Comparative study on the wake description using actuator disc models with increasing level of complexity

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Abstract. The present work evaluates the benefits obtained when different levels of geometric and aerodynamic information of wind turbine blades are included in the actuator disc (AD) model, progressively increasing its descriptive capabilities. A novel AD model is presented, equivalent in precision to the AD coupled with the blade element momentum method, but avoiding the need to modify the CFD code by the use of a pre-calculated table. It is compared against three classical AD models, particularly aiming at the simulation of the wind farm wake interaction. The NREL-5MW reference wind turbine is adopted as test case, and configurations with single and two shifted wind turbines are analyzed.

1. Introduction

When CFD simulation of wind turbine wakes in wind farms is conducted, the correct description of the phenomenon with a reasonable computational cost is desirable. This makes the Actuator Disc (AD) family of models a widely used compromise solution [1–3]. The AD models range from the basic model with only axial force uniformly distributed on the disc area, which is improved incorporating a tangential force uniformly distributed along the blade span, up to the models with non-uniform distribution of forces. These distributed forces can be pre-calculated or computed on-the-fly from the local velocity on the disc and the aerodynamic characteristics of the blade applying the blade element momentum (BEM) theory. Accordingly, each of this AD models requires different level of knowledge of blade aerodynamics and geometry.

In this work we propose an AD variant which should perform equivalently to the BEM based AD, but avoiding to coupling the BEM inside the fluid solver. This allows to input turbine characteristics from different sources without modifying the CFD code. This new variant has the capability to also include the effect of complex phenomena appearing in wind turbine operation, herein tested with blade deformation. The implementation of this new AD was developed in a common framework which includes other classical ADs and allows their comparison.

Since the wake shape depends on the force distribution on the disc, the benefits of incorporating an increasing level of aerodynamic and geometrical information of the wind turbine blades in the model formulation are evaluated in this work. Some comparisons against measurements and other advanced models have been previously conducted. For single wake
cases, the simplest uniform AD without rotation and the AD with distributed forces coupled with the BEM are compared against wind turbine wake measurements from a field campaign in [4] and wind tunnel experiments in [5]. In [6] two AD models with distributed forces are compared with results from full rotor simulation: the AD coupled with the BEM and a non-uniform AD with forces computed scaling a master force curve obtained from full rotor simulations. A more extensive analysis was carried out in [7], where the simple uniform AD, with and without rotation, is compared with the AD with scaled non-uniform force distribution. In wake interference cases, scarce studies for AD comparisons are found. In [8] the power interference between two wind turbines is analyzed by means of the two AD models with distributed forces (BEM-coupled and force scaling from a master curve). In sum, those comparative studies do not compare the full range of AD models for wind turbine interaction cases, and AD models performance for wind velocities above the rated value have not been thoroughly analyzed yet.

Three AD models of different descriptive level are compared along with the new variant in this work. The four are implemented in OpenFOAM [9] and stationary RANS simulations are carried out under ABL wind conditions. The NREL-5MW reference wind turbine [10] is adopted as test case, and configurations with single and two interacting wind turbines are simulated under low ambient turbulence intensity, resulting in scenarios with below- and above-rated wind speeds under complex flow patterns producing local off-design conditions.

2. Methodology

2.1. Actuator disc models

Depending on the available information on the wind turbine working setting and the geometrical and aerodynamic characteristics of the blades, different AD models can be created with increasing detail in the forces producing the wake. For most commercial wind turbines, only the relation between global power ($C_P$) and thrust ($C_T$) coefficients and the reference wind speed ($U_{ref}$) is available, and the most simplified AD model (herein referred as AD-unif) can be created uniformly distributing the axial force ($f_n(r)$) on the disc surface [11]. If the relation between the rotational speed ($\omega$) and $U_{ref}$ is also known, the tangential force ($f_\theta(r)$) on the disc surface can be added representing a uniformly distributed force on the blade span (AD-unif+rot) [8]. If a more realistic non-uniform distribution of axial and tangential forces is desired, the BEM calculation, in terms of the local velocity on the disk and the lift and drag coefficients ($C_l$, $C_d$) for each of the blade profiles, can be introduced into the solver (AD-airfoil) [6]. This version of the AD model needs substantially more information about blade geometry and turbine configuration, e.g. the $\omega$, pitch angle ($\theta_p$) vs. $U_{ref}$ relation, etc. An actuator disc with an intermediate level of complexity that does not imply coupling the BEM inside the CFD code can be created [8]. This AD model uses master curves for axial and tangential distributed forces which are scaled according to the working situation and allows to obtain results qualitatively equivalent to those of the AD-airfoil model as long as the force distribution remains similar.

