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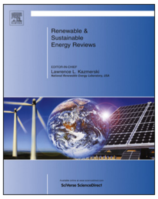

Wind turbine wake models developed at the technical university of Denmark: A review

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ABSTRACT

Wind turbine wakes are one of the most important aspects in wind power meteorology because they decrease the power production and increase the loading of downstream wind turbines. Therefore, there is a continuous need to find a 'good' wake model to properly plan wind power plant-level control strategies, predict the performance and understand the fatigue loads of turbines. In this paper, six widely used approaches of wake modelling (Jensen, Larsen, Dynamic Wake Meandering, Fuga and, Ellipsys3D LES and RANS together with their interpretations) that were developed at Technical University of Denmark, are described and the model subcomponents are analysed. The models are evaluated using data from the Sexbierum (onshore) and the Lillgrund (offshore) wind farms to understand how to best utilize them.

The paper provides a comprehensive conceptual background to wake modelling combined with the overview of the state-of-the-art models including their implementations on operating wind farms.

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1. Introduction

Wind turbine wake modelling concentrates on characterizing the flow behind wind turbines. There are two main physical phenomena of interest in the wake: (1) the momentum (or velocity) deficit, which causes a reduction in the power output of the downstream turbines, and (2) the increased level of turbulence, which gives rise to unsteady loading on downstream turbines.

The wake-induced power losses and blade loadings are studied in two regions within the wake, referred to as near and far wake. The near wake starts right after the turbine and extends to approximately 2–4 rotor diameters (D) downstream [1,2]. In this region, the flow is highly influenced by the rotor geometry, which leads to the formation of the blade tip vortices. In addition, there are steep gradients of pressure and axial velocity, and wake expansion. In the far wake, the effects of the rotor geometry are limited to the reduced wind speeds and increased turbulence intensities. Further, the turbulence is the dominating physical property in the far wake [3]. In addition to the rotor induced turbulence, the region further downstream is influenced by the large scale (or atmospheric) turbulence. The turbulence mixing accelerates the wake recovery in terms of both the velocity deficit and the turbulence intensity. In the far wake, the velocity deficit approaches a Gaussian profile, which is axisymmetric and self-similar [4]. Moreover, the meandering of the wake might also contribute to the recovery of the velocity deficit although it significantly increases the unsteady loading on the downstream turbine(s). All these elements lead to different approaches for the development of wind turbine wake models. Out of the many, widely used six models and their interpretations developed at the Technical University of Denmark (DTU) are presented here. First, the components of wake modelling are described in order to demonstrate the differences between the modelling approaches better and then the benchmark study for onshore and offshore cases has been performed. The paper is organized as follows: in Section 2, the Navier–Stokes equations are presented with the incorporated turbulence modelling form of Reynolds Averaged Navier–Stokes (RANS) and Large Eddy Simulation (LES), discussed in Sections 2.1 and 2.2, respectively. In Section 3, the subcomponents of wake modelling, namely the inflow generation, the wake summation, the calculation of the wind speed at the rotor, the modelling of the wind turbine in the simulations, and the assessment of wind direction and speed are listed. Note that all of these concepts are originally much more comprehensive than their descriptions presented here and are only explained in the frame of wake modelling. The wake models Jensen, Larsen, Dynamic Wake Meandering, Fuga and the flow solver Ellipsys3D (both RANS and LES versions) are described in Section 4 and they are implemented on the onshore Sexbierum and offshore Lillgrund wind farms in Section 5. Accordingly, the models are evaluated in terms of their targets of application in Section 6.

2. Governing equations

It is convenient to say, except for the blade tip region, that the physics of wind turbine wakes can be described by the incompressible Navier–Stokes equations, where the atmospheric flow velocities upstream and downstream of a wind turbine typically range between 4 and 25 m/s. The governing equations in Einstein notation and Cartesian coordinates are:

$$\frac{\partial u_j}{\partial x_j}=0, \tag{1}$$

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}(2\nu S_{ij})+f_i, \tag{2}$$