An adaptation of the super-Gaussian wake model for yawed wind turbines

Frédéric Blondel¹, Marie Cathelain¹, Pierre-Antoine Joulin¹, Pauline Bozonnet¹

¹IFP Energies nouvelles, 1-4 avenue du Bois Préau, Rueil-Malmaison 92852, France
E-mail: frederic.blondel@ifpen.fr

Abstract. The wake of a yawed wind turbine tends to be deflected and does not follow the incoming wind direction. This phenomenon, often referred to as “wake deflection”, has recently received a lot of attention from the wind energy research community: it is possible to dynamically optimize a wind farm power production by yawing some turbines to deflect their wakes, thus minimizing wake losses over the whole wind farm. In the present work, an analytical model for estimating the deflection of a yawed wind turbine wake is proposed. This new model is based on a super-Gaussian shape assumption for the velocity profile, enabling the estimation of the wake deflection in both near and far wake regions. First, the super-Gaussian model will be briefly introduced. Then, the new wake deflection model will be presented, as well as an updated version of the well known Jiménez model. This revised model allows a proper comparison with the proposed super-Gaussian model, since it is based on a similar definition of the wake width. Finally, results will be compared with experimental data from the literature.

1. Introduction

Behind a yawed wind turbine, observations ([3], [8], [4], [14]) and numerical simulations ([9], [17], [13], [11]) have shown that the wake does not follow the mean wind direction but is deflected, in a plane parallel to the ground, to one side or the other depending on the wind turbine yaw angle. This well-known phenomenon, often referred to as “wake deflection”, is of industrial interest. Indeed, in the case of a turbine operating in the wake of an upwind turbine, the upwind one can be yawed in order to deflect its wake away from the downwind one. This leads to an overall power increase: the loss of power production associated to the yaw offset, can be lower than the loss of production due to full-waked or even partial-waked operating conditions of the downwind turbine.

In practice, numerical solvers can be used to find, for each wind turbine in a wind farm, the yaw angle that maximizes the power output of the farm, for a given wind velocity and wind direction, finally maximizing the Annual Energy Production (AEP). However, the impact of the yaw misalignment on the wake behaviour is difficult to predict, and discrepancies have been revealed between analytical models and high-fidelity simulations or measurements ([13], [11]). High-fidelity Computational Fluid Dynamics (CFD) models could be used, but the numerical optimization implies hundreds of evaluations of a wind farm AEP (which already results of numerous combinations of wind speed and wind direction), which is currently unreachable using such solvers. In this context, improved analytical models for the wake deflection are of high interest.
One of the first analytical models for estimating the wake deflection has been proposed by Jiménez et al. [9]. Assuming a top-hat distribution of both velocity profiles (see figure 2) and wake deflection angles, Jiménez et al. derived a rather simple formulation of the wake deflection based on the momentum conservation. However, this model shows large deviations with measurements and high-fidelity simulations, which is probably due to a combination of an insufficient or unsuited calibration and too restrictive hypotheses.

Bastankhah & Porté-Agel [4] proposed an alternative model, based on a theoretical analysis of the Reynolds-Averaged Navier-Stokes equations. The top-hat shape assumptions are replaced by more physical Gaussian shape assumptions in the far wake. In the near wake, a transition is defined from a top-hat to a Gaussian shape, but the velocity deficit is kept constant. Qian & Ishihara [13] later proposed an alternative model, based on a theoretical framework similar to the one of Jiménez et al., but considering a Gaussian shape assumption for the velocity deficit. Another interesting approach has been proposed by Shapiro et al. [15]. In their approach, Shapiro et al. modelled the rotor as an elliptically loaded lifting-line. The main advantage of this model is its capacity to estimate the initial deflection, and to provide a reliable initial condition to the far-wake model. Later on, Martínez-Tossas et al. [12] revisited the lifting-line approach, proposing a semi-analytical model to predict velocity deficit, wake deflection and curl effect (i.e. change of wake shape due to yaw) effect. Although results are promising, the model is based on the resolution of simplified Navier-Stokes equations on a cartesian grid, which leads to very large computational times compared with analytical models (×1000 according to [10]), which is an issue when considering the wake steering optimization problem of a large wind farm.

