Validation of the Actuator Line Model with coarse resolution in atmospheric sheared and turbulent inflow

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Abstract. Wind energy has become cost competitive in recent years for several reasons. Among them, wind turbines have become more efficient, increasing its size, both rotor diameter and tower height. This growth in size makes the prediction of the wind flow through wind turbines more challenging. To avoid the computational cost related to resolve the blade boundary layer as well as the atmospheric boundary layer, actuator models have been proposed in the past few years. Among them, the Actuator Line Model (ALM) has shown to reproduce with reasonable accuracy the wind flow in the wake of a wind turbine with moderately computational cost. However, its use to simulate the flow through wind farms requires a spatial resolution and a time step that makes it unaffordable in some cases. The present paper aims to assess the ALM with coarser resolution and larger time step than what is generally recommended, taking into account an atmospheric sheared and turbulent inflow condition and comparing the results with the Actuator Disk Model with Rotation (ADM-R) and experimental data. To accomplish this, a well known wind tunnel campaign is considered as validation case.

1. Introduction
Wind energy is one of the most popular energy technologies, the increase in wind power in 2015 was close to half of global electricity growth, increasing wind power capacity 17% from 2014 to 2015 [1]. This amazing development of wind energy has been supported by technological improvements which are related to an increase in hub height, rotor diameter and unit power, which has led to larger capacity factors for the same wind speed [2]. This growth in size means, among other things, that the area of interest of the atmospheric boundary layer (ABL) swept by current wind turbine rotors reaches higher altitudes and it is placed further away from the surface. Also, the influence of different atmospheric conditions, such as turbulence intensity and vertical velocity gradient, in the wake of a wind turbine and in its performance would be larger [3][4][5][6].

Two approaches exist in order to represent the presence of a wind turbine in a simulation: actuator models, in which the blades are represented as body forces, and direct representation of the blade's geometry through the computational mesh [7].

Among the actuator models, the Actuator Line Model (ALM) has been widely validated recently [8][9][10][11][12][13], taking into account different inflow conditions. In general, it is recommended to use a spatial resolution of at least R/30 (R, rotor radius) and to set the time step size in order to limit the movement of the rotor tip to a grid cell length in each time step [13].
Recently, the ALM has been evaluated with coarser resolutions and also larger time steps, obtaining good results in the wake [14], for a stand alone and two in-line model wind turbines subjected to uniform inflow condition, almost without turbulent fluctuations [18][19], using two spatial resolutions (R/8 and R/16) and CFL, computed based on the tip speed, between 0.2 and 3.2.

The aim of the present paper is to continue the research done in the past years, taking into account an atmospheric boundary layer (ABL) like inflow condition, and to assess the capability of the ALM to simulate accurately the main characteristics of the wake with coarser resolutions. The wind tunnel campaign considered in [15] is selected as validation case.

2. Numerical method

caffa3d.MBRi [16][17] is an open source, finite volume (FV) code, second order accurate in space and time, parallelized with MPI, in which the domain is divided in unstructured blocks of structured grids. For further information please see [20][21]. Recently, the ALM and the Actuator Disk Model with Rotation (ADM-R) have been implemented in the code [22].

In the ALM, the wind turbine rotor is represented as a body force field, each blade is represented as a line that moves with the rotational speed of the rotor and it is discretized in radial sections where the aerodynamic forces are computed. To compute the force in each radial section, geometrical properties (chord length and twist angle) as well as aerodynamic properties (lift and drag coefficients) are found. The latter are obtained from tabulated airfoil data.

After computing the aerodynamic forces, it is required to project them from the representation of the rotor onto the computational domain. To accomplish this, a smearing Gaussian function is often used, taking into account the distance between each grid cell and radial section (d), in order to compute the additional source term. For the simulations presented in this paper, a smearing function with three coefficients, one for each direction (n-normal direction, r-radial direction, t-tangential direction), is used.

![Figure 1. A cross-sectional airfoil radial section.](image)

3. Validation case

3.1. Experimental campaign
An experimental campaign, performed at the St. Anthony Falls laboratory atmospheric boundary layer wind tunnel, is selected for validation [15]. It consists of one three-blade model wind turbine GWS/EP-6030×3 subject to a shear inflow condition with turbulent fluctuations (the mean wind speed is 2.2m/s at hub height and the turbulence intensity is 7.8%). The rotor diameter is 0.150m and the hub height is 0.125m. For further information please see [15].

3.2. Numerical setup
The size of the computational domain is 4.32m x 0.72m x 0.46m. Three spatial resolutions are considered, dividing uniformly the domain in each direction. Details of the numerical setup are presented in Table 1. It can be seen that the spatial resolutions used are less demanding than what is generally recommended (R/30).

