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Large eddy simulation of the wind turbine wake characteristics in the numerical wind tunnel model

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ABSTRACT

Large Eddy Simulation of NREL Phase VI wind turbine was performed in a virtual wind tunnel (24.4 m × 36.6 m) in order to achieve a better understanding of the turbine wake characteristics. For this purpose, ANSYS-Fluent package was used to run the simulation using the dynamic Smagorinsky-Lilly model. For the purpose of validation, the pressure distribution at different span-wise sections along the turbine blade and the power produced by the wind turbine were compared with the published experimental results for the NREL phase VI rotor tested in the NASA wind tunnel with the same dimensions as in the model and a good agreement was found between the two. The airflow immediately behind the wind turbine was observed to be a system of intense and stable rotating helical vortices, which determined the dynamics of the far-wake. The system of vortices in the near-wake became unstable and broke down due to wake instability at a distance of five rotor diameters downstream of the wind turbine. This was defined as the boundary between the near- and far-wake regions. The collapsed spiral wake was found to spread in all directions in the far-wake resulting in the formation of the two pairs of counter-rotating vortices which caused the gradual increase of turbulence in these regions. The turbulence intensity in the wake was observed to increase immediately behind the turbine with a maximum of 12.12% at a distance of three rotor diameters downstream of the turbine, after which a gradual decrease in the turbulence intensity was observed in the near-wake regions due to wake instability. However, in the far-wake regions, due to counter-rotating vortices formed by the wake instability, the turbulence intensity showed a tendency to increase intensity. Finally the time-averaged wake velocities from the LES, with and without the blockage corrections, were compared with WAsP and a comparatively good agreement for the axial velocity predictions was observed in the far-wake.

1. Introduction

Wind farms are locally clustered groups of wind turbines in the same location used to produce electric power. There are many advantages to this commercial structure; however profitable wind resources are limited to distinct geographical areas with relatively higher wind speeds. The introduction of multiple turbines into these areas increases the total wind energy produced and results in a reduction of the overall cost from an economic point of view due to the concentration of maintenance equipment and spare parts (Manwell et al., 2002). As of October 2010, 52 wind farms greater than 100 kW capacity operate in Australia (WEC, 2010). The Waubra wind farm near Ballarat, Victora, completed in 2009, is the largest wind farm in the southern hemisphere, consisting of 128 turbines spread over 173 km and rated at 192 MW. However, in terms of generating capacity, Lake Bonney wind farm near Millicent, South Australia is the largest with 239.5 MW, despite having only 99 turbines (ABS, 2010; WEC, 2010).

However, despite the commercial benefits of locally concentrated wind turbines, several drawbacks cannot be overlooked because in a wind farm most wind turbines operate in the wakes of other wind turbines. Wakes behind horizontal axis wind turbines are complex turbulent flow structures with rotational motion induced by the turbine blades, radial pressure slopes and tip vortices originating from the tip vortex-trailing edge interaction by local cross flows along the trailing edge (Mo and Lee, 2011; Wagner et al., 1996). From the perspective of a wind farm optimal layout, there are two major issues related to the wakes of wind turbines. The first one is the velocity deficit, which results in reduced power production for the downwind wind turbines. The second is the increase in the turbulence levels, which leads

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directly to an increase in the dynamic loads and hence has negative effects on the fatigue life of the turbine blades (Barthelmie et al., 2009,2008; Chamorro and Porté-Agel, 2009).

The wake behind a wind turbine can be classified either as near-wake or as far-wake; however no distinct classification of the two regions exists. According to Vermeer et al. (2003), the near-wake is defined as the area just behind the wind turbine rotor and is considered to be one diameter downstream. It is the region of the wake where the effects of the rotor aerodynamics are apparent on the wake structure. On the other hand, the far-wake is the region beyond the near-wake. Here the effects of the wake on the downstream wind turbines in farm situations are generally considered. Understanding the turbulent wake characteristics behind a wind turbine has been the subject of research, both experimentally and numerically, over the last few decades (Vermeer et al., 2003; Corten and Nederland, 2001; Crespo et al., 1985).

In general the approaches reviewed by Vermeer et al. (2003) and Crespo et al. (1985) have been adopted to study wind turbine wakes. The work presented here is a continuation of the UPMWAKE model proposed by Crespo et al. (1985) and Crespo and Hernández (1989) which was based on the $k-\varepsilon$ closure methods and the explicit algebraic model for the predictions of components of the turbulent stress tensor as proposed by Gómez-Elvira et al. (2005). However, in all these methods, the Reynolds-Averaged Navier–Stokes (RANS) was used over all the turbulence scales and thus made it difficult to accurately predict the turbulence characteristics of the wake.

