Evaluation of the Actuator Line Model with coarse resolutions

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Abstract. The aim of the present paper is to evaluate the Actuator Line Model (ALM) in spatial resolutions coarser than what is generally recommended, also using larger time steps. To accomplish this, the ALM has been implemented in the open source code caffa3d.MBRi and validated against experimental measurements of two wind tunnel campaigns (stand alone wind turbine and two wind turbines in line, case A and B respectively), taking into account two spatial resolutions: R/8 and R/15 (R is the rotor radius). A sensitivity analysis in case A was performed in order to get some insight into the influence of the smearing factor (3D Gaussian distribution) and time step size in power and thrust, as well as in the wake, without applying a tip loss correction factor (TLCF), for one tip speed ratio (TSR). It is concluded that as the smearing factor is larger or time step size is smaller the power is increased, but the velocity deficit is not as much affected. From this analysis, a smearing factor was obtained in order to calculate precisely the power coefficient for that TSR without applying TLCF. Results with this approach were compared with another simulation choosing a larger smearing factor and applying Prandtl's TLCF, for three values of TSR. It is found that applying the TLCF improves the power estimation and weakens the influence of the smearing factor. Finally, these 2 alternatives were tested in case B, confirming that conclusion.

1. Introduction
Wind energy has evolved significantly during the last decades, becoming one of the fastest-growing energy sources. Despite this amazing development, it is still a hard task to simulate accurately the wind flow over stand alone wind turbines and wind farms [1].

To overcome the computational cost required to simulate the blade boundary layers, 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 [1].

The ALM [5] has been widely validated, taking into account different inflow conditions, from uniform to shear flow with and without turbulent fluctuations, with special focus on the near wake or the far wake and the interaction between wind turbines. For example in [9] the ALM has been implemented in a finite volume code and results were presented of a Large Eddy Simulation (LES) of a wind farm that consists of 48 wind turbines with a rated power of 2.3MW, obtaining good results for the time-averaged power production, except for the sixth turbine and beyond in each wind-aligned. In [10] results obtained with the ADM-NR, ADM-R and ALM were compared with wind tunnel measurements of the wake of a model wind turbine subject to turbulent-shear inflow conditions, finding in general that the characteristics of the simulated wake with the ADM-R and ALM were in
good agreement with the measurements. A similar comparison between the ADM-R and the ALM against a full rotor simulation was performed in [11], obtaining a fairly good agreement of the mean axial velocity between them up to 2 rotor diameters downstream in the wake for laminar inflow, but further downstream the full rotor simulation predicted a faster recovery, related to a higher turbulence level respect to the ADM-R and ALM. However, for turbulent inflow conditions, the differences in axial velocity and turbulent kinetic energy were reduced significantly. As a conclusion the authors suggested that when simulating wind turbines in the atmospheric boundary layer (ABL), it is sufficient to use the ADM-R or ALM, and that there are no big differences between them in the predicted wake. In [12] the ALM is used to simulate the MEXICO rotor under yawed conditions, computing loads as well as wake characteristics. Finally, in [13] the capability of the ALM to compute vortex structures in the near wake was evaluated taking into account the MEXICO experimental data, obtaining satisfactory results of the wake expansion, circulation and velocity distributions.

These references are just a few of many possible examples showing the capabilities of the ALM to predict the wake characteristics as well as loads and power performance. 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 [14]. For example, in [9] the spatial resolution was R/26 and it took one million processor-hours to simulate ten minutes of wind plant flow. In [11] and [12] the spatial resolution used in the simulations with the ALM was R/30. However, in [13], taking into account the main objective of that work, the rotor is discretized using 80 grid points, distributed so that the resolution near the tip region is almost R/122.

Taking into account those recommendations and the good performance of the ADM-R, it is uncertain whether the ALM could be used with coarser resolutions and larger time steps. Regarding the latter, as the computed aerodynamic forces are projected into the domain through a smearing function, with spatial resolutions where the chord length is close to or less than the grid length (blades almost immersed in a grid cell), the restriction of limiting the tip movement one grid cell length may not be strictly required, as the forces are smeared to neighbor cells despite the chord is immersed in just one grid cell. In that sense, it is like the ALM approaches the ASeM.

