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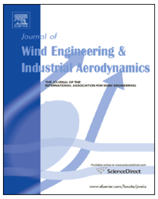

Experimental and numerical studies on the wake behavior of a horizontal axis wind turbine

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ABSTRACT

The wake characteristics of a horizontal axis wind turbine have been investigated, both experimentally and numerically. The computational numerical solution was carried out for the full rotor model, using a Navier–Stokes solver, employing the k–ε model appropriately modified for the atmospheric flows. The experiments were conducted at a 2 MW wind turbine for the measurements of upstream wind speed profiles, using SOund Detection and Ranging (SODAR), and wake wind speed profiles using Light Detection and Ranging (LIDAR), at varying distances between 2 and 7 times the rotor diameters downstream of the wind turbine. The evaluation of the computational model is made by comparing the predicted and measured velocities at the prescribed downstream locations at different upstream wind speeds. The present numerical setup employing the k–ε model and the fully mesh resolved rotor shows good agreement with the measurements. The model is used to find the relation between the wind speed and the wake recovery.

1. Introduction

The wake modeling of wind turbines has been a major issue of ongoing research, and a very challenging problem in the technical planning of wind projects, especially in last few decades, to maximize the energy production and to ensure the structural integrity of the wind turbines. Despite intense effort, and the progress made by many researchers around the world, in the possibility of generalizing the turbulence models used to predict the wake behavior under different conditions, a general solution has still not been found. As the rotational motion is induced by the turbine blades and the atmospheric stability is also expected to have a significant impact on the flow structure, the study of wind turbine wakes is a complicated problem, and depends on a large number of parameters. Therefore, it is one of the most important issues, that requires a detailed and in-depth study for prediction, as well as measurement of the horizontal axis wind turbine wakes. The ability to predict the spatial distribution of the mean wind speed deficit is essential, to optimize the design of wind farms. The spatial distribution of the turbulence intensity generated in the wake is very important in the determination of the fatigue loads on the subsequent wind turbines located downstream.

In order to verify the CFD results, the actual measurements are needed on large wind turbines. The wind speeds are measured at fixed distances from the wind turbine at the wind farm, over a long duration, using the meteorological masts (Barthelmie et al., 1996; Frandsen et al., 1996), but the disadvantages are, that the location of the measurements is fixed, so the wake distance is fixed, and the data are only available up to the hub height, and are rarely made above that height. The hub heights rise to around 100 m at present, and the huge wind turbines pose a difficulty in the wake measurement, using the meteorological mast. This limitation led to the widespread use of two remote sensing instruments, Sodar and Lidar, in the wind energy industry. Steven and Eamon (2011) compared the data measured by Sodar and Lidar instruments, with that measured by an instrumented mast, in a semi-complex terrain. Their regression analyses provided a good correlation between the remote sensing data and the mast data. Sodar instrument was used by Barthelmie et al. (2012), to determine the magnitude and vertical extent of the wake. The Sodar measured the wake wind speed profiles at different distances downstream of the wind turbine, and the freestream wind profiles were obtained, by the same device, by shutting down the turbine. The vertical profiles reported by them showed that the Sodar data compared well with the mast data. A ZephIR Lidar was installed

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in the rotating spinner of a large wind turbine, to investigate the approaching wind fields (Mikkelsen et al., 2010). They aimed to use the measured data as input to the wind turbines yaw and pitch control systems.

In recent years, more advanced Computational Fluid Dynamics (CFD) models are available, solving the three-dimensional (3-D) Navier–Stokes equations for the wake modeling. In these models, a wind turbine rotor can be represented by the actuator disk (Larsen et al., 2008) or actuator line approach (Troldborg et al., 2010). These models are capable of predicting the flow field behind the turbine, without using any initial near-wake data to start their calculations with. However, there is still a gap between the results of these CFD models and the actual data, and hence, a better use of the CFD is possible by providing more accurate representation of the physical problem including the boundary conditions, turbulence, and rotor modeling for modeling wakes, for better wind farm and turbine design, and for more load calculations and control strategies.

Atmospheric, blade-generated, and wake shear-generated turbulence are the three major contributors to the turbulence generated in the wake downstream of wind turbines. Using the eddy viscosity turbulence modeling, good predictions of the mean and turbulent flow fields depend on reasonable descriptions of the turbulent scales inside the flow. The standard k–ε model proposed by Launder and Spalding (1974), is the commonly-used isotropic two-equation turbulence model. This model, with standard model constants, has been employed for a large number of turbulent flow problems. Crespo et al. (1985) have proposed values for the model constants appropriate for the neutral atmospheric boundary layers. Since the dissipation rate equation is highly empirical, enhancement in the model performance is achieved by modifying the dissipation rate equation (Hanjalic and Launder, 1980). Chen and Kim (1987) have proposed a general approach, that was tested for a wide variety of turbulent flow problems, and yielded much better results than the standard k–ε model.