In the present work, we introduce a new wake deflection model, that is able to handle both near and far wake deflection: in previous approaches ([4] and [13]), the wake deflection is assumed to increase linearly in the near wake, which is not consistent with observations. As in [4] and [13], the curl effect is neglected: an ellipsoidal wake shape is assumed. This is assumed to be a reasonable assumption, since the curl effect occurs mainly at high yaw angles (φ ≥ 20°), which may not be considered by wind turbine manufacturers, since such high yaw angles could lead to a high increase of fatigue damage. Furthermore, the secondary steering effect, predicted by the curled wake model, can be accounted for using the recent work of King et al. [10]. The main feature of the present model is the use of a super-Gaussian shape function for the velocity deficit. The super-Gaussian function is used to model the smooth transition from a top-hat shape, observed in the near wake, to a Gaussian shape, observed in the far wake. Thus, the model is assumed to be valid in both near- and far-wake regions. Models for the velocity deficit based on a super-Gaussian shape function have recently been proposed by Shapiro et al. [16] and Blondel & Cathelain [5]. The idea of extending these models to wake deflection comes very naturally. Furthermore, theoretical frameworks that have already been developed by others ([4], [13]) can be adapted to the super-Gaussian hypothesis. In this work, the framework proposed by Qian & Ishihara [13] is followed, the only change we introduce being the use of the super-Gaussian shape assumption. Unfortunately we could not use the theoretical framework proposed by Bastankhah & Porté-Agel [4], since some integrals could not be resolved. The new model makes it possible to estimate the deflection in both near and far wake, and enables the use of a super-Gaussian-based velocity deficit model together with the super-Gaussian based wake deflection model, thus relying on similar assumptions for both velocity deficit and wake deflection.

Throughout this paper, a set of experimental data provided by the École Polytechnique Fédérale de Lausanne (EPFL) will be used. These data have been obtained using stereoscopic particle image velocimetry measurements in the wake of a yawed and non-yawed wind turbine in an atmospheric boundary layer wind tunnel, as described in [4]. According to [4] the following thrust coefficients have been used: $C_{Tφ=0} = 0.82$, $C_{Tφ=10} = 0.78$, $C_{Tφ=20} = 0.73$, $C_{Tφ=30} = 0.67$, with φ the wind turbine yaw angle.
The paper is organized as follows: first, in section 2 we will recall the main equations of the super-Gaussian model for the velocity deficit as proposed in [5]. Then, the wake deflection model will be introduced in section 3, and finally comparisons with other models and experimental data will be shown in section 4. The Gaussian model used in the comparison is fully described in [4]. The present implementation includes the near-wake formulation.

2. The super-Gaussian model

2.1. Theoretical model

The main idea of the super-Gaussian model for the velocity deficit, first presented in [16] and later refined in [5], is to model the transition from the near to the far wake with a shape function \( f(\tilde{r}) \) that smoothly transitions from a nearly top-hat shape to a Gaussian shape. To do so, a super-Gaussian function is used, as shown in equation (1):

\[
\frac{U_\infty - U_w}{U_\infty} = C(\tilde{x}) f(\tilde{r}) = C(\tilde{x}) \exp \left(-\frac{\tilde{r}^n}{(2\tilde{\sigma}^2)}\right),
\]

with \( U_\infty \) the infinite wind velocity, \( U_w \) the velocity within the wake, \( C(\tilde{x}) \) the normalized maximum velocity deficit, \( \tilde{r} \) the distance to the wake centerline normalized by the wind turbine diameter \( d_0 \), \( n \) the super-Gaussian order, and \( \tilde{\sigma} \) the standard deviation also normalized by \( d_0 \). Hereinafter, the tilde symbol will denote a normalization by the wind turbine diameter. For high values of \( n \), \( f(\tilde{r}) \) tends towards a top-hat shape, while for \( n = 2 \), the Gaussian shape is recovered. After applying the mass and momentum conservation principle, the following form is obtained for \( C(\tilde{x}) \) (see [5]):

\[
C(\tilde{x}) = 2^{2/n-1} - \sqrt{\frac{2^{4/n-2} - nC_T}{16\Gamma(2/n)\tilde{\sigma}^{4/n}}},
\]

with \( C_T \) the wind turbine thrust coefficient and \( \Gamma \) the gamma function.