The aim of the present paper is to evaluate the ALM in spatial resolutions coarser than what is generally recommended (R/30-R/60), also using larger time steps. The paper is organized as follows: section 2 presents the solver and the ALM implementation, section 3 describes the experimental campaigns 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 [15][16] 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.
2.2. ALM

In the ALM, the wind turbine rotor is represented as a body force field, instead of resolving the blade boundary layers 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 (Figure 1). 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

$$f = -\frac{1}{2} \rho V_{rel}^2 c (C_L \vec{e}_L + C_D \vec{e}_D) \, dr$$

(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, $\vec{e}_L$ is a unit vector in the direction of the lift force, $\vec{e}_D$ 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 (smearing factor $E$) is often used, taking into account the distance between each grid cell and radial section ($d$), in order to compute the additional source term.

$$f(d) = \frac{1}{(E \pi^{0.5})^3} e^{-\frac{d^2}{E^2}}$$

(2)

3. Validation cases

3.1. Experimental campaigns

Two experiments, performed at the wind tunnel of the Department of Energy and Process Engineering at The Norwegian University of Science and Technology, are selected for validation. The wind tunnel has a test section of 1.80m (height) x 2.71m (width) x 11.14m (length).

The first experiment, hereafter case A, consists of one model wind turbine subject to uniform inflow condition almost without turbulent fluctuations (turbulence intensity at the inlet was 0.3%). The rotor diameter is 0.894m and the hub height is 0.817m. The blades use the NREL S826 airfoil along the entire span. For further information please see [17].

The second experiment, hereafter case B, consists of two model wind turbines subject to uniform inflow condition almost without turbulent fluctuations (turbulence intensity at the inlet was 0.3%). The rotor diameter of the upstream wind turbine is 0.944m and the rotor diameter of the downstream wind
turbine is 0.894m, while the hub height of both is 0.817m. The blades use the NREL S826 airfoil along the entire span of both wind turbine models. For further information please see [18].

3.2. Numerical setup
Two spatial resolutions are tested, R/15 and R/8. Details of the numerical setup are presented in Table 1. The inflow conditions are of uniform non-turbulent velocity, while zero velocity gradient is imposed at the outlet. No slip condition is used at walls in order to represent the wind tunnel.

| Resolution | Lx(m) | Ly(m) | Lz(m) | Nx | Ny | Nz | Δx (m) | Δy (m) | Δz (m) |
|------------|-------|-------|-------|----|----|----|--------|--------|--------|
| R/15       | 11.14 | 2.71  | 1.82  | 384| 96 | 64 | 0.029  | 0.028  | 0.028  |
| R/8        | 11.14 | 2.71  | 1.82  | 192| 48 | 36 | 0.058  | 0.056  | 0.051  |

We use the second order backward Euler scheme to advance in time and the scale dependent Smagornsky dynamic model to compute the subgrid scale stress. The convective term is discretized using a variable blending factor (varying between 0.95 and 1.00), depending on the distance and position of a grid cell relative to the wind turbine rotor (in a similar way as presented in [14]). To accomplish this, three regions are defined taking into account the distance from the rotor, the blending factor close to the rotor is 0.95 and far away is 1.00, while it varies linearly between those regions. To represent the wind turbine rotor the ALM is used with 27 radial sections in each line, distributing the forces with a three dimensional Gaussian function defined by a smearing factor $E$. The presence of the tower and nacelle are taking into account in a similar approach as presented in [4], through drag coefficients. The airfoil data is taken from [19].

First a sensitivity analysis for case A is performed in order to check the influence of the smearing factor $E_s$ and the size of the time step $dt$ in the wake as well as in the power and thrust coefficients ($C_p$ and $C_t$ respectively) without applying a tip loss correction factor and for design conditions (tip speed ratio, $TSR=6$). The following smearing factors and time step sizes are considered:

| Table 2. Sensitivity analysis - Smearing factor |
|-----------------------------------------------|
| Smearing factor (m) | Line type/colour | Ratio $E_i/\Delta x$ |
|---------------------|------------------|------------------|
| 0.044 (E1)          | Blue             | 1.51             |
| 0.065 (E2)          | Red              | 2.25             |
| 0.116 (E3)          | Green            | 4.00             |

| Table 3. Sensitivity analysis - time step size |
|-----------------------------------------------|
| Time step size (s) | Line type/colour | CFL-tip$^b$ |
|---------------------|------------------|-------------|
| 0.0002 (T1)         | Solid            | 0.4         |
| 0.0010 (T2)         | Dotted           | 2.1         |
| 0.0015 (T3)         | Dashed           | 3.2         |

$^a$Used in Figure 3
$^b$CFL computed with tip speed

From the sensitivity analysis, a value for the smearing factor is defined, $E_s$, for the larger $dt$ and spatial resolution R/8 in order to calculate precisely the power coefficient at $TSR=6$. The results with this smearing factor $E_s$ are compared with another simulation where Prandtl’s tip loss correction factor (TLCF) is applied and thus a larger smearing factor $E_p$ is calibrated to match the $C_p$ at $TSR=6$, for $TSR=3$, 6 and 10 in case A and $TSR=2.5$ and 4 in case B. Those values in the latter case are related to the downstream wind turbine, while the upstream wind turbine operates at design condition ($TSR=6$).

