Simulation of a 7.7 MW onshore wind farm with the Actuator Line Model

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Abstract. Recently, the Actuator Line Model (ALM) has been evaluated with coarser resolution and larger time steps than what is generally recommended, taking into account an atmospheric sheared and turbulent inflow condition. The aim of the present paper is to continue these studies, assessing the capability of the ALM to represent the wind turbines’ interactions in an onshore wind farm. The ‘Libertad’ wind farm, which consists of four 1.9MW Vestas V100 wind turbines, was simulated considering different wind directions, and the results were compared with the wind farm SCADA data, finding good agreement between them. A sensitivity analysis was performed to evaluate the influence of the spatial resolution, finding acceptable agreement, although some differences were found. It is believed that these differences are due to the characteristics of the different Atmospheric Boundary Layer (ABL) simulations taken as inflow condition (precursor simulations).

1. Introduction
Wind energy has expanded rapidly in recent decades all over the world. The increase in wind power in 2015 was close to half of global electricity generation growth and wind power capacity increased by 17% from 2014 to 2015 [1]. The growth rates have become lower in recent years, nevertheless the installed capacity is projected to increase in the following years [2]. This 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 [3]. This growth in size means, among other things, that the area of interest of the atmospheric boundary layer (ABL) swept by these wind turbine rotors, reaches higher altitudes and it is placed further away from the surface. It also means that 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, is larger [4][5][6][7].

Two approaches exist in order to represent the presence of a wind turbine in a simulation [8]: 1) actuator models, in which the blades are represented as body forces, 2) direct representation of the blade's geometry through the computational mesh. The Actuator Line Model (ALM) has been widely validated [9][10][11][12][13][14], showing to reproduce with reasonable accuracy the wind flow in the wake of a wind turbine with moderate computational cost. In general, it is recommended to use a spatial resolution of at least R/30, being ‘R’ the rotor radius, and to limit the movement of the rotor tip to a grid cell length in each time step [14]. Recently, the ALM has been evaluated with coarser resolutions and also larger time steps, considering a uniform inflow condition [15] as well as an Atmospheric Boundary Layer (ABL) like inflow condition. For the latter the ‘Horns Rev’ offshore wind farm and a well-known wind
tunnel campaign, were considered as validation cases [16][17], finding good agreement with the SCADA data in the power deficits in [17] and accuracy to reproduce the wake of the wind turbine in [16].

The aim of the present paper is to continue the research done in the past years, analyzing the power produced by the turbines and the influence of the wakes. For this, ‘Libertad’ onshore wind farm was simulated, considering different wind speeds and wind directions. The paper is organized as follows: Section 2 presents the solver and the ALM implementation, Section 3 describes the validation case used for the evaluation and the numerical setup, Section 4 presents the main results, discussing the effect of considering three different resolutions, and summary is given in Section 5.

2. Numerical method

2.1. Solver

caffa3d.MBRi [18] [19] is an open source, finite volume (FV) code, with second order accuracy in space and time, parallelized with MPI, in which the domain is divided in unstructured blocks of structured grids. Representation of complex geometries can be handled through a combination of body fitted grids and the immersed boundary method over both, Cartesian and body fitted grid blocks. Geometrical properties and flow properties, which are expressed in primitive variables, are always expressed in a Cartesian coordinate system, using a collocated arrangement. The large-eddy simulation (LES) technique is used in the simulations. For further information please see [18] [19].

The ALM has been implemented in the referred code [20]. In this model, the wind turbine rotor is represented as a body force field, where 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 determined. 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. In order to compute the additional source term, a Gaussian smearing function with three coefficients, is used, taking into account the distance between each grid cell and radial section (d), for each direction (n-normal direction, r-radial direction, t-tangential direction):

\[
f(d) = \frac{1}{E_n E_r E_t \pi^{1.5}} e^{-\left(\frac{d_n}{E_n}\right)^2} e^{-\left(\frac{d_r}{E_r}\right)^2} e^{-\left(\frac{d_t}{E_t}\right)^2}
\]  

