Modelling one row of Horns Rev wind farm with the Actuator Line Model with coarse resolution

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Abstract. Actuator models have been used to represent the presence of wind turbines in a simulation in the past few years. The Actuator Line Model (ALM) has shown to reproduce with reasonable accuracy the wind flow through wind turbines under different operational conditions. Nevertheless, there are not many simulations of wind farms performed with the ALM mainly because of its computational cost. The aim of the present paper is to evaluate the ALM in spatial resolutions coarser than what is generally recommended, also using larger time steps, in a simulation of a real wind farm. To accomplish this, simulations of one row of Horns Rev wind farm are performed, for different wind directions. It is concluded that the ALM is able to capture the main features of the interaction between wind turbines relaxing its resolution requirements. A sensitivity analysis is performed to assess the influence of the smearing factor and the spatial resolution.

1. Introduction

Wind energy has expanded rapidly in recent decades all over the world, with annual growth rates of installed capacity around 20%. The growth rates have become lower in recent years, nevertheless the installed capacity is projected to increase in the following years [1].

The computational cost required to resolve the blade boundary layer as well as the atmospheric boundary layer is too large to perform a simulation of the wind flow through a wind farm resolving all the scales involved. To overcome the computational cost, in the past few years actuator models have been proposed: Actuator Disk Model (without and with rotation, ADM-NR and ADM-R respectively) [3][4], Actuator Sector Model (ASeM) [5], Actuator Line Model (ALM) [6][7] and Actuator Surface Model (ASM) [8]. For a comprehensive review see [2].

The ALM has been widely validated [6][7][9][10][11][12], taking into account different inflow conditions. Despite this, there are not many studies that simulate real operation wind farms with this approach because of the high computational cost. For example, in [9] about 315 million cells are used in the wind plant mesh to simulate Lillgrund wind farm. In general, it is recommended to use a spatial resolution of at least R/30 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 [12].

The aim of the present paper is to perform the simulation of one row of the offshore wind farm Horns Rev in order to validate the ALM, taking into account a coarser spatial resolution and larger time step than what is generally recommended, in a similar way as [13], with a real wind farm. To accomplish this, a control strategy to adjust the rotational speed of the rotor to the operational
conditions, similar to the one developed in [17], is implemented. The ALM allows for a closer representation of a wind turbine rotor [2], as each blade is represented as a line, so it could be used to assess actual operational strategies like independent pitch control, taking into account the power production as well as relevant loads. In addition to this, regarding the projection of the aerodynamic forces onto the domain, the ALM may have a lower computational cost related to ADM-R when the wind turbines are yawing during a simulation. For this reasons, it is interesting to evaluate if the ALM could be used with coarser spatial resolutions as its computational cost has limited its use to simulate wind farms [2]. 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 and summary is given in section 5.

2. Numerical method

In this section a brief description of the main features of the Navier-Stokes solver is provided and then the ALM implementation is presented shortly.

2.1. Solver
caffa3d.MBRI [14][15] 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. 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.

Recently, the ALM and the ADM-R have been implemented in the code [16].

2.2. ALM

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.

At each radial section the aerodynamic force is computed as

\[ \tilde{f} = -\frac{1}{2} \rho V_{rel}^2 c (C_L \tilde{e}_L + C_D \tilde{e}_D) dr \]  

(1)
where $\rho$ is the air density, $V_{rel}$ is the relative velocity, $c$ is the chord length, $C_L$ is the lift coefficient, $C_D$ is the drag coefficient, $\vec{d}_L$ is a unit vector in the direction of the lift force, $\vec{d}_D$ is a unit vector in the direction of the drag force (Figure 2) and $dr$ is the length of the radial section.

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:

$$f(d) = \frac{1}{E_n E_r E_t n^{1.5}} e^{-\left(\frac{dr}{E_n}\right)^2} e^{-\left(\frac{dr}{E_r}\right)^2} e^{-\left(\frac{dr}{E_t}\right)^2}$$  \hspace{1cm} (2)

3. Validation case

3.1. Horns Rev

Horns Rev is an offshore wind farm, located 14km from the west coast of Denmark. It consists of 80 pitch-controlled variable speed wind turbines, Vestas V80, with a hub height of 70m, rotor diameter of 80m and rated power of 2MW [20]. It has been considered by several authors as validation case (see for example [18][17][19]).

Two cases are evaluated, single wake and multiple wake. In the first one, the power deficit obtained between two wind turbines is computed taking into account different wind directions, while in the second case the power deficit along a row of ten wind turbines is computed for a narrower wind direction sector.