The standard deviation, \( \tilde{\sigma} \), that defines the wake width, is a function of the normalized downstream position, \( \tilde{x} \), of a parameter \( k \), and of the thrust coefficient \( C_T \) (through \( \epsilon \)):

\[
\tilde{\sigma} = k\tilde{x} + \epsilon.
\]

With \( c_s \) a constant to be determined, \( \epsilon \) writes:

\[
\epsilon = c_s \sqrt{\beta} = c_s \sqrt{\frac{1 + \sqrt{1 - C_T}}{2\sqrt{1 - C_T}}}.
\]

The super-Gaussian order \( n \) is a function of \( \tilde{x} \) only:

\[
n \approx a_f e^{b_f \tilde{x}} + c_f,
\]

with \( a_f, b_f \) and \( c_f \) coefficients to be determined. Although they should probably be functions of the turbulence intensity (TI) and thrust coefficient (\( C_T \)), as mentioned in [5], these coefficients are kept constant in the present work.

2.2. Calibration

In order to calibrate the model, we use the non-yawed case of the aforementioned experimental dataset. The wake is assumed to be fully Gaussian in the far wake and thus \( c_f = 2 \). The maximum value of the super-Gaussian order is set in order to fulfill the actuator-disk theory: the velocity at the disk should be equal to \( U_{disk} = U_\infty (1 - a) \) with \( a \) the axial induction factor,
calculated from the thrust coefficient \(a = 1/2 \left( 1 - \sqrt{1 - C_T} \right)\). Thus, at the disk, \(C(0) = a\). A value of \(a_f = 4\) is obtained. The last coefficient, that scales the rate of decrease of \(n\) against \(\tilde{x}\), is set to \(b_f = -1.15\), based on comparison to measurements (cf. figure 1).

It is worth noting that although the super-Gaussian model introduces three additional parameters compared with the standard Gaussian model, two of them are fully determined using physical assumptions, and only one is based on a calibration process. The parameter \(c_s\) that scales the initial wake diameter is set to \(c_s = 0.195\), while the rate of increase of the standard deviation is set to \(k = 0.027\). \(k\) should be a function of the turbulence intensity at least, and eventually of the thrust coefficient, as suggested in [13]. However, our purpose here is not to propose a fully calibrated model, but to demonstrate the feasibility of a super-Gaussian-based wake deflection model. The generalization to any thrust coefficients and turbulence intensities requires additional data and will be undertaken in future work.

Based on these values, comparisons between the Gaussian model, the super-Gaussian model and the experimental velocity profiles are shown in figure 1 at several downstream positions. As a preliminary remark, it is of importance to notice that close to the rotor \((\tilde{x} = 1)\), the presence of the hub and nacelle induces an additional velocity deficit, around \(\tilde{y} = 0\). This is not accounted for in the models. Indeed, it is assumed to be of secondary importance, since the additional velocity deficit vanishes quickly \((i.e.\ it\ is\ not\ observed\ at\ \tilde{x} = 2)\). Additional studies with low turbulent mixing \((i.e.\ with\ low\ atmospheric\ TI)\ should\ be\ performed\ to\ validate\ this\ assumption.

A very good agreement is obtained between the analytical models and experimental data in the far wake \((\tilde{x} \geq 4)\). In the near wake, the super-Gaussian model accurately predicts the maximum velocity deficit and wake shape, despite a slight under-estimation of the maximum velocity deficit at \(\tilde{x} = 3\). Excluding the hub/nacelle effect \((visible\ only\ at\ \tilde{x} = 1\ for\ this\ dataset)\), the Gaussian model accurately predicts the velocity profile at \(\tilde{x} = 1\). Downstream, at \(\tilde{x} = 2\) and \(\tilde{x} = 3\), the maximum deficit is underestimated \(due\ to\ the\ constant\ near-wake\ maximum\ velocity\ deficit\ assumption\ used\ in\ the\ Gaussian\ model)\, and the wake shape is not correctly predicted.

![Figure 1](image-url)  
**Figure 1.** Wake velocity profiles at hub-height and several downstream positions behind the non-yawed wind turbine.

3. Wake deflection modelling

Figure 2 introduces the angle and notation conventions used in the wake deflection model derivation. A nearly top-hat velocity profile \(near\-wake\ conditions\) and a nearly Gaussian velocity profile \(far\-wake\ conditions\) are included to illustrate the wake shape evolution when using a super-Gaussian wake model.
3.1. A super-Gaussian-based wake deflection model

Our derivation of the wake deflection model based on the super-Gaussian shape function very closely follows the one proposed by Qian & Ishihara in [13]. Thus, only the main steps will be recalled here.