A novel strategy is proposed in this work formulating the AD based on a pre-calculated table where the force distribution is stored in terms of different working situations, hereafter named as AD-precalc. This pre-calculated table can be obtained from different sources: external full-rotor simulation [6], scaling reference blade loads, using BEM code results, etc. allowing to represent the turbine behavior with the quality of the AD-airfoil even when the force distribution shapes change. This strategy has the added advantage of allowing to include additional effects such as the deformation of the blades, the use of flow control devices or complex control actions, without further CFD code modification. In this work, the AD forces for regular and off-design conditions are obtained from an advanced BEM model [12], as described in section 2.2. Table 1 summarizes the four AD models compared in this work and their inputs.

Wind turbines in wind farms are affected by non-uniform velocity fields due to the ABL flow, the influence of the topography and the upstream wind turbine wakes. This imposes the
need to estimate from the average wind speed over the disc $< U_d >$ an unknown upstream reference wind speed $U_{ref}$ which defines the turbine setting: $\omega$, $\theta_p$, etc. Also, the wind speed at a certain location on the disc $U_{cell}$ not necessarily coincides with $< U_d >$, specially under complex flow patterns. This $U_{cell}$ is the velocity that defines the local effect of the actuator disc on the flow. In the AD-airfoil this is the speed used in the BEM computation. In the other three methods, given a particular turbine setting defined by $U_{ref}$, at each location there will be a relation between $U_{cell}$ and a corresponding unperturbed wind speed $U_\infty$ which will determine the local forces. This differentiation between the wind velocity adopted in the wind turbine setting $U_{ref}$ and the unperturbed wind velocity used to calculate the AD forces $U_\infty$, is an innovation in both the classical AD models (AD-unif and AD-unif+rot) and the one developed in this work (AD-precalc), and gives them the capability to calculate the axial and tangential forces regarding disc regions that work under off-design conditions. In this work, the relations between $< U_d >$ and $U_{ref}$, and $U_{cell}$ and $U_\infty$ are obtained from the BEM (section 2.2) through the computed global and local induction factor. In order to ensure consistency, $C_T$ and $C_P$ are computed from the BEM force distributions for each combination of $U_{ref}$ and $U_\infty$. This way, the information required by the different AD models is obtained from one single source.

In the two classical AD models, the local force contribution of each cell is computed as usual in terms of the combination of $U_{cell}$, which defines $\omega$, $C_T$ and $C_P$, and $U_\infty$ which is taken as the unperturbed velocity in the equations of thrust and power [3]. Briefly, the computation process starts with the $< U_d >$ given by the CFD code. Then the corresponding $U_{ref}$ is found in the table which also gives $\omega$, $C_T$ and $C_P$ in accordance. Next, with the velocity $U_i$ in each cell, a $U_\infty$ is found in the table relating $U_d$ and $U_\infty(U_{ref})$, and the cell contribution to the thrust is computed as $T_i = \frac{1}{2} \rho C_T U_\infty^2 A_d (V_i/V_{disc})$ with $V_i/V_{disc}$ the volume relation between the cell $i$ and all the cells representing the AD. Computation of power and torque contribution of each cell is analogous.

