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Comparison of wind farm large eddy simulations using actuator disk and actuator line models with wind tunnel experiments

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ABSTRACT

We compare wind farm large eddy simulations with the EPFL wind tunnel measurement by Chamorro and Porté-Agel (Bound-Lay. Meteorol. 136, 515 (2010) and Energies 4, 1916 (2011)). We find that the near turbine wake, up to 3 turbine diameters downstream, of a single turbine is captured better with the actuator line method than using the actuator disk method. Further downstream the results obtained with both models agrees very well with the experimental data, confirming findings from previous studies. For large aligned wind farms we find that the actuator disk model predicts the wake profiles behind turbines on the second and subsequent rows more accurately than the wake profile behind the first turbine row. The reason is that the wake layer profile that is created at hub height in very large wind farms is closer to the assumptions made in the actuator disk model than the logarithmic profile found in the inflow conditions. In addition, we show that, even in relatively coarse resolution simulations, adding the effect of the turbine nacelle and tower leads to a significant improvement in the prediction of the near wake features at 1 and 2 diameters downstream.

1. Introduction

Large eddy simulation (LES) has become a prominent tool for performing high-fidelity numerical simulations of wind farm flows [1,2,3]. When performing wind farm simulations with many turbines, fine grid resolutions are often not affordable. Therefore, coarse resolutions (on the order of 5–10 LES grid points across the rotor) must be used. In this paper we compare the performance of the actuator disk model (ADM) and the actuator line model (ALM) on relatively coarse grids, while we also consider the influence of modeling the nacelle and tower.

The validation of simulation codes against high fidelity experimental data is an important task that has been considered in several recent studies. Here we mention the blind tests workshops by Krogstad et al. [4,5], and Pierella et al. [6] in which the wake evolution behind single or two wind turbines was compared with different simulation and modeling approaches. The WAKEBENCH project [7] provides a comparison between different models for the Sexbierum single wake experiment. Comparisons between wind tunnel experiments, field experiments, and models were a focus of the ENDOW [8] and UPWIND [9] projects, and the well known MEXICO (Model Experiments in Controlled Conditions) experiments [10,11]. For an overview of different wind turbine modeling approaches we refer to the reviews by Sanderse et al. [12] and Sørensen [1]. Comparisons of wind farm LES with field measurement data can, for example, be found in Refs. [2,13,14,15,16,17,18]. Different wind farm modeling approaches are reviewed in Ref. [19].

The blind test comparison by Krogstad et al. [4,5] and Pierella et al. [6], in which different numerical methods are compared with experimental measurements, showed that the lack of a tower and nacelle in simulations results in a high velocity jet in the center of the rotor, which is not observed in measurements. Single turbine simulations, see for example Mittal et al. [20] and Santoni et al. [21], have shown that including the turbine tower and nacelle using an immersed boundary method is important to accurately capture the flow directly behind the wind turbine. Such a detailed approach is not possible for large wind farms, in which the resolution is too coarse to capture tower and nacelle using immersed boundary method. Therefore, attempts have been made to model the tower and nacelle with body forces. Wu and Porté-Agel [22] and Churchfield et al. [23] imposed a steady drag force to mimic the tower and nacelle and showed good agreement with measurement data, while Sarlak et al. [24] used an oscillating force with a

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frequency similar to the Strouhal frequency behind the cylinder that agree well with detailed immersed boundary method simulations presented by Santoni et al. [21]. Here we follow a similar approach by modeling the tower and nacelle using body forces and we present a systematic comparison of actuator disk and line model simulations, with and without nacelle, to show that on coarse resolutions this approach indeed gives improved predictions for the velocity profiles directly behind the turbine.

In this study, we validate our LES code for the simulation of a neutral atmospheric turbulent boundary layer flow with the single turbine and aligned wind farm measurements performed by Chamorro and Porté-Agel [25,26]. These measurements have already been used by previous authors to benchmark LES codes, see for example the work by Wu and Porté-Agel [3,22,27], Yang and Sotiropolous [28], Yang et al. [29], and Xie and Archer [30]. In an earlier study we used the Chamorro and Porté-Agel measurements [25,26] to compare ALM simulations with the single turbine case in order to study the effect of spatial filtering on the results in relatively coarse LES [31]. Here we focus on a comparison for the wind farm case [26], while we have now also added results obtained using the ADM for comparison. In section 2 we first introduce the LES approach before providing a detailed discussion on how the concurrent precursor method [32] can be used to reproduce the inflow conditions in the experiment. Subsequently, we introduce the ADM and ALM used to represent the model turbines in our simulation, and address how the turbine nacelle and tower can be included in relatively coarse resolution simulations. In section 3 we discuss the simulation results obtained with the ADM and ALM in comparison to the experimental wind tunnel measurements, and in section 4 we finish with the paper conclusions.