After applying momentum conservation over a control volume around the wind turbine (see [13]), and assuming a top-hat distribution of the wake deflection angle $\alpha$, the following expression is obtained for $\alpha$:

$$
\alpha = \frac{-F_y}{\rho \int_{A_0} U_w^2 dA_0}, \tag{6}
$$

with $F_y$ the component of the thrust force acting in the spanwise direction:

$$
F_y = -\frac{1}{2} \rho A_0 (U_\infty \cos(\phi))^2 \sin(\phi) C_{T,\phi=0}, \tag{7}
$$

with $\phi$ the yaw angle. A small angle approximation has been used to obtain equation (6). This is a fair assumption, since the wake deflection angle takes small values ($\alpha < 10^\circ$), even for high yaw angles ($\phi \approx 30^\circ$). Given an estimation of the wake radius $\Delta_w$, the integral in equation (6) is calculated as follows:

$$
\int_{A_0} U_w^2 dA = U_\infty^2 \int_0^{2\pi} d\theta \int_0^{\Delta_w} (1 - C(\tilde{x}) f(\tilde{r}))^2 d\tilde{r}. \tag{8}
$$

Such an integral has a definite solution for our shape function $f(\tilde{r})$, that reads:

$$
\int_{A_0} U_w^2 dA = 2\pi U_\infty^2 \left[ C(\tilde{x}) \left( \Gamma \left( \frac{1}{n}, \frac{\tilde{r}^n}{2\tilde{\sigma}^2} \right) - \frac{2^{\frac{n+1}{2}}}{n} - C(\tilde{x}) \Gamma \left( \frac{1}{n}, \frac{\tilde{r}^n}{2\tilde{\sigma}^2} \right) \right) \right]^{\Delta_w}_{\tilde{\sigma}}, \tag{9}
$$

with $\Gamma$ the upper incomplete Gamma function, available in most programming languages. In the present work, the wake diameter is estimated from the standard deviation, and is assumed to be twice the full width at half-height of the Gaussian function, leading to the following expression of the wake radius $\Delta_w$ at any downstream position $\tilde{x}$:

$$
\tilde{\Delta}_w = 2\sqrt{2\ln(2)}\tilde{\sigma}, \tag{10}
$$

Equation (9) can be inserted in equation (6) to get an analytical expression of the wake deflection angle. Finally, the wake deflection is obtained by integrating the deflection angle, $\alpha$, over $\tilde{x}$. Assuming the wind turbine is located at $\tilde{x} = 0$, the wake deflection $\delta$ reads:

$$
\delta(\tilde{x}) = \int_0^\tilde{x} \alpha d\tilde{x}. \tag{11}
$$
Since we did not find an analytical solution for equation (11), it is integrated numerically.

To account for the deflection in the super-Gaussian model, equation (11) is integrated into the expression of the radial distance to the wake center, equation (13).

The wake standard deviation and maximum velocity deficit are also impacted when the turbine operates under yawed conditions. Following Bastankhah & Porté-Agel [4] and Qian & Ishihara [13], the maximum velocity deficit is modified as follows:

\[ C(\tilde{x}) = 2^{2/n-1} - \sqrt{2^{4/n-2} - \frac{nC_{T_\phi}\cos(\phi)}{16\Gamma(2/n)\tilde{\sigma}^{4/n}}}. \] (12)

In order to account for the ellipsoidal shape of the wake, we follow the work of Abkar & Porté-Agel [1]:

\[ \tilde{r} = \sqrt{\left(\frac{\tilde{\sigma}_z}{\tilde{\sigma}}(\tilde{y} - \delta)\right)^2 + \left(\frac{\tilde{\sigma}_y}{\tilde{\sigma}}(\tilde{z} - \tilde{z}_{hub})\right)^2}. \] (13)

Using such a correction, the wake standard deviation now reads:

\[ \tilde{\sigma} = \sqrt{\tilde{\sigma}_y\tilde{\sigma}_z}, \] (14)

and the standard deviations in the \( \tilde{y} \) and \( \tilde{z} \) directions take the following forms:

\[ \tilde{\sigma}_y = k\tilde{x} + \epsilon \cos(\phi), \] (15)
\[ \tilde{\sigma}_z = k\tilde{x} + \epsilon, \] (16)

with \( \epsilon \) defined by equation (4). As shown in [4], the wake growth rate \( k \) is not impacted by the yaw angle.