3.2. Numerical setup

The size of the computational domain for the single wake case is 3.20km x 0.56km x 0.50km. The domain is uniformly divided into 128 x 48 grid cells in the streamwise and spanwise directions respectively, while a stretched grid is used in the vertical direction with 64 grid cells. The inflow condition is obtained from a precursor simulation (mean wind speed at hub height 8.6m/s and turbulence intensity 8.0%), while 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. Periodic conditions are used in the lateral boundaries. The spatial resolution implies a resolution close to R/1.6, R/3.4 in the streamwise and spanwise directions respectively, while in the normal direction 17 grid nodes cover the rotor diameter. Different wind directions are considered changing the layout while keeping the distance between the wind turbines and the West boundary as inlet boundary (Figure 3).

In the multiple wake case a domain twice larger in the streamwise direction than the one used in the single wake case is used (6.40km x 0.56km x 0.50km), taking into account the same spatial resolution and boundary conditions. Different wind directions (267.50°, 268.75°, 270.00°, 271.25° and 272.50°) are considered changing the layout while keeping the distance between wind turbines and the West boundary as inlet boundary, as mentioned above.

![Figure 3. Simulation configuration.](image-url)
We use the Crank-Nicolson scheme to advance in time and the scale dependent dynamic Smagorinsky model to compute the subgrid scale stress. To represent the wind turbine rotor the ALM is used with 11 radial sections in each line, distributing the forces with a smearing function taking into account three values of the smearing factor depending on the distance in each direction. The presence of the tower and nacelle are taken into account in a similar approach as presented in [4], through drag coefficients. The chord and twist angles are taken from [17], as well as the airfoil's data. The relationship between the rotational speed of the rotor and its torque is obtained from the SCADA data of an onshore wind farm in Uruguay consisting of ten Vestas V80. An efficiency of 0.93 is considered to compute the power generated [17]. The time step is 0.25s, taking into account the maximum rotational speed of the rotor, it means that the rotor rotates 24º approximately in each time step.

4. Results
First, the mean power obtained in the first wind turbine of the single wake case taking into account three different precursor simulations is presented to assess the capability of the present approach to reproduce the power curve of the Vestas V80 wind turbine. It can be seen that the power is well reproduced below a wind speed of 10m/s. The deviation obtained at 10 m/s could be related to the fact that the pitch was kept constant at the same value for all the simulations despite the wind speed. A pitch control is planned to be implemented in the near future.

![Figure 4. Power curve for the Vestas V80 [20], including computed mean power.](image)

4.1. Single wake
The mean power deficit is presented in Figure 5 for different wind directions. The result of the present method for wind direction $d$ are obtained by averaging the results from the simulations of two wind directions: $d-2.5^\circ$ and $d+2.5^\circ$, except wind direction 270° where the results from wind directions 267.5°, 270° and 272.5° are considered. In addition to this, the figure includes the SCADA data as well as the results labeled RANS and FUGA in [21] and the results obtained from a Matlab implementation of the Jensen model implemented in WAsP (wake decay constant equal 0.04) [22]. The results are in an acceptable agreement with the SCADA data, with a slight underestimation of the width of the mean power deficit curve. Nevertheless the results are within the SCADA measurement spreading and with an overall better agreement than other approaches.
4.2. Multiple wake

Figure 6 depicts the normalized mean power output obtained along the row of ten wind turbines for different wind directions, comparing the results with the SCADA data (±1.5º). In top of the figure, the normalized mean power for each simulated wind direction is presented. As expected, the larger power deficit is obtained when the wind turbines are perfectly aligned with the wind direction, nevertheless the difference in the last wind turbines in the row is less pronounced. In the bottom the average normalized mean power is shown including the results presented in [17] (wind direction 270º+/−1.0º), in [19], in [20] labeled FUGA and RANS and the results obtained from a Matlab implementation of the Jensen model implemented in WAsP (wake decay constant equal 0.04) [22].

The results of the simulations agree well with the SCADA data for the first five wind turbines in the row, overestimating the normalized mean power output for the downstream wind turbines in the row. It should be mentioned that the wind direction uncertainty plays a major role when evaluating narrow wind sectors [23].
In addition to this, an assessment of the wake is performed, finding similar results for the velocity deficit and turbulence intensity as presented in the literature (see for example [24]). Figure 7 shows contours of the mean streamwise velocity component as well as the streamwise turbulence intensity in the middle vertical plane perpendicular to each wind turbine rotor. The wake downstream of each wind turbine is clearly visible, characterized by a reduced velocity and larger turbulence intensity particularly at top tip height. The wake seems to recover faster from the fifth wind turbine further downstream, achieving an "equilibrium" state, which is consistent with the normalized power presented above. This "equilibrium" is clearer in Figure 8 and Figure 9, that show the vertical profiles of the mean streamwise velocity component and the streamwise turbulence intensity respectively in the middle plane with zero span 1 diameter upstream and 2, 3 and 5 diameters downstream of each wind turbine.