In the case of the AD-precalc proposed in this work, each $(U_{ref}, U_\infty)$ combination corresponding to $< U_d >$ and $U_{cell}$ determines the axial and tangential distributed forces at the cell position on the disc obtained here from the BEM pre-computation (section 2.2). Concisely, the computation process starts as above and once the $U_{ref}$ is found, $f_n$ and $f_\theta$ are obtained in terms of the corresponding $U_\infty$ for the cell position along the radius. In this case, as we allow interference variations with the radius, the relation between $U_i$ and $U_\infty$ will be a function of the position obtained from another intermediate table provided also by the BEM.

2.2. AD model inputs

The AD models described in section 2.1 require different information about the effect of the turbine on the flow. In this work, the inputs demanded by all AD models were produced by means of the DRD-BEM model [12], considering only the aerodynamic phenomena and disregarding the

| AD model     | Forces applied                                      | Wind turbine information needed                      |
|--------------|-----------------------------------------------------|------------------------------------------------------|
| AD-unif      | $f_n$ (uniform)                                     | $C_T$, $C_P$ vs. $U_{ref}$, $U_\infty$               |
| AD-unif+rot  | $f_n + f_\theta \cdot 2\pi r$ (uniform)            | $C_T$, $C_P$, $\omega$ vs. $U_{ref}$, $U_\infty$     |
| AD-precalc   | $f_n + f_\theta$ (pre-calculated)                   | $F_n(r)$, $F_\theta(r)$ vs. $U_{ref}$, $U_\infty$ or $f_n(r)$, $f_\theta(r)$, $C_T$, $C_P$ vs. $U_{ref}$, $U_\infty$ |
| AD-airfoil   | $f_n + f_\theta$ (from airfoil data)                | $\omega$, $\theta_p$ vs. $U_{ref}$ (control setting) |
|              |                                                     | AIRFOIL, twist vs. $r$ (blade geometry)              |
|              |                                                     | $C_t$, $C_d$ vs. $\alpha$ for each AIRFOIL (aerodynamics) |
Figure 1. Below- and above-rated distribution of the normalized axial ($\bar{f}_n(r)$) and tangential ($\bar{f}_\theta(r)$) forces over the disk, with and without blade deformation.

mechanical and electrical losses. Details of the BEM model configuration used in this work can be found in [12]. From the DRD-BEM the distribution of the axial $F_n(r)$ and tangential $F_\theta(r)$ [N/m] forces along the blade were obtained for different working conditions. The counterpart of those forces distributed on the disc are calculated as $f_n(r) = F_n(r)/(2\pi r)$ and $f_\theta(r) = F_\theta(r)/(2\pi r)$ [N/m²]. The axial and tangential forces distributed on the disc accounting for the contribution of the 3 blades can be normalized multiplying by 3 and dividing by $(0.5\rho U_{ref}^2)$. These normalized forces are herein noted as $\bar{f}_n(r)$ and $\bar{f}_\theta(r)$.

Off-design data was obtained for different values of the unperturbed wind speed $U_\infty$, keeping fixed the magnitudes related to the reference wind speed adopted by the turbine $U_{ref}$ ($\omega$ and $\theta_p$). In addition to the distribution of forces, a table with the variation of the induction factor $a(r)$ on the disc for each pair $U_\infty$, $U_{ref}$ was calculated, which allows to obtain the corresponding speed at the disc ($U_d$). Figure 1 shows the normalized axial and tangential forces given by the BEM model for the NREL5MW turbine (see section 2.4) under uniform wind profile below and above the rated wind speed ($U_{ref} = 8$m/s and $U_{ref} = 18$m/s respectively). It can be seen that while for $U_{ref} = 8$m/s the distribution of $\bar{f}_n$ is fairly uniform over the disc along the active part of the blade, for $U_{ref}$ greater than the rated speed there is a maximum near the blade root. The distributed tangential force $\bar{f}_\theta$ exhibits a dependency with $1/r$ inherited from an almost constant $F_\theta(r)$ in the active part of the blade. This reveals the fact that for cases where the distribution of the axial force is highly non-uniform, the results obtained from the simplified AD models with homogeneous distribution will be imprecise in the near wake. The DRD-BEM is able to account for blade deformation and other complex control actions, considering their effect on thrust, torque, and distributed forces. As can be observed in figure 1, the blade deformation effect introduce a reduction of $\bar{f}_n(r)$ near the blade tip, while $\bar{f}_\theta(r)$ is homogeneously reduced. As these are forces distributed on the disc surface, this last behavior corresponds to variation of the force per unit length distributed on the blade span depending on the radius.