An analytical model for the impact of wind veer can also be integrated. We follow the work of Abkar & Porté-Agel [2]:

\[ \tilde{r} = \sqrt{\left(\frac{\tilde{\sigma}_z}{\tilde{\sigma}}(\tilde{y} - \delta + \tilde{x}\tan(v)(\tilde{z} - \tilde{z}_{hub}))\right)^2 + \left(\frac{\tilde{\sigma}_y}{\tilde{\sigma}}(\tilde{z} - \tilde{z}_{hub})\right)^2}, \] (17)

with \( v \) the wind angle as defined in [2]. In case the yawed thrust coefficient is unknown, it can be estimated using a relation of the form:

\[ C_{T_\phi} \approx C_{T_\phi=0}\cos(\phi)^p, \] (18)

with \( p \) a parameter to be determined. It usually takes values between 1.5 and 3. In our case, \( C_{T_\phi} \) is assumed to be known, based on experimental measurements. Thus, we do not use equation (18).

### 3.2. A modified Jiménez model

In the next section, the super-Gaussian-based wake deflection model will be compared to the Jiménez et al. model [9], which is based on a top-hat shape assumption for the wake velocity profile. However, the definition of the wake diameter in the Jiménez model \( 2\Delta_w = 1 + 2k_J\tilde{x} \) with \( k_J \) a parameter of the model) is not consistent with the one used in the Gaussian and super-Gaussian models, which may lead to an unfair comparison and poor performance of the Jiménez model, as obtained in [13] or [11]. It is thus redefined here. Based on the momentum
conservation principle, Jiménez et al. derived an expression for the wake deflection angle, $\alpha(\tilde{x})$, at a given position $\tilde{x}$:

$$
\alpha(\tilde{x}) = \frac{d\tilde{\delta}}{dx} = \left(\frac{1}{2\Delta_w}\right)^2 \cos^2(\phi) \sin(\phi) \frac{C_T}{2}.
$$

(19)

Consistently with the super-Gaussian model, the wake diameter is defined as:

$$
2\Delta_w = 4\sqrt{2\ln(2)}\bar{\sigma} = 4\sqrt{2\ln(2)} (k\tilde{x} + \epsilon) = S_d (k\tilde{x} + \epsilon).
$$

(20)

Inserting equation (20) into equation (19) leads to the deflection at a given downstream position $\tilde{x}_i$:

$$
\tilde{\delta}(\tilde{x}) = \int_0^{\tilde{x}_i} \alpha = \cos^2(\phi) \sin(\phi) \frac{C_T}{2} \int_0^{\tilde{x}_i} (S_d (kB \tilde{x} + \epsilon))^{-2} d\tilde{x}.
$$

(21)

In equation (19), the small angle approximation has been used. This approximation has already been justified in section 3.1. Thanks to this approximation, the wake deflection takes a simpler form than in [7], with a negligible loss of precision. The wake deflection, expressed in terms of distance to the non-yawed wake center, can be computed using the Cavalieri’s quadrature formula:

$$
\int (ax + b)^n \, dx = \frac{(ax + b)^{n+1}}{a(n+1)}.
$$

(22)

Considering $\tilde{\delta}(\tilde{x}) = 0$ at $\tilde{x} = 0$, the wake deflection reads:

$$
\tilde{\delta}(\tilde{x}) = \frac{\cos^2(\phi) \sin(\phi) C_T}{S_d^2 k_B \epsilon} \left(1 - \frac{\epsilon}{k_B \tilde{x} + \epsilon}\right).
$$

(23)

Based on the aforementioned scaling factor for the wake diameter $S_d$, a rather poor agreement is observed with experimental data. To compensate, we modify the definition of $S_d$:

$$
S_d = 4.75\sqrt{2\ln(2)}.
$$

(24)

This choice is totally empirical and acts against our original objective to use similar definitions of the wake width between the models, but it is the only way we found to get a reasonable agreement between the Jiménez et al. model and other models.

4. Results

4.1. Centerline deflection

The centerline deflection $\tilde{\delta}$ predicted by the modified Jiménez et al. model (”Top-hat”), the modified Jiménez et al. model with an enlarged wake (equation (24), “Top-hat mod.”), the Gaussian model of Bastankhah and Porté-Agel (”Gaussian”) and the proposed model (”super-Gaussian”) are compared with experimental data from reference [4] in figure 3. According to [4], the experimental wake centerline is estimated by taking the loci of the maximum velocity deficit in the measured PIV planes. The time-averaged experimental results show small fluctuations in the far-wake region, which could be explained by the residual of averaging the meandering wake over a finite measurement time span. A good agreement is observed between the super-Gaussian model and experimental data. To compensate, we modify the definition of $S_d$.