3. Validation case

3.1. Libertad wind farm

Libertad is a 7.7MW onshore wind farm, located in the south of Uruguay. It consists of four Vestas V100 wind turbine generators (WTG), two with rated power of 1.9MW (WTG1 and WTG2) and two of 1.95MW (WTG3 and WTG4), all four with a hub height of 95m and a rotor diameter of 100m. It has a meteorological mast with anemometers and wind vanes that measure wind speed and wind direction at 93m height. The wind farm location and layout are shown in Figure 1.
3.2. Numerical setup

The size of the computational domain is 3.00km in the streamwise direction, 1.50km in the spanwise direction and 0.75km in the vertical direction. The domain is uniformly divided into 144 x 128 grid cells in the streamwise and spanwise directions respectively, while a stretched grid with 80 grid cells, is used in the vertical direction. The spatial resolution implies a resolution of $R/2.4$, $R/4.3$ in the streamwise and spanwise directions respectively, while in the vertical direction, 19 grid nodes cover the rotor diameter. A zero velocity gradient is imposed at the outlet and a wall model based on the log law is used to compute the stress at the surface while periodic conditions are used in the lateral boundaries. We use the Crank-Nicolson scheme to advance in time and the scale dependent dynamic Smagorinsky model to compute the subgrid scale stress [21][22].

The inflow condition is obtained from a precursor simulation. Figure 2 shows vertical profiles at the inlet boundary of the mean wind speed and turbulence intensity, averaged in the spanwise direction. At hub height the mean wind speed is 8.85m/s and the turbulence intensity 7.5%. Turbulence intensity is defined as the ratio between the standard deviation and the mean of the streamwise velocity.

Figure 2. Mean wind speed (left) and turbulence intensity (right) vertical profiles at inlet boundary

To represent the wind turbine rotor, the ALM is used with 12 radial sections in each line. To find the chord length and twist angle in each radial section, the geometrical characteristics of the Vestas V80 wind turbine presented in [23], were modified according to the following methodology: We apply the Blade Element Momentum (BEM) model [24] with different wind speeds ($U_{BEM}$), all of them lower...
than the rated wind speed. For each $U_{BEM}$ the SCADA data is sorted by $U_{MET} \in [U_{BEM} \pm 0.25 \text{ m/s}]$, where $U_{MET}$ is the wind speed measured by the met mast anemometer. The blade rotating speed we use in BEM is the mean angular speed of the sorted dataset. The pitch angle is $0^\circ$ in every case. Then, we compare the obtained power curve from BEM with the manufacturer’s one and with the power curve obtained from the filtered SCADA data. We modify the geometrical characteristics of the blade and repeat the procedure until an acceptable agreement is obtained between the power curves. The airfoil used is the NACA 63-415 for the entire blade. Lift and drag coefficients were also obtained from [23]. The fact that the chord and twist angle obtained along the blades with this procedure are not the exact values of a V100 blade, contributes to the uncertainties of the results presented below. Figure 3 shows the designed chord length and twist angle, the power curve obtained from BEM compared with the SCADA data and the manufacturer’s power curve (V100 PC), and the angular speed considered in BEM method.

![Figure 3](image-url)

**Figure 3.** Designed chord length (top left), twist angle (top right), power curve (bottom left) and angular speed (bottom right) from BEM, SCADA data and manufacturer’s power curve.

In the ALM implementation a variable rotational speed is considered, in a similar approach as explained in [23] for the Actuator Disk Model with Rotation, obtaining the relationship between the rotational speed of the rotor and its torque from the wind farm SCADA data. An efficiency of 0.93 is considered to compute the generated power from aerodynamic power [23].