As stated above, inputs for the AD-precalc model could be obtained from several sources besides the DRD-BEM: e.g. external full rotor simulations or scaling a master force distribution curve. In the latter case, this development will be equivalent to the AD model in [8]. The advantage of obtaining the input table from the BEM is that the force distribution shape variation can be taken into account, a situation particularly significant for above-rated wind speeds as seen in figure 1. Also, the ability to include other complex phenomena without modifying the CFD code is highlighted.

2.3. Software configuration

The open source finite volume OpenFOAM [9] software is used for the simulation, with solver, re-meshing and cell selection tools capable to be run in parallel. The domain is created from
the location of the wind turbine disc centers, adding margins upstream (3D), downstream (10D and to the sides (5D), and with total height of 1500m ≈ 12D. The mesh is composed by a background mesh, with equal horizontal cell dimensions and increasing vertical dimension, ranging from 1m near the ground up to 150m at the top. in the AD zone the vertical cell dimension is kept constant. This background mesh is densified around each AD halving all cell sizes. The cell size inside the densified zone is set to D/20, following the recommendations in the mesh sensitive analysis by [7]. An example of the cell selection containing the volumetric forces that represent the AD can be seen in figure 2, along with the background and densified mesh. AD thickness of 0.10D is adopted, encompassing 2 cell layers, following common practice [13], and allowing an AD with orientation capability [3].

The boundary conditions for inlet, lateral and top faces are set according to a neutral ABL profile created by imposing the velocity at hub height and the terrain roughness coefficient (z0), which is adjusted to get to the target turbulence intensity (TI). A low value of TI = 4% is chosen, representing situations that generally occur in stable onshore ABL, in order to allow wake details to remain further downstream. An outlet condition is adopted on the downstream face, and the ground has a wall condition. The stationary solver SimpleFoam is chosen, obtaining the time averaged flow solution solving the RANS equations. These equations need to be closed by a turbulence model, and for this the Realizable k-ε model [14] is chosen, as it has shown good agreement with wake velocity measurements in ABL flows [15, 16].

2.4. Wind turbine model

The widely studied NREL-5MW reference wind turbine, with 3 blades and D = 126m, is used in the study. Regarding the wind turbine operational configuration, figure 3 (left) shows the rotational speed ω and the pitch angle (θp) variation with respect to the reference wind speed Uref at the hub height. Two control regimes can be observed: below the rated speed (Uref = 11.4m/s) ω grows linearly and θp=0°, and above the rated speed ω remains constant and θp increases. In figure 3 (right) it can also be observed that the consideration of the deformation of the blades without changing the pitch setting of the blades reduce the values of CT and CP for all the Uref range, with greater impact near the nominal speed. Although this is not the normal behavior of commercial wind turbines where this power deficit due to blade deformation is corrected by modifying the pitch, we keep the standard configuration of the turbine given by the original report where no correction is specified.

3. Results

3.1. Single wind turbine wake

This first case, the simulation of an individual wind turbine, is aimed to evaluate the impact of a more detailed turbine-flow interaction on AD forces and wake shape and validate the AD-precalc implementation. The AD-unif implementation was presented and validated in [3]. The axial
Figure 3. NREL-5MW working configuration: (left) rotational speed $\omega$ and the pitch angle ($\theta_p$) and (right) thrust ($C_T$) and power ($C_P$) coefficients, with and without blade deformation.