In the far-wake region ($\tilde{x} > 6$), wake deflections predicted by the Gaussian and the super-Gaussian models are similar. A slight overestimation compared to the experimental data is observed for all yaw angles. This could have been compensated by the use of a lower value for the parameters $k$ or $c_s$. However, this would have impacted the maximum velocity deficit, and a poorer agreement would have been observed when comparing the wake velocity profiles that will
be shown later (figure 4). In the far wake, the deflections predicted using the updated Jiménez et al. with the modified wake diameter based on equation (24) are satisfactory, although at the highest yaw angle a slight over-prediction of the wake deflection is noted. At the lowest yaw angle, a slight under-prediction (compared with the other models, the agreement with experimental data being very good) is observed.

In the near-wake region, the agreement between the super-Gaussian model and experimental data is also satisfactory. The rate of increase of the deflection is well caught at all yaw angles. The top-hat model is also in good agreement with the experimental data in the near wake. The impact of the scaling factor that determines the wake diameter based on the standard deviation is strong. The proposed value of $4.75\sqrt{2\ln(2)}$ leads to reasonable results, while using a value of $4\sqrt{2\ln(2)}$, wake deflections are strongly overestimated. This overestimation strongly increases with the yaw angle. As expected, the Gaussian model does not reproduce the experimental trends in the near wake, since a linear assumption is assumed for the deflection in this region, which does not correspond to experimental and numerical observations. Wake deflection is under estimated in the near wake, up to downstream positions of $\tilde{x} = 5$, which corresponds to common inter-distances observed in wind farms.

4.2. Velocity profiles

Wake velocity profiles are shown in figure 4. Although the wake width is slightly overestimated, a very good agreement is observed with the experimental data. As for the aligned flow case, the
Figure 4. Wake velocity profiles at hub-height and several downstream positions behind the yawed wind turbine for yaw angles of 10, 20 and 30 degrees from top to bottom, respectively.

Gaussian model predicts the velocity profiles at $\tilde{x} = 1$ very well, but at $\tilde{x} = 2$ and $\tilde{x} = 3$, the maximum velocity is underestimated. At higher downwind positions, results of the Gaussian and super-Gaussian models match very well. Even very close to the rotor plane ($\tilde{x} = 1$), the super-Gaussian model fits quite well with the experimental data (excluding the additional deficit due to the hub presence). This good agreement is important to obtain, since a good prediction of the near-wake velocity profiles induced a satisfactory prediction of the near-wake deflection, and thus a good onset for the far-wake deflection.

Figure 5. Relative $L^2$ norm error between the Gaussian and super-Gaussian models and experimental data at several downstream position.

The analysis of the relative $L^2$ norm error between the models and the experimental velocity
deficit profiles provides a more quantitative insight (figure 5). The relative errors at each \( \tilde{x} \) plane are averaged for all yaw angles for the sake of readability (similar behaviors were noticed for all yaw angles). At \( \tilde{x} = 1 \), the \( L^2 \) norm error is large, which might be due to the nacelle effect that is not accounted for in the models. Downstream, in the near-wake, the super-Gaussian based wake deflection model leads to an improvement of the prediction compared to the Gaussian model: a noticeable reduction of the relative error is observed at \( \tilde{x} = 2 \) and 3. In the far wake (\( \tilde{x} > 4 \)), both models perform well, with relative errors around 5%. From these results, it can be concluded that our objective to improve the Gaussian model in the near-wake region, without deteriorating the far-wake predictions, is fulfilled.

5. Conclusions and perspectives
A wake deflection model based on a super-Gaussian velocity profile has been introduced. The model has been derived following the theoretical framework introduced by other authors. Thanks to the super-Gaussian assumption, the model is able to accurately predict the wake deflection in the full wake, including both near and far wake regions, which is a noticeable improvement compared with previous analytical models. The main drawback of the model lies in the integration of the wake deflection, that needs to be numerically solved. This may lead to a computational burden, that might be unacceptable for operational, real-time wind farm control. A revised form of the Jiménez et al. model has also been introduced. The initial objective was to use consistent wake width definitions in the super-Gaussian and top-hat models. However, obtained results were not satisfactory. Thus, it has been decided to enlarge the wake to get a better agreement with measurements and other models. Although a good agreement has been obtained in the presented cases, integrating a dependence on the turbulence intensity and on the thrust coefficient would make the model more generic. Additional phenomena such as stability induced deflection ([17]), secondary steering ([6], [10]) and nacelle effects should be considered.

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