We use the Crank-Nicolson scheme to advance in time and the scale dependent dynamic Smagorinsky model to compute the subgrid scale stress [23][24]. To represent the wind turbine rotor the ALM is used with 8 radial sections in each line, distributing the forces with a three dimensional
Gaussian function defined by three values of the smearing factor depending on the distance in each direction. The presence of the tower and nacelle are taking into account in a similar approach as presented in [15], through drag coefficients. The chord and twist angles are taken from [15] and the airfoils are considered as flat plates. The time step is 0.005s, taking into account the rotational speed of the rotor (1120 RPM), it means that the rotor rotates 33º approximately in each time step. A simulation using the ADM-R is performed for comparison with each grid resolution.

Table 1. Numerical setup

| Resolution | Nx  | Ny  | Nz  | ∆x (m) | ∆y (m) | ∆z (m) | R/∆x | R/∆y | R/∆z |
|------------|-----|-----|-----|--------|--------|--------|-------|-------|-------|
| R0         | 192 | 72  | 96  | 0.0225 | 0.0100 | 0.0048 | 6.7   | 15.0  | 31.3  |
| R1         | 128 | 48  | 64  | 0.0338 | 0.0150 | 0.0072 | 4.3   | 10.0  | 20.8  |
| R2         | 96  | 32  | 48  | 0.0450 | 0.0225 | 0.0096 | 3.3   | 6.7   | 15.6  |

4. Results

4.1. Comparison between ALM and ADM-R

In this section, the capability of the numerical approaches considered in this study are assessed by comparing the computed mean streamwise velocity component, streamwise turbulence intensity and shear stress against the experimental data at different locations in the wake in a vertical plane through the rotor centre and at a cross-section located 5D downstream from the rotor plane.

First, the computed mean streamwise velocity component is evaluated, as it plays a major role in the interaction between wind turbines within a wind farm. Figure 2 depicts the mean streamwise velocity component at different locations in the wake computed with the ALM and ADM-R, taking into account the spatial resolutions presented above. There are no significant differences between the wind turbine models considered, despite the spatial resolution used, as all of them are able to compute the mean velocity deficit in the wake accurately. The velocity deficit is larger in the centre of the wake close to hub height and it decreases towards the edges of the wake as expected. It should be mentioned that there is a slight difference between the precursor simulations as it can be observed in the vertical profile of the mean streamwise velocity component at 1D upstream of the rotor plane. The differences in the precursor simulations are more pronounced when considering the turbulence intensity as shown below.

Figure 3 presents contour plots of the mean streamwise velocity at a downwind distance of 5D. The simulation results are in acceptable agreement with the experimental data from [15], obtaining in general better results with the ALM. Nevertheless, both models are able to capture the asymmetry in the wake, characterized by lower velocity values close to the surface. It seems that the ALM is less sensitive to the spatial resolution compared with the ADM-R.

Regarding the turbulence intensity, Figure 4 shows the streamwise turbulence intensity at the same locations in the wake as presented above. Both approaches predicts with reasonable accuracy the turbulence intensity in the wake at 5D downstream from the rotor plane and further away, capturing the peak value located in the top tip level. Closer to the rotor plane the differences between the simulations and the experimental data are larger, in particular at 2D downstream from the rotor plane where the peak value at the top tip level is not captured. It should be mentioned that the main focus of this study is not the near wake (<3D from the rotor plane), where the geometrical characteristics of the wind turbine rotor determines the main characteristics of the wake as well as the performance of the wind turbine. Below hub height the models underestimate the turbulence intensity, in a similar way as [15]. From Figure 4, spatial resolution R2 seems to be too coarse to capture the evolution of the turbulence intensity peak along the wake. Figure 5 depicts the streamwise turbulence intensity at a cross-section located 5D downstream from the rotor plane. This results are consistent with the ones presented before, in general the turbulence intensity is slightly underestimated. Nevertheless, the simulations, particularly with the ALM, reproduce with an acceptable agreement the turbulence intensity patterns present in the experimental data.
Figure 2. Mean streamwise velocity at different locations in the wake. Grid: R0, R1 and R2.

Figure 3. Mean streamwise velocity at a cross-section located 5D from the rotor plane. a) ALM/R0, b) ALM/R1, c) ALM/R2, d) ADM-R/R0, e) ADM-R/R1, f) ADM-R/R2, g) experimental data [15].
Figure 4. Streamwise turbulence intensity at different locations in the wake. Grid: R0, R1 and R2.

Figure 5. Streamwise turbulence intensity at a cross-section located 5D from the rotor plane. a) ALM/R0, b) ALM/R1, c) ALM/R2, d) ADM-R/R0, e) ADM-R/R1, f) ADM-R/R2, g) experimental data [15].
Figure 6. Shear stress (m$^2$/s$^2$) at different locations in the wake. Grid: R0, R1 and R2.

Figure 7. Shear stress (m$^2$/s$^2$) at a cross-section located 5D from the rotor plane. a) ALM/R0, b) ALM/R1, c) ALM/R2, d) ADM-R/R0, e) ADM-R/R1, f) ADM-R/R2, g) experimental data [15].
With respect to the shear stress, the numerical approaches considered are able to capture the main features, by identifying two main regions with peak values of opposite sign close to the tip levels, above and below hub height, as presented in Figure 6 and Figure 7. As with the streamwise turbulent intensity, the shear stress is larger in the top tip level compared with its absolute value in the lower level. The non-symmetrical distribution of the shear stress with respect to \( y=0 \) is clearly visible in Figure 7. Both models tend to overpredict the peak value of the shear stress \( 7D \) downstream of the rotor plane and beyond, in a similar way as [15]. Again, there is not much influence of the spatial resolution and the actuator model used, although results obtained with grid R2 are slightly worse than the others.