Figure 4. Velocity induction downstream a single wind turbine (right) and corresponding normalized AD forces (left), $U_{ref} = 8\,m/s$ and $\theta_p=0^\circ$: axial force and velocity deficit horizontal variation at hub height (top), and vertical variation at the wind turbine center (middle); tangential force and vertical velocity at hub height (bottom).

and tangential forces at the disc are compared, and the axial velocity deficit and the induced tangential velocity are analyzed at distances 1, 2.5, 5 and 7.5D downstream, covering the near and far wake. Two reference wind velocities are studied, corresponding to below and above-rated situations, $U_{ref} = 8\,m/s$ and $U_{ref} = 18\,m/s$ respectively (see figure 3).
Results for $U_{ref} = 8\text{ m/s}$ are shown in figure 4. Also, the data obtained by means of LES simulation using the AD-airfoil model by [8] are also added for comparison. The major differences between the AD models, are seen in the near wake, where the wake responds to the detailed force distribution. In the top panel, the AD-unif is shown to produce a uniform and symmetrical wake, while the addition of the rotation in the AD-unif+rot creates a slight asymmetry, with a maximum located in the side where low velocity intensity is convected from lower levels. The major differences can be found when the non-uniform force distribution is imposed by the AD-precalc and AD-airfoil models, describing both models similar wakes. At $2.5D$, results of both models are similar to those of the LES simulation, and differences are in the expected range due to the different resolution of the turbulence in LES and RANS. The middle panel shows how the AD models react to the non-uniform ABL inlet condition. The AD-unif and AD-unif+rot models produce similar wake shapes, while the AD-precalc, with the addition of the forces adaption capability, gives similar results to the AD-airfoil model. In the bottom panel, the AD-unif model does not induce any tangential velocity. The three AD models with rotation induce tangential velocities, with the AD-precalc and AD-airfoil models producing higher maximums values and located closer to the disc center, due to the difference in force distribution. The maximum of the induced tangential velocity is less than 25% of the deficit induced in the axial velocity. The three panels show that for distances further than $5D$ the four AD models axial velocity deficit shapes closely overlap. The corresponding AD normalized forces plotted on the left of each panel help to explain the near wake differences. An important point to highlight here is that, as expected, in each case the forces of the AD-precalc and AD-airfoil show a high correspondence, supporting the validation of the proposed method.

Figure 5 presents results for $U_{ref} = 18\text{ m/s}$ which, compared to those of figure 4, show that the strong non-uniform force distribution due to the turbine setting concentrate the wake deficit near the disc center in the AD-precalc and AD-airfoil models. This causes higher differences with the AD-unif and AD-unif+rot models and the wakes predicted are clearly different still at $7.5D$. These differences are noticeable for the axial and tangential velocities, revealing the incapability of uniform AD models to represent above-rated or off-design conditions where the force distribution shape change. The same will be true for implementations of the AD-precalc where forces are scaled from master force distribution curves.

Given the capability of the DRD-BEM model to consider blade deformation, we compare the wakes produced by the AD-precalc model with and without the blade deformation effect. This is the only of the four models that can account for this and other control phenomena through the modification of the force data. This kind of results could also be obtained directly coupling an structural model with the CFD code, as done for example by [13], but that would imply an in-depth modification of the original code. Figure 6 shows results for the rated reference wind speed $U_{ref} = 11.4\text{ m/s}$ and an above-rated speed $U_{ref} = 18\text{ m/s}$. It can be seen that the wake is slightly reduced in the active part of the blade, while the effect of the deformation is less noticeable for the higher $U_{ref}$ as the lower aerodynamic forces produce less deformation.