The numerical calculations using the standard k–ε model significantly underpredict the near-wake velocity deficit, compared with the measurements, especially in neutral atmospheric conditions (El Kasmi and Masson, 2008). These observations were made on the basis of the results obtained by the full 3-D Navier–Stokes model, and the rotor disk was simulated as a momentum sink in the Navier–Stokes equations through the actuator force. In order to improve the predictions, El Kasmi and Masson suggested a modification for the dissipation turbulence term in the ε equation, and used the model constants of Crespo et al. (1985). They impute the wake deficit underestimation to the rapid changes of turbulent kinetic energy production and dissipation rates close to the rotor leading to non-equilibrium turbulence. They have added an extra term to the dissipation rate equation, first suggested by Chen and Kim (1987), to represent the rate of energy transfer from large scale turbulence to small scale turbulence more effectively. A detailed survey on wind turbine wakes can be found in Crespo et al. (1999), Vermeer et al. (2003), and Sørensen (2011). Overall, it is not possible to establish any of the wake models as having a superior performance individually with respect to the measurements.

Abelsalam and Velraj (2014) compared the results of the full rotor approach using the standard k–ε turbulence model with the results of the actuator disk approach using the standard k–ε turbulence model and two modified k–ε models used by the earlier researchers. They concluded that the full rotor model showed good agreement with the available experimental data, in comparison with the improvement achieved by the actuator disc approach using modified versions of the k–ε model. It is understood from the literature that, there is little documentation available for the large scale wake measurements, especially in the near-wake regions for which very few datasets are available. Hence, in the present work, an experiment was conducted at a 2 MW wind turbine to provide additional data for the near and far wake regions. These datasets were also used to validate the CFD modeling and analysis performed to predict the wind turbine wakes at various wind speeds and to examine the performance of the k–ε model appropriately modified for the atmospheric flows, using the direct rotor modeling. Both Sodar and Lidar were used to measure the wind speed profiles in the upstream, and in the wake of a wind turbine respectively.

2. Experimental details

The measurement campaign was conducted on the three bladed 2 MW Kenersys wind turbine located at Kayathar, Tirunelveli, Tamil Nadu state, India. Two measuring instruments were used in the present work: (1) a Triton Sodar was used to measure the inflow wind speed profiles, and (2) a ZephIR 300 Lidar was used to measure the wake at different downstream locations. The layout depicting the top view of the wind turbine and the location of the two measuring devices is shown in Fig. 1.

The wind turbine, which has been operating since 2009 and located in a flat terrain, is yawed mostly toward the west (prevailing wind direction). The hub height is 80 m and the rotor diameter is 82 m. The period between 23rd July and 10th August was chosen for the experiment to avoid periods of rains and very low wind speeds. Further, to measure the wakes, wind speeds also have to be above the turbine cut-in wind speeds of 4 m/s, making the chosen time period more attractive. A histogram with the percentage occurrence of the mean hub height upstream wind velocity is presented in Fig. 2 (a). It shows that during most periods of measurements, the site is characterized by a high wind, with typical velocities between 9 and 12 m/s. Regarding the wind direction, the one with the highest incidence is 265° from the north as shown in Fig. 2(b). A high occurrence of turbulence intensity between 8% and 10 % is observed, as shown in Fig. 2(c).

2.1. Sodar measurements

The Sodar employed was the Second Wind's Triton® Sonic Wind Profiler, which is an ultramodern device designed for use in wind energy applications. The Sodar was installed at 2D upstream the wind turbine. No echo problems were encountered in the data records. The Triton was programmed to measure the wind parameters at 16 levels, in-between 38 m and 200 m above the ground. The Sodar was set to record the wind speed, wind direction, turbulence, and vertical wind speed continuously, and the average measurements of every 10 min were considered for the analysis.

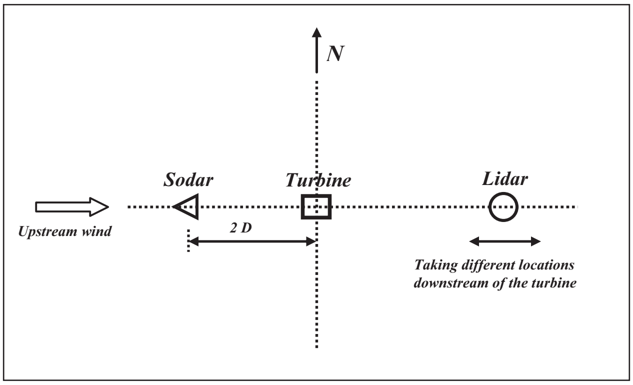

Fig. 1. Layout of the 2 MW wind turbine at Kayathar, India, with the location of Sodar and Lidar measuring instruments.