4.2. Sensitivity analysis

To assess the influence of the subgrid scale model, another simulation is performed considering the standard Smagorinsky model (SM) with a wall damping function [25] with grid R1. A precursor simulation is performed as before, taking into account this subgrid scale model. Figure 8 depicts the mean streamwise velocity component at different locations in the wake computed with the ALM using the SM and the SDDSM as subgrid scale models, as well as the turbulence intensity and the shear stress at the same locations. It should be mentioned that the inflow conditions are different, overestimating the mean streamwise velocity with the SM. At 3D the mean streamwise velocity in the centre of the wake is well predicted by both subgrid scale models, but some differences are clearly visible close to the edges of the wake. Further away from the rotor plane, the wake obtained with the SM departs from the results obtained with the SDDSM and the experimental data, recovering slower than both of them. Regarding the turbulence intensity and the shear stress, there are slight improvements of the SDDSM over the SM. From this, it can be concluded that the results from the SDDSM are in closer agreement than the ones obtained with the SM, supporting the generalization of the dynamic procedure proposed in the SDDSM, particularly taking into account that no explicit filter is used (the implicit filter is unknown). The use of the SDDSM in a FV code deserves further investigation.

![Figure 8: Mean streamwise velocity (top), turbulence intensity (centre) and shear stress (bottom). Grid: R1.](image)

Regarding the influence of the smearing factor presented by several authors [14][26][27], a simulation is performed taking into account a 50% larger smearing factor in each direction (labelled EPS1), keeping the other parameters and using grid R1. Figure 9 presents the mean streamwise velocity component as well as the turbulence intensity and shear stress at different locations in the
wake. The differences are almost negligible, although there is some departure in the turbulence intensity 3D from the rotor plane. Looking at the turbulence intensity at a cross-section located 5D from the rotor plane (Figure 10), the differences are more pronounced, achieving a closer agreement with the lower smearing factor.

Figure 9. Mean streamwise velocity (top), turbulence intensity (centre) and shear stress (bottom). Grid: R1.

Figure 10. Turbulence intensity: experimental data [15] (left), EPS0 (centre) and EPS1 (right). Grid: R1

5. Conclusions
Actuator models have become one of the most popular techniques to represent wind turbines in a simulation performed with a computational fluid mechanics code. Among them, the ALM and ADM-R have been widely used recently to simulate single wake and multiple wake configurations under different inlet conditions. In general, it is argued that the ALM represents a closer representation of the wind turbine rotor, which would allow to obtain improved results in the wake closer to the wind turbine rotor plane. In addition to this, the ALM would allow to simulate different operational conditions, for example independent pitch control, in a more comprehensive way.

As a general rule, it is stated that the computational cost of the ALM is larger than the computational cost of the ADM-R, related to the spatial and temporal requirements. Previously, it has been argued by the authors that the spatial and temporal resolutions restrictions related to the ALM could be relaxed, using coarser resolutions and larger time steps than what is generally recommended.
In any case, taking into account the same grid and time step size, the computational cost of the ALM could be lower than the one achieved with the ADM-R. Further, if the wind turbine yaw could change during a simulation, the computational cost of the projection of the aerodynamic forces would be larger, probably increasing more the computational cost of the ADM-R. For that reasons, it is interesting to assess if the ALM can be used with coarser spatial resolutions and larger time steps.

In the present work, the ALM and ADM-R have been used to simulate a stand alone model wind turbine, subject to an ABL inlet condition, taking a well known wind tunnel campaign as validation case. From the simulations performed it is concluded that the ALM is able to capture the main characteristics of the wake with coarse spatial resolutions and using large time steps. The difference between the results obtained with the ALM and the ADM-R are almost negligible, with a slight improvement of the ALM. Taking into account the spatial resolution used and because of the projection function, the ALM approaches the Actuator Sector Model [28], in that sense it could be used with coarser resolutions achieving results with reasonable accuracy as has been shown, allowing to perform simulations with a closer representation of a wind turbine rotor. The results are not greatly influenced by the spatial resolution, however with the coarser resolution used both actuator models tend to overpredict the turbulent statistics despite computing accurately the mean streamwise velocity component.

A sensitivity analysis has been performed in order to evaluate the influence of the subgrid scale model and the smearing factor of the projection function. Regarding the former, the SDDSM performs better than the SM, particularly when computing the mean streamwise velocity component. With respect to the latter, there is some difference in turbulent intensity in the near wake region, being negligible further downstream.

As the ALM allows for a more realistic representation of the wind turbine rotor, for instance through independent pitch control, it is believed that the approach presented in this paper could help to simulate real operation wind farms with moderately computational cost.

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