3.2. Wake interaction for two wind turbines

In this section the case of wake interaction between two turbines is presented with the objective of validating the local adaptation methodology of forces in the AD-unif, AD-unif+rot and AD-precalc models, which are compared with the AD-airfoil model that intrinsically adapt its response to the local velocity. The two turbines are separated $5D$, a typical distance in wind farms, and oriented in such a way that cross-flow turbine separation is $0.5D$. In this case, strong wake-turbine interaction takes place as the wake of the upstream turbine impinges on almost half of the disc of the downstream one, being the AD models strongly challenged with a non-uniform velocity distribution on the disc. The velocity deficit is analyzed at 0 (second turbine position), 2.5, 5 and 7.5D downstream the second wind turbine. The forces exerted by
Figure 5. Velocity induction downstream a single wind turbine (right) and corresponding normalized AD forces (left), $U_{ref} = 18 \text{ m/s}$ and $\theta_p = 14.92^\circ$: axial force and velocity deficit horizontal variation at hub height (top), and vertical variation at the wind turbine center (middle); tangential force and vertical velocity at hub height (bottom).

Figure 7 shows the results for $U_{ref} = 8 \text{ m/s}$ and $U_{ref} = 18 \text{ m/s}$. In the first case, at 0D distance it can be seen that, while downstream the first turbine the wake is already mixed and the predictions of all AD models coincide, the second turbine wake is just being generated and there are major differences between the four AD models. The AD-precalc model shows good agreement with the AD-airfoil model, validating the local force adaptation. The uniform AD (AD-unif and AD-unif+rot) models also represent quite well the resulting wake but less precisely than the non-uniform ones (AD-precalc and AD-airfoil). Further downstream, even at 2.5D all wakes result quite similar, even more among rotating AD models. As was observed for the single wake case, strong difference are seen at $U_{ref} = 18 \text{ m/s}$, due to the non-uniform forces related to the turbine setting. In this case, at 0D distance wakes of uniform and non-uniform models clearly differ and it becomes even worse behind the second turbine. Comparing with the $U_{ref} = 8 \text{ m/s}$ case, greater distances, as long as 7.5D, are needed to get equivalent wake representations by the different models. The forces of the second AD in figure 7 (left) help clarify the previous observations as the contrast of forces in the above-rated case is more prominent. In the rated wind speed case, however, the uniform ADs perform quite well thanks
Figure 6. Deformation effect in the AD-precalc model. Velocity induction downstream a single wind turbine (right) and corresponding normalized AD forces (left) for $U_{ref} = 11.4m/s$ (top), and for $U_{ref} = 18m/s$ (bottom).

Figure 7. Velocity induction downstream a single wind turbine (right) and corresponding normalized AD forces (left), for $U_{ref} = 8m/s$ (top) and $U_{ref} = 18m/s$ (bottom). Axial force and velocity component deficit at hub height. (Turbine streamwise separation not in scale)

to adaptive behavior.

4. Conclusions
The inclusion of increasing levels of geometric and aerodynamic information of the wind turbine in AD models generates more detailed force distributions on the actuator area and the wake
shape in the close distances downstream. Further downstream all AD model wakes become equivalent, confirming that all of them consistently apply the same total thrust to the fluid. However, the distance at which the wake shape for all the AD models become equivalent highly depends on the forces distribution. For $U_{ref}$ below the rated velocity, where the hypothesis of the uniform ADs are closer to reality, a distance of $5D$ seems to be enough, but above the rated velocity, where the force distributions change markedly, the differences may still be noticeable further than $7.5D$.

The novel AD-precalc shows good agreement with the AD-airfoil model. The use of the DRD-BEM to calculate AD forces for design and off-design wind turbine working conditions overcomes the limitations of approaches based on the scaling of a master force distribution which are only valid while the shapes of the force distribution are analogous (i.e. usually below the rated speed)[8]. Also, the capability of including complex phenomena, like deformation in this case, without further modifying the CFD code makes it valuable, and opens new possibilities to study other mechanisms and control actions. Depending on the phenomena to be studied and the distance downstream, the simplest AD models can also achieve acceptable results, due to the added capacity for adaptation to the turbine setting and local flow condition. This improvement already present in other work [17] was implemented here by differentiating between $U_{ref}$ and $U_{\infty}$ in each case, integrating the implementation of the AD-unif, the AD-unif+rot and the AD-precalc in a common framework.

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