MODELLING OF WIND TURBINE WAKES

Jens N. Sørensen, Robert Mikkelsen, Niels Troldborg and Valery Okulov
Department of Mechanical Engineering
Technical University of Denmark

Abstract

In this paper we give an overview of models for the description of wakes behind wind turbines. Further, we present a new analytical vortex model as well as a numerical technique for simulating wake flows. The analytical vortex wake model, which is an extension of the classical work of Joukowsky, consists of distinct tip vortices embedded in a helical vortex core. Further, Large Eddy Simulation (LES) is combined with an actuator-line technique to study the genesis of the wake behind stand-alone turbines as well as behind a row of turbines. This technique is further employed to generate turbulence in the interior of wind farms. The advantage of utilizing numerical modelling in lieu of experiments is that the inflow conditions are easily controlled and that all relevant flow properties are described in detail. A computational grid of about 10 millions mesh points is employed. The interior of the wind farm is simulated using both conventional and cyclic boundary conditions, with the rotor simulated using actuator line technique with tabulated airfoil data. The simulated data are used to determine wake velocities and to derive turbulence intensities and associated low-dimensional turbulence models for later use in engineering BEM codes.

1. Introduction

Modern wind turbines are often clustered in wind parks in order to reduce the overall installation and maintenance expenses. Because of the mutual interference between the wakes of the turbines the total power production of a park of wind turbines is reduced as compared to an equal number of stand-alone turbines. Thus, the total economic benefit of a wind park is a trade-off between the various expenses to erect and operate the park, the available wind resources at the site, and the reduced power production because of the mutual influence of the turbines. A further unwanted effect is that the turbulence intensity in the wake is increased because of the interaction from the wakes of the surrounding wind turbines. As a consequence, dynamic loadings are increased that may excite the structural parts of the individual wind turbine and enhance fatigue loadings. The turbulence created from wind turbine wakes is mainly due to the dynamics of the vortices originating from the rotor blades. The vortices are formed as a result of the rotor loading. To analyze the genesis of the wake, it is thus necessary to include descriptions of the aerodynamics of both the rotor and the wake. Although many wake studies have been performed over the last two decades, a lot of basic questions still need to be clarified in order to elucidate the dynamic behaviour of individual as well as multiple interactive wakes behind wind turbines. Some of these questions are:

- How important is the dynamics of the vortex system
- How does the strength of the vortices depend on the blade load
- How does roll-up take place
- Is it possible to determine the conditions for the stability of the wake
- How far does ’far-wake’ refer to
- How far downstream can BEM be applied

- What is the relationship between vortex dynamics and meandering
- How does the added turbulence intensity relate to the loading

When regarding wakes, a distinct division can be made between the near and the far wake region. The near wake is normally taken as the area just behind the rotor, where the properties of the rotor can be discriminated, so approximately up to one rotor diameter downstream. Here, the presence of the rotor is apparent by the number of blades, blade aerodynamics, including stalled flow, 3-D effects and the tip vortices. The far wake is the region beyond the near wake, where the focus is put on the influence of wind turbines in park situations, hence modelling the actual rotor is less important. The near wake research is focussed on performance and the physical process of power extraction, while the far wake research is more focussed on the mutual influence when wind turbines are placed in clusters or wind farms.

In the work reported herein the main attention is put on near wake modelling, wake interference and generation of turbulence in wakes, and the presented results are restricted to uniform, steady and parallel inflow conditions, thereby excluding wind shear, tower interference and dynamic inflow. Although some of our recent research activities deal with skewed and turbulent inflow conditions, the results are not yet published, and will not be included in this presentation. In a recent survey by Vermeer, Sørensen and Crespo (2003) both near wake and far wake aerodynamics are treated, whereas a survey focusing solely on far wake modelling was earlier given by Crespo, Hernandez and Frandsen (1994). For general overviews on wind turbine rotor aerodynamics and aero-elasticity we refer to the surveys by Snel (1998), Leishman (2002) and Hansen et al. (2006).

In the past years we have developed analytical and numerical techniques for studying wind turbine wakes. The analytical model, which is an extension of the classical vortex wake model of Joukowsky, consists of distinct tip vortices embedded in a helical vortex core. In the numerical model the gross flow field around the rotor is simulated by the Navier-Stokes equations, using direct or Large Eddy Simulation (LES) techniques, with the rotor loading represented by body forces. This technique enables to study wake dynamics without having to resolve in detail the viscous boundary layer of the rotor blades. The computational results are analyzed for their content of organized anisotropic and coherent structures. The computations form the background for the development of a low-dimensional wake turbulence model based on proper orthogonal decomposition.

In the presentation we give a survey of wake models, and show and discuss recent results from simulations of multiple wakes and demonstrate how they can be used to create low-dimensional turbulence models.

2. Survey of Wake Models

At a first glance the aerodynamics of wind turbines may seem much simpler than the aerodynamics related to aircrafts. The description is complicated, however, by the fact that the inflow is always subject to stochastic wind fields and that, for machines that are not pitch-regulated, stall is an intrinsic part of the operational envelope. Indeed, in spite of the wind turbine being one of the oldest devices for exploiting the energy of the wind, some of the most basic aerodynamic mechanisms governing the power output are not yet fully understood. Although there are a large variety of methods for predicting performance and loadings of wind turbines, the only approach used today by wind turbine manufacturers is based on the blade element/momentum (BEM) theory. A basic assumption in the BEM theory is that the flow takes place in independent stream tubes and that the loading is determined from 2-dimensional sectional aerofoil characteristics. The advantage of the model is that it is easy to