4. Results

Simulations considering different wind directions were performed by changing the layout while keeping the distance between wind turbines and the West boundary as inlet boundary [17]. Three wind sectors were considered, $150 \pm 5^\circ$, $150 \pm 2.5^\circ$ and $132.5 \pm 2.5^\circ$, as shown in Figure 1. In order to compute the power associated to each wind sector, weighted averages were computed taking into account the results of the simulations of different directions:

$$P_{av\ 150\pm5^\circ} = 12.5\%\ P_{145^\circ} + 25\%\ P_{147.5^\circ} + 25\%\ P_{150^\circ} + 25\%\ P_{152.5^\circ} + 12.5\%\ P_{155^\circ}$$

(2)

$$P_{av\ 150\pm2.5^\circ} = 25\%\ P_{147.5^\circ} + 50\%\ P_{150^\circ} + 25\%\ P_{152.5^\circ}$$

(3)

$$P_{av\ 132.5\pm2.5^\circ} = 25\%\ P_{130^\circ} + 50\%\ P_{132.5^\circ} + 25\%\ P_{135^\circ}$$

(4)

The power obtained in the simulations and the weighted averages were compared with the power registered in the SCADA data, which was filtered as follows. Only 10-minute periods which met the following criteria were considered:
• $U_{MET} \in [U_{MET \, sim} \pm 0.2 \, m/s]$, where $U_{MET}$ is the wind speed registered by the met mast anemometer and $U_{MET \, sim}$ is the mean wind speed obtained in the simulation at the met mast position.

• $D_{MET} \in [D_{sim} \pm \Delta D \, ^\circ]$, where $D_{MET}$ is the wind direction measured by the met mast wind vane, $D_{sim}$ is the wind direction which is being simulated and $\Delta D$ is the wind sector considered, 5° in the first case and 2.5° in the other two.

• The four wind turbines were available, their power was greater than zero and no alarms were reported.

No filtering was made in terms of turbulence intensity or atmospheric stability. The sorted data is represented as the mean power value ± 1 standard deviation.

When comparing the simulation results with SCADA datasets, the yaw misalignment of the turbines, the spatial variability of the wind direction within the wind farm and the variability of the wind direction within the averaging period, contribute to the uncertainties, as presented in [25].

The power simulation results and their average, are presented in Figure 4 and Figure 5, including also the SCADA data.

**Figure 4.** Power production of wind turbines for each direction (150+/−5°) (top) and power weighted average by direction (bottom).
Figure 5. Power production of wind turbines for each direction (150±-2.5º) (top) and power weighted average by direction (bottom)

The results show good agreement with the SCADA data in both cases, with no major differences between them, so a wind direction window of ±2.5º was used when taking into account another wind sector below. The power deficit of WTG3 due to the wake of WTG4 is clearly shown in both figures, and it is slightly higher at 150º than in other directions, because the two wind turbines are aligned in that direction.

Another case was simulated, considering direction 132.5º, where WTG3, WTG2 and WTG1 are aligned. The mean wind speed at the met mast position is 8.89m/s. The results are depicted in Figure 6.

Figure 6. Power production of wind turbines for each direction (132.5±-2.5º) (top), power weighted average by direction (bottom)

Results also show acceptable agreement with SCADA data, capturing WTG2 and WTG1 power deficits and overestimating WTG3 power production. An explanation of why this happens is presented below.
A simulation considering another inflow condition was performed, only for wind direction 150º. In this case, at the inlet and at hub height the mean wind speed is 7.60m/s and the turbulence intensity is 8.4%. In Figure 7, the SCADA data is represented as scattered points, showing mean wind speed measured at the met tower and power production of the wind turbines, including the results of the simulations and also the manufacturer's power curve (V100 PC). The SCADA data is filtered by wind direction (150º ± 2.5º). Good agreement is observed for the four WTG. Notice how the SCADA scattered points of WTG3 are ‘deviated’ from the manufacturer power curve, due to the WTG4 wake.

![Simulated wind turbines mean power and scattered SCADA data filtered (wind direction 150º+/-2.5º), for two inflow conditions.](image)

**Figure 7.** Simulated wind turbines mean power and scattered SCADA data filtered (wind direction 150º+/-2.5º), for two inflow conditions.

