Renewable Energy 94 (2016) 510–523

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Validation of four LES and a vortex model against stereo-PIV measurements in the near wake of an actuator disc and a wind turbine

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ARTICLE INFO

Article history:
Received 17 June 2015
Received in revised form
22 February 2016
Accepted 21 March 2016

Keywords:
Horizontal axis wind turbine
Wind turbine wake
Large eddy simulation
Actuator disc
LES validation

ABSTRACT

In this paper we report the results of a workshop organised by the Delft University of Technology in 2014, aiming at the comparison between different state-of-the-art numerical models for the simulation of wind turbine wakes. The chosen benchmark case is a wind tunnel measurement, where stereoscopic Particle Image Velocimetry was employed to obtain the velocity field and turbulence statistics in the near wake of a two-bladed wind turbine model and of a porous disc, which mimics the numerical actuator used in the simulations. Researchers have been invited to simulate the experimental case based on the disc drag coefficient and the inflow characteristics. Four large eddy simulation (LES) codes from different institutions and a vortex model are part of the comparison. The purpose of this benchmark is to validate the numerical predictions of the flow field statistics in the near wake of an actuator disc, a case that is highly relevant for full wind farm applications. The comparison has shown that, despite its extreme simplicity, the vortex model is capable of reproducing the wake expansion and the centreline velocity with very high accuracy. Also all tested LES models are able to predict the velocity deficit in the very near wake well, contrary to what was expected from previous literature. However, the resolved velocity fluctuations in the LES are below the experimentally measured values.

1. Introduction

In the last two decades, many new numerical wind turbine models have been developed, with varying degrees of complexity [27]. The ultimate challenge in computer modelling of wind farm aerodynamics is to obtain an accurate representation of the physics and an affordable computational cost, to enable the industrial use of computational fluid dynamics. Most industrial codes used today continue to rely on simplified physics and tuneable parameters, which need to be calibrated against experimental data (if available) or tuned according to the case [1,11,15,33]. One of the factors influencing the performance and computational cost of a numerical code, is the method used for modelling the wind turbine rotor. Various methods are available; ranging from detailed to very simplified, the two extremes are:

- fully-resolved blade geometry with its own boundary layer,
- modelling the effect of the wind turbine as an imposed velocity deficit.

Within these extremes, lies the moderately simple but efficient concept of the actuator disc (AD) [34], which models the turbine as a disc with a distribution of constant or variable body forces. As far as the flow field simulation is concerned, usually the Navier-Stokes equations are solved using a large eddy simulation (LES) or a steady or unsteady Reynolds Average Navier-Stokes (RANS and U-RANS) approach. While simple analytical models are still the standard for industrial applications [27,33], LES has been receiving more

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http://dx.doi.org/10.1016/j.renene.2016.03.070

attention by the wind energy community because of its ability to resolve unsteady and anisotropic turbulent flows characterised by large-scale structures and turbulent mixing, even though its computational cost is high [31]. Comparison against wind tunnel experiments can serve to validate computational models. Previous benchmarking studies have shown that numerically reproducing the wake of a single or two interacting wind turbines in a uniform inflow is a complicated task, despite the simplicity of the set-up (see the Blind Test 1 workshop in Refs. [17,18] and in the Blind Test 2 workshop in Ref. [27].