Other semi-empirical methods like the Lissaman model (Lissaman and Bate, 1977; Lissaman et al., 1982) and its derivatives (Vermeulen et al., 1981) and the Risø model (Jensen, 1983; Katic et al., 1986) are based on using a near-Gaussian wake shape and a top-hat shape for the velocity deficits respectively. Furthermore, certain details in the flow field around the turbine are neglected and the wakes are assumed to expand linearly with distance. A number of attempts have been made to establish more accurate wake models. However, so far advanced and detailed wake models, even when including an explicit representation of turbulence and its impact on the wake expansion, have not been able to produce convincingly better predictions (Barthelmie et al., 2006). Therefore, to overcome the limitations of these models, large eddy simulation (LES) has been used in this research as the tool to investigate the details of the wind turbine wake. LES will reproduce the unsteady oscillations of the flow characteristics over all scales larger than the grid size; consequently, the much-needed details of the turbulent characteristics of the wake in controlled environments have been obtained and presented in this paper.

To the best of our knowledge, very little work has been published in which LES is used to simulate a wind turbine rotating in a wind tunnel. A number of researchers have used CFD, based on the RANS equations to acquire comparatively fast results (Menter et al., 2006; Potsdam and Mavriplis, 2009; Sørensen et al., 2002b). Others have used LES to simulate the wake flows without the turbines, combined with the actuator line and disc methodologies (Wu and Porté-Agel, 2001). However, the approach of "return to the basics" as proposed by Vermeer et al. (2003) is highly valuable, in that it provides the opportunity to study the aerodynamics of the wind turbines in controlled environments like wind tunnels. The objective of this investigation is to achieve a better understanding of the turbulent wake characteristics behind the wind turbine (NREL Phase VI wind turbine) that was tested in the NASA Ames 24.4 m × 36.6 m wind tunnel. For this, LES was carried out using the commercial CFD code, ANSYS FLUENT 13. The results of the LES have been compared with the aerodynamics of the wind turbine blade that were obtained experimentally by the NREL (Hand and Simms, 2001; Simms, 2001). Particular emphasis has been placed on the study of the distribution of the overall wake structure, time-averaged axial velocity (corresponding to velocity deficit) and the increased turbulence intensity in cross-sectional planes perpendicular to the axis of the wake at uniform incoming velocity. The study will be useful for the designers to plan and design future wind farms for the purpose of improvement of the overall wind farm efficiency and the fatigue life of the wind turbines. It also provides understanding of the turbulent wake characteristics of a wind turbine and the much needed results required for validation of turbine wake models. For this reason, the results of LES were also compared with the simple equations provided by WAsP to estimate the wake velocities in the far-wake.

2. Numerical simulation

2.1. Specification of the NREL phase VI wind turbine

In May 2000, NREL successfully completed the analysis of the Phase VI wind turbine in the NASA Ames 24.4 m × 36.6 m wind tunnel. The details of the experiment and the results were then released on the NREL website [1] in order to verify the performance of commercially available analytical codes developed around the world, while keeping the dependence on upstream parameters, such as the atmospheric boundary layer velocity and turbulence intensity profiles, to a minimum. The purpose was therefore to gain an insight into the wind turbine aerodynamics and loads with minimal interference from the upstream. Following in similar footsteps, the aim of the present article is to gain an in-depth understanding of turbine wake characteristics by suing the NREL Phase VI wind turbine for CFD simulations, as the

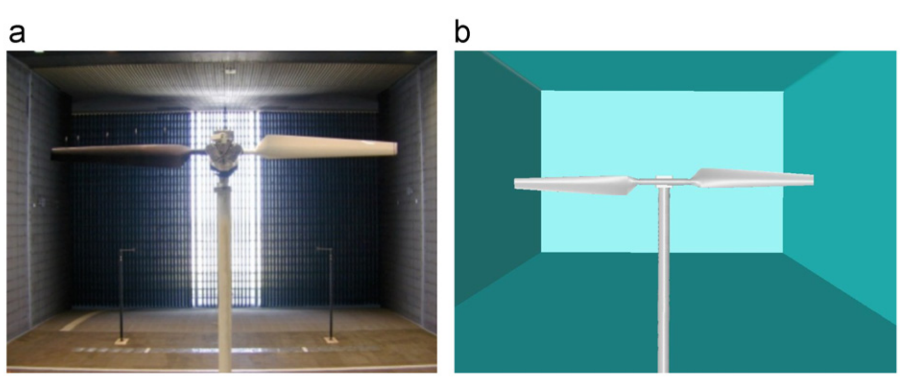

Fig. 1. (a) NREL Phase VI wind turbine in the NASA-Ames 24.4 m by 36.6 m wind tunnel and (b) CFD model of the turbine in a numerical wind tunnel.