Results

3.3. Sensitivity analysis
A sensitivity analysis is performed in order to get some insight into the influence of the smearing factor and time step size in the wake as well as the power and thrust coefficients. In the legend of the following figure, type and colour of each line is selected as defined in Table 2 and Table 3. Figure 3
depicts the velocity deficit (left) and the turbulent kinetic energy (TKE, right), both normalized with the inlet velocity, at 3D from the rotor plane (where D is the rotor diameter) in case A for a TSR value of 6 (design condition), using grid R/8. Comparing this results with the corresponding results using grid R/15 (not shown here), it seems that the tower model is highly affected by the spatial resolution.

Figure 3. Normalized mean velocity deficit (left) and normalized turbulent kinetic energy (right), without applying a TLCF. Distance: 3D. TSR: 6. Case A. Spatial resolution: R/8.

Figure 4 presents the error in the computed $C_p$ for the 18 simulation runs, combining different settings. The error is plotted against the smearing factor, normalized by the rotor radius (left) and by the spatial resolution (right). From this figure, we can conclude that the computed $C_p$ depends strongly on the smearing factor and also on the time step size, but the influence of the latter is related to the value of the smearing factor. For higher values of the smearing factor, the dependency on the time step size is less significant. In addition to this, there is not a clear relationship between the spatial resolution, the smearing factor, the time step size and the error in the computed $C_p$. A set of criteria could not be obtained to ensure the convergence of the error to a small value.

Figure 4. Error in $C_p$. TSR: 6. Case A.

Taking into account the above results, it is concluded that as the smearing factor is larger/the time step size is smaller the power is increased, but the velocity deficit is not as much affected.
3.4. Influence of applying a tip loss correction factor

From the above analysis, a value of 0.0608m ($E/R=0.136$) for the smearing factor is selected, using the larger time step ($T3$) and the coarser spatial resolution ($R/8$), in order to estimate the $Cp$ value precisely (please see Figure 4). In addition to this, another option is considered that takes a value of 0.0715m and applies Prandtl's TLCF. The latter should be larger in order to achieve a better estimation of the $Cp$ value (with the same smearing factor, $E/R=0.136$, a lower $Cp$ would be obtained).

First, the wake characteristics are presented, reporting the mean velocity deficit and turbulence statistics. Figure 6, Figure 5 and Figure 7 depicts the mean velocity deficit (left) and $TKE$ (right), both normalized with the inlet velocity, at 3D from the rotor plane in case A for a TSR value of 6, 3 and 10 respectively. In general, there is a good agreement in the mean velocity deficit and the ALM is able to capture the main characteristics, despite finding some discrepancies close to the rotor centre probably related to the rough models used to represent the tower and the nacelle. Regarding turbulent characteristics, the $TKE$ profile for design condition is almost one order of magnitude smaller than the experimental data in the tip region, similar results were presented in [17]. In [20] it is argued that small fluctuations in the upcoming flow help to trigger instabilities in the vortices, finding better results with a low-intensity free-stream turbulence than with laminar inflow.

![Figure 5](image5.png)

**Figure 5.** Normalized mean velocity deficit (left) and normalized turbulent kinetic energy (right), without applying a TLCF (dashed black line) and applying a TLCF (solid blue line). Experimental data: red circles. Distance: 3D. TSR: 3. Case A.

![Figure 6](image6.png)

**Figure 6.** Normalized mean velocity deficit (left) and normalized turbulent kinetic energy (right), without applying a TLCF (dashed black line) and applying a TLCF (solid blue line). Experimental data: red circles. Distance: 3D. TSR: 6. Case A.
Regarding case B, Figure 8 and Figure 9 depict the mean velocity normalized with the inlet velocity (left) and the turbulence intensity (right) at 4D from the rotor plane in case B for a TSR value of 4 (design condition) and 2.5 respectively of the downstream wind turbine while the upstream wind turbine operates at design condition (TSR=6). The turbulent statistics have improved, compared to case A, but there is a lower recovery in the mean velocity compared to the experimental data. This could be related to the inlet condition applied in this study, that generates a lower turbulence level in the wake.

