the rotor with a permeable disc of equivalent area where the body forces are distributed on. Despite the fact that the AD approach cannot reproduce completely the wake flow behind the turbine, especially the fluid motion due to blade's swirl in the near wake region, it has proven its ability to model the far wake, providing acceptable results of the velocity deficit and the turbulence level [13,15–17]. Furthermore, Aubrun et al. [18] found out that the predicted wakes of full rotor rotating model and AD model are indistinguishable after 3 rotor diameters downstream of the rotor. All these works indicate that the AD approach strikes a reasonable balance between accuracy and computational cost for wake simulations, especially for wind farm simulations.