Figure 7. Mean streamwise velocity component (top) and streamwise turbulence intensity (bottom) in a plane passing through each rotor centre. The black bars represent the wind turbine rotors. Wind direction: 270°.

Figure 8. Vertical profile of the mean streamwise velocity component at -1D, 2D, 3D and 5D from each wind turbine in the row. Wind direction: 270°.
Figure 9. Vertical profile of the streamwise turbulence intensity at -1D, 2D, 3D and 5D from each wind turbine in the row. Wind direction: 270º.

4.3. Sensitivity analysis
The above simulations considered a precursor simulation with a mean wind speed at hub height of 8.6m/s, which is a bit larger than the wind speed bin related to the SCADA data (8.0+/-0.5m/s) in the multiple wake case. In order to evaluate the influence of the wind speed profile in the results of the multiple wake case, another precursor simulation is performed (mean wind speed at hub height 7.5m/s and turbulence intensity 8.0%) and used as inlet condition in the multiple wake case taking into account only 270º as wind direction (labeled Uin7.5_EPS0).

It has been documented that the projection function has a great influence in the power estimation as well as in the wake characteristics when performing simulations with both ADM-R and ALM [13][25][26]. In that sense, another simulation is performed, taking into account the same precursor simulation as presented previously, but using 50% larger smearing factors in each direction (labeled Uin8.6_EPS1).

Figure 10. Normalized power output with different precursor simulations (top) and with different smearing factors (bottom). SCADA data is represented by its mean value and 1, 2 and 3 standard uncertainties (shaded area).
Figure 10 shows at the top the normalized power output along the row of ten wind turbines taking into account different inflow conditions as mentioned above. The differences are almost negligible, the variation in wind speed seems to influence to a lesser extent the normalized power output than wind direction. On the other hand, the smearing parameters, as depicted in Figure 10 at the bottom, have a significant influence in the normalized power of the second to fourth wind turbines in the row.  

Looking at the vertical profile of the mean streamwise velocity component in Figure 11, there are some differences in the wake of the first wind turbine in the row (lower velocity deficit) which affect the power production of the second wind turbine (higher power production). Comparing the wake of the second and third wind turbines, the differences in the mean streamwise velocity are less pronounced, consistent with the power estimation. Nevertheless, the influence in the power estimation of the projection of the aerodynamic forces onto the computational grid should be further analyzed.  

Finally, the influence of the spatial resolution is assessed. Three spatial resolutions are tested, details of the numerical setup are presented in Table 1. The inflow conditions are obtained through a precursor simulation for each spatial resolution. The number of grid nodes covering the rotor diameter in the vertical direction is 12, 17 and 26 for R0, R1 and R2 respectively. Figure 12 depicts the normalized power output along the row of ten wind turbines computed with each grid resolution. The results are influenced by the spatial resolution when comparing R2 with R0 and R1, nevertheless the results are within the spread of the SCADA data.

Table 1. Numerical setup

| Resolution | Lx(m) | Ly(m) | Lz(m) | Nx  | Ny  | Nz  | Δx (m) | Δy (m) | Δz_{min} (m) |
|------------|-------|-------|-------|-----|-----|-----|--------|--------|--------------|
| R0         | 6400  | 560   | 500   | 192 | 32  | 48  | 33.33  | 17.50  | 4.5          |
| R1         | 6400  | 560   | 500   | 256 | 48  | 64  | 25.00  | 11.68  | 3.0          |
| R2         | 6400  | 560   | 500   | 384 | 72  | 96  | 16.67  | 7.78   | 2.0          |
5. 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. A drawback of the ALM is its high computational cost, related with its spatial and temporal resolutions requirements. This study has focused on this issue, following the work presented by the authors previously.

Simulations of Horns Rev, both single wake and multiple wake cases, have been performed in order to validate the simulation framework presented in this paper. From this simulations, it is concluded that the numerical solver caffa3d.MBRi, using the ALM with a coarse resolution and large time step, is able to predict with reasonable accuracy the power performance and to capture the main characteristics of the wake.

It is thought that this approach, with lower computational cost than what is generally recommended, would allow to simulate the wind flow through wind farms under different operational conditions, like individual pitch control and changes in yaw during the simulation, with a reasonable compromise between accuracy and computational cost.

Future research will focus on the implementation of different control strategies to adjust the angular velocity of the rotor as well as the individual pitch of each blade and on the evaluation of different approaches to maximize the global energy production of a wind farm through collective control. It is unknown whether this approach could be used to estimate wind turbine loads with reasonable accuracy, an issue that will be evaluate in the near future.

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