The influence of the spatial resolution in the results was analyzed, by considering two more resolutions, which are R00 and R02, being R01 the original resolution. Their characteristics are presented in Table 1. As the length in the vertical direction is not uniform, only the height of the first cell is shown. NzD represents the number of cells which cover the WTG rotor in the vertical direction.  

|    | Nx  | Ny  | Nz   | Δx(m) | Δy(m) | Δz_{min} (m) | R/Δx | R/Δy | NzR |
|----|-----|-----|------|-------|-------|--------------|-------|-------|-----|
| R00| 192 | 144 | 96   | 15.6  | 10.4  | 2.5          | 3.2   | 4.8   | 23  |
| R01| 144 | 128 | 80   | 20.8  | 11.7  | 3.0          | 2.4   | 4.3   | 19  |
| R02| 128 | 96  | 72   | 23.4  | 15.6  | 3.0          | 2.1   | 3.2   | 17  |

Simulations considering wind direction 150º and mean velocity at the inlet and at hub height of 8.8m/s, were performed. It is important to highlight that for each case a different precursor simulation was used, as the resolutions of the precursor simulations and the simulations with WTG must be the same. It is planned to implement the same precursor simulation for cases with different resolution in the near future. In Figure 8 the results for the three spatial resolutions are presented.
Figure 8. Power production of wind turbines considering three spatial resolutions, wind direction 150°. SCADA data filtered by wind direction: 150°+/−2.5°, wind speed 8.91+/−0.2 m/s.

Notice the dispersions in the results. For example, for R00 the power production of WTG4 is well predicted but the power production of WTG2 and WTG1 is overestimated, while in R01 the power production of WTG4 is slightly overpredicted and that of WTG1 is underpredicted. The reason for this is that as the precursor simulations are different, the velocity upstream the wind turbines is different in each case despite having almost the same velocity profile averaged in the spanwise direction. This is observed in Figure 9, where the mean streamwise velocity component (U) is plotted, as vertical profiles at the inlet and at the met mast position. This figure also shows a surface plot of the streamwise velocity at the inlet section, with the WTG positions represented by the dotted circles, and the met mast position, by the smaller circle.

Figure 9. Vertical profiles of the mean streamwise velocity component (U), averaged in the spanwise direction at the inlet (left above) and at the position of the meteorological mast (left bottom), and at the inlet section (right), for the three spatial resolutions considered.

Although the mean velocity averaged in the spanwise direction at the inlet is very similar for the three cases, notice how there are zones where the velocity is lower or higher than this value. When this zone is upstream of a WTG, the power production will be associated to this low/high velocity. For the same reason, it is also important to observe that at the position of the met mast the velocity may not represent the velocity averaged at the inlet, so when comparing the SCADA data of the wind turbines and the met mast data with the results of the simulations, this has to be taken into account. This explains why the power production of WTG2 and WTG1 are overestimated in R00, and why the power production of WTG1 is underestimated in the case of R01. This issue can also be observed in Figure 10, which shows the mean streamwise velocity (U) in a horizontal plane at hub height, for the three resolutions.
5. Summary and conclusions

The ALM has been validated under different conditions and used in different numerical codes, being one of the chosen approaches in the academic community, to represent the presence of wind turbines in a simulation. Expanding the work previously presented by the authors and to continue validating the capability of the numerical solver caffa3d.MBRi to simulate the flow through wind farms, the ‘Libertad’ onshore wind farm was simulated, representing the wind turbines with the ALM and with an atmospheric boundary layer like inflow condition.

Two different wind sectors (150° and 132.5°) with the same precursor simulation, and two precursor simulations with the same wind direction (150°) and different wind speed at hub height, were considered, in order to analyse the interactions and wakes of the wind turbines. Also for wind direction 150°, three spatial resolutions were considered. Good agreement with the SCADA data was found when assessing the power deficits observed in the data under those different conditions. When analysing the results with the three spatial resolutions, some differences were obtained. The causes may be related to the fact that the velocity at the position of the met mast may not be an accurate representation of the velocity at the inlet, as the velocity of the precursor simulation is not uniform in the spanwise direction, which leads to different velocities upstream of the positions of the wind turbines and the met mast.

Future research will be focused on the implementation of different control strategies to adjust the angular velocity of the rotor and the individual pitch of each blade, enabling to estimate power production at higher wind speeds and also assessing the operation of down-regulated wind farms. In addition to this, we plan to implement the same precursor simulation for different spatial resolutions, including mesoscale forcing, and to develop and evaluate wind farm control strategies, aiming to maximize the global power production of a wind farm.

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