2. Method

We use a LES code that solves the filtered incompressible Navier-Stokes equations using a pseudo-spectral discretization in the horizontal directions and a centered second-order finite differencing scheme in the vertical direction [33,34,35]. In our simulations we use the scale-dependent Lagrangian subgrid model [36]. Coriolis and thermal effects are not specifically included, an approach also used in previous studies such as [22,37,38,39]. A second-order accurate Adams-Bashforth scheme is used for the time integration. Due to the very large Reynolds numbers considered here we parameterize the bottom surface by using a classic wall stress boundary condition [36,40]. This boundary condition relates the wall stress to the velocity at the first grid point using the standard logarithmic similarity law [33]. For the top boundary we use a zero vertical velocity and zero shear stress boundary condition so that the flow studied corresponds effectively to a ‘half-channel flow’ with an impermeable centerline boundary. The flow is driven by an applied pressure gradient in the x-direction, which in equilibrium determines the wall stress u_*^2 and the velocity scale u_* used to normalize the results of the simulations, together with the domain height H used to normalize length scales. In the remainder of this section we will first address how the inflow conditions obtained in the EPFL experiments can be reproduced in our LES before we discuss the ADM and ALM, and the modeling of the nacelle and tower.

The inflow condition is generated with the concurrent precursor method described in Ref. [32]. In this method the computational domain in the streamwise direction is divided in two sections. In the first section a neutral turbulent atmospheric boundary layer is simulated in a periodic domain using a pressure gradient forcing. Each time step the flow field from this simulation is used to provide the inflow condition for a second section in which the wind farm is placed. In the wind farm section, which is periodic due to the use of spectral methods in the horizontal directions, a long fringe region at the end of the computational section is used to make sure that there is a smooth transition from the flow formed behind the wind farm towards the applied inflow condition. In atmospheric boundary layer simulations a pronounced pattern of high and low velocity speed streaks is formed. We found that these streaks influence the results, especially for this case in which very local profiles are compared. To reduce this effect we average the results over very long times (up to 100 to 200 flow-through times) and very slowly shift the entire flow in the inflow generating domain in the spanwise direction to get well converged (streak independent) results. We note that this method is essentially an automated sequence of “individual” long simulations in which the position of the streaks is shifted with respect to the turbine location to get better statistics (see Munters et al. [41] for a more explicit shifted inflow method).

According to Wu and Porté-Agel [3,22] the roughness height in the wind tunnel experiments [25,42] is 0.03 mm and they report a boundary layer depth of about 0.45 m for the single turbine case and about 0.675 m for the wind farm case. The turbines used in the experiment have a diameter $D = 0.15$ m and the hub height z_h of 0.125 m. To match the inflow conditions from the experiments we set the domain height H in our simulations equal to the reported boundary layer depth δ, i.e. $3D$ for the single turbine case and $4.5D$ for the wind farm case. This defines the ground roughness height $z_{0,\mathrm{lo}}$, which is $z_{0,lo}/H = 6.667 \times 10^{-5}$ for the single turbine case and $z_{0,lo}/H = 4.444 \times 10^{-5}$ for the wind farm case. Fig. 1 shows a sketch of the simulation configuration and Fig. 2 the LES and experimental inflow profiles measured $1D$ in front of the first turbine row. Fig. 2 shows that the LES data capture the experimental profiles quite accurately.

To show how the roughness height $z_{0,lo}$ and boundary layer depth δ can be selected when this information is not directly available we compare the profiles in Fig. 2 with the theoretical estimates for the mean [43],

$$\langle \overline{u} \rangle / u_* = \kappa^{-1} \ln(z/z_{0,lo}) \tag{1}$$

and turbulence intensity [44],

$$\sigma(z) = \frac{\left[\left\langle \overline{(u'^{+})^2} \right\rangle\right]^{1/2}}{\langle \overline{u} \rangle} = \frac{\left[B_1 - A_1 \log(z/\delta)\right]^{1/2}}{\kappa^{-1} \ln(z_\mathrm{h}/z_{0,lo})} \tag{2}$$

observed in high Reynolds number turbulent boundary layer. Here the turbulence intensity is based on the observation of the logarithmic law for the variance

$$\left\langle \overline{(u'^{+})^2} \right\rangle = B_1 - A_1 \log(z/\delta), \tag{3}$$

while we use the velocity at hub height for normalization as is done for the experimentally reported measurements [3,22,25,26]. The constants A_1 and B_1, are measured in high Reynolds number turbulent boundary layers experiments, see Marusic et al. [43] for an overview. They concluded that $A_1 \approx 1.25$ is universal, while $B_1 \approx 1.5 - 2.1$ depends on the flow geometry. We previously found that for half channel flow $B_1 \approx 1.6$ gives a good estimation of the velocity fluctuations [40]. Fig. 2 confirms that the theoretical profiles represent the (LES) inflow conditions accurately for $z/\delta \lesssim 0.25$. As δ and $z_{0,lo}$ are the only unknown parameters that determine the mean velocity and turbulence intensity profiles these equations can be used to get a reasonable estimate for these parameters.