In this article, the results of the benchmark test organised in 2014 by the Delft University of Technology (TUDelft), the Netherlands, are reported. The purpose of this benchmark is to evaluate the accuracy and reliability of state-of-the-art numerical models in the near wake of a single actuator disc, a case that is highly relevant for modelling the flow behind wind turbines. In fact, it is known from literature that the AD concept often fails at reproducing the effects of flow turbulence, due to the absence of the blade tip vortices and their eventual breakdown [20]. In this regard, [33] emphasises the importance reducing the inaccuracy of the AD model within the wake spanning 5 rotor diameters downstream of the turbine, while stating that including rotational effects can visibly improve the model's performance. The experiments of [20]; however, have demonstrated that the actuator disc concept, should in principle, be able to reproduce with acceptable accuracy, the turbulent flow in the near wake. Comparison between LES and wind tunnel experiments by Ref. [38] revealed that the flow profiles behind turbines in a very large wind farm are reasonably well predicted when an actuator disc method is used, especially for turbines from the second row on. With the increased demands on utilization of available wind-farm space, the limitation to large downstream distances is no longer acceptable for many engineering applications. For example, in the Lillgrund off-shore wind farm, the turbines are separated by 3.3–4.3 diameters [13], while at the Horns Rev off-shore wind farm, the spacing is 7 diameters [5]. It is therefore crucial that numerical codes can resolve the near wake of wind turbines. In fact, the inability to correctly resolve the flow in the near wake of the turbines in the first row, has been identified as factor that influences the accuracy of power predictions for the rows that follow, as the incoming flow develops from an atmospheric boundary layer to a wind farm *canopy* boundary layer [32]. There a rich literature on the numerical simulation of the far wake and several benchmarks have been organised; e.g. the IEA project Wakebench was entirely focussed on the validation of numerical models for the far wake simulation [32]. However, currently a high-resolution validation of the performance of CFD codes in the prediction of the turbulent flow in the near wake an actuator disc is not available, in part due to a lack of high-quality experimental data for such a flow. For our validation study, we rely on the high-resolution measurements reported by Refs. [20]; with a stereoscopic particle image velocimetry (SPIV) analysis of the turbulent flow in the near wake of a porous disc (emulation of the numerical actuator disc) and a two-bladed wind turbine under the same operating conditions in two separate experiments. The experimental campaign was conducted in the large Open Jet Facility (OJF) at the Delft University of Technology: the experiments offered the rare opportunity to compare the wake of a wind turbine to the one of an actuator disc model directly in the wind tunnel under the same conditions. The double set of experimental wake data, in both the WT and AD wake, allows to compare the results of the actuator disc numerical simulations with both a real wind turbine and an actuator disc physical reproduction. Our benchmark pivots on a set of LES codes, which are often considered, despite recent blind test [27] results, to be the most accurate numerical models. The benchmark also includes comparisons with a vortex model, which unlike LES, offers a simpler inviscid, representation of the flow. Researchers with a suitable LES code were invited to simulate the experimental case using as input the known disc and turbine drag coefficient, the inflow characteristics, as well as the boundary conditions of the wind tunnel test. The challenge for the participants was to select the best LES turbulence sub-grid model, setting up the optimum numerical grid, and choosing the best model parameters in order to optimize their results. The high quality and reproducible experimental data were subsequently used to evaluate the performance of the different calculations.

2. Method

The experiments of [20] have been used as test case for benchmarking LES and a vortex model. In the above-mentioned study, two experimental campaigns were performed for providing a thorough analysis of the near-wake turbulent flow of a wind turbine (WT) and a porous disc emulating the AD numerical model. The turbulent velocity field in the wake was measured with a SPIV setup. The AD was reproduced with a porous disc manufactured to match the diameter and drag coefficient of the WT model. The WT wake analysis was conducted in presence of an instability of the tip-vortex helical structure, the so-called *leap-frogging*, a critical near-wake feature that determines a discontinuity in the development of turbulence. This phenomenon cannot be reproduced with the AD model and as such constitutes a major difference between the AD and the WT.

As mentioned in Section 1, this study comprises a set of LES codes and a simple vortex code. Five institutions participated in this study: the Technical University of Denmark, the Johns Hopkins University, the Energy research Centre of the Netherlands and the Catholic University of Leuven, each with their in-house LES code and the Delft University of Technology with its in-house vortex model. The study and subsequent validation focusses on:

- the comparison of the time-averaged axial velocity field and the wake's expansion;
- the comparison of the turbulence intensity in the wake;
- an accompanying grid convergence study of the LES codes.

The wake expansion is theoretically calculated as the width of the stream-tube encompassing the edge of the disc. Due to limitations in the data acquisition system, it was not possible to calculate the coordinates of the stream-tube in the flow field measured with stereo PIV. For this reason and consistent with the definition in Refs. [20]; the wake-width is defined as the locus of the points where the flow reaches 99% of the inflow velocity. The turbulence intensity *TI* is calculated as in Ref. [19] and shown in Eq. (1):

$$TI = \frac{1}{U_\infty} \sqrt[2]{\frac{1}{3}\sum_{i=1}^{3} \overline{u_i' u_i'}} \tag{1}$$

where U_∞ is the inflow velocity, the index i refers to the direction and is $i = 1,2,3$ respectively for the x-, y- and z-direction (axial, radial and out-of-plane, see Fig. 1 for a complete representation of the reference system) and the quantity $\overline{u_i' u_i'}$ represents the normal Reynolds stresses calculated as in Eq. (2)

$$\overline{u_i' u_i'} = \frac{\sum_{k=1}^{N} \left[u_i(t_k) - \overline{u_i}\right]^2}{N} \tag{2}$$

with N being the number of samples, t_k the sampling time and $\overline{u_i}$