**Figure 7.** Normalized mean velocity deficit (left) and normalized turbulent kinetic energy (right), without applying a TLCF (dashed black line) and applying a TLCF (solid blue line). Experimental data: red circles. Distance: 3D. TSR: 10. Case A.

**Figure 8.** Normalized mean velocity (left) and normalized turbulent kinetic energy (right), without applying a TLCF (dashed black line) and applying a TLCF (solid blue line). Experimental data: red circles. Distance: 4D. TSR: 6 and 4 (upstream and downstream wind turbine respectively). Case B.
Figure 9. Normalized mean velocity (left) and normalized turbulent kinetic energy (right), without applying a TLCF (dashed black line) and applying a TLCF (solid blue line). Experimental data: red circles. Distance: 4D. $TSR$: 6 and 2.5 (upstream and downstream wind turbine respectively). Case B.

From those figures, it can be concluded that the ALM with a coarse resolution captures the main characteristics of the wake and that the TLCF has not a significant influence on the wake. Regarding the performance coefficients, Figure 10 presents the $C_p$ (left) and $C_t$ (right) computed in case A (top) and in case B (bottom). There is a better agreement when applying a TLCF for all the $TSR$ values considered. Moreover, in case A, despite adjusting the smearing factor to compute precisely the $C_p$ at design condition without applying a TLCF, the $C_p$ obtained when the wind turbine is operating under different conditions is overestimated by 40% ($TSR=3$) or underestimated by 37% ($TSR=10$), while those errors are reduced significantly when applying a TLCF (8% and 1% respectively). In case B, the $C_p$ is overestimated with both approaches, but the error is lower when applying a TLCF (26% compared to 36% for $TSR=4$ and 25% compared to 46% for $TSR=2.5$). Nevertheless, despite using the same model and parameters for both wind turbines, the error in $C_p$ for the downstream wind turbine is quite higher than the error for the upstream wind turbine.

Figure 10. Power coefficient (left) and thrust coefficient (right), without applying a TLCF (diamond black marker) and applying a TLCF (square blue marker). Experimental data: red circles. Case A: top, case B: bottom (full markers correspond to the downstream wind turbine).

Tests with Blind Test 3 were performed (not shown here) and better results of $C_p$ were obtained, which suggests that the required smearing factor is affected by the inflow condition at each wind turbine. Regarding the $C_t$, its value is under-predicted regardless of the operating condition. A similar
under-prediction was obtained in [20][21] with the ALM and in [22] with a blade element momentum method. As reported in [21] following [22], the accuracy of the ALM is based on, among other parameters, the airfoil data used, so our results may be affected by this.

4. Conclusions
The ALM has been implemented in the open source code caffa3d.MBRi and validated against wind tunnel experimental campaigns using coarser spatial resolutions and larger time steps. Regarding the latter, generally it is recommended 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. In the present work it is argued that as the computed aerodynamic forces are projected into the domain through a smearing function, with spatial resolutions where the chord length is close to or less than the grid length, the restriction of limiting the tip movement one grid cell length may not be strictly required, as the forces are smeared to neighbor cells despite the chord is immersed in just one grid cell, so the time step size should be related to the region of the domain where the forces are projected.

A sensitivity analysis, taking into account two spatial resolutions (R/8 and R/15), was performed in order to assess the influence of the smearing factor and time step size on power and thrust as well as the wake characteristics. Power and thrust are highly dependent on the projection function as well as spatial resolution, but the mean velocity deficit in the wake is not as much affected. The influence of the time step size is diminished with larger smearing factors. Nevertheless, further investigation is needed in order to determine a procedure to adjust the evaluated parameters. Moreover, more complex models to represent the tower and the nacelle should be tested in order to improve the results in the wake centre.

From the above analysis, a value for the smearing factor was defined for the larger time step size and coarser resolution in order to calculate precisely the power coefficient at $\text{TSR}=6$ for the validation case with one model wind turbine. The results with this smearing factor were compared with another simulation choosing a larger smearing factor and applying Prandtl's tip loss correction factor, for $\text{TSR}=3/6/10$. It is found that applying the tip loss correction factor improves the power estimation in all operational conditions. This two alternatives were tested in a validation case with two model wind turbines, confirming that conclusion, although with higher errors in power production.

Overall, we have shown that the ALM is able to capture the main characteristics of the wake in coarser spatial resolutions and using larger time steps. In addition to this, applying a tip loss correction factor improves the power estimation, besides obtaining the expected behavior of the aerodynamic forces along the blades.

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