Referee:1

General comments:

The paper compares six analytical wake models with three different experimental datasets

for the near-wake (x/D=2 – 3.5) of a model-scale turbine, for the far-wake (x/D= 4-11) of another model-scale turbine, and for the intermediate wake (x/D=2-6) of a full-scale wind turbine. The model comparisons are first tuned and then compared for a non-yawed turbine wake and thereafter compared for several yawed wake configurations.

The work includes a novel experimental dataset (near wake model scale) and two existing datasets from other publications. Furthermore, the work proposes a new wake model with yaw-capabilities. From the model description it seems that the new model mainly combines the wake deflection sub-model by Bastankhah and Porte-Agel (2016) and the double Gaussian deficit model by Keane (2021). The model description should be clearer about which equations were adapted from these models, and which are new additions.

The paper is well-organized, features concise language, and is very interesting to read. It features a detailed analysis of the modeled mean velocity deficits and a quantification of the mean absolute error for the different wake configurations.

The paper addresses the scientifically relevant topic of improved analytical wake modelling for non-yawed and yawed cases, while specifically the near-wake modelling and the full-scale applicability are highlighted as novel contributions. Full-scale wake flow validations are indeed considered essential, and the authors emphasize the need for validating yawed wake models for further full-scale cases. The need for accurate modelling of the near-wake could be justified more, as it is not completely clear how wind farm models would benefit from improved near- wake modeling. The importance of accurate near-wake models for wind farm simulations should be motivated in more detail.

We thank the reviewer for providing valuable positive feedback on our manuscript. In the following document we address each of their comments, enhancing the revised version to meet the standards for publication. Any modifications made to the manuscript are highlighted in blue and, when relevant, have been included below to address the reviewer's specific comment.

The authors would like to take a moment to highlight the novelty of this submission, which comes in three forms:

- The inclusion of a high resolution near-wake dataset.
- A comparison of current analytical models using three experimental datasets (including full-scale), where previous literature would have mostly only included one experimental dataset.
- The proposition of an analytical model as the combination of two previous models.

The authors are thankful to the reviewer for their valuable insight on addressing motivation of the importance of accurate near-wake models. It is of the authors opinion that the near-wake modelling is necessary because:

- Under certain circumstances (U_h, T_i) the near-wake extends beyond 5D, therefore in some farms, the near-wake will influence other turbines.
- Recent work has been conducted to understand the influence of objects within the near-wake of a turbine, for example transmission lines (challenging the current view and guidelines that overhead transmission lines should not be installed within 3D of a wind turbine; see [1]) and bird clusters [5].

We thank the reviewer for their comment on the clarity of combining work by [3] and [2]. The method is now stated more clearly in the manuscript, alongside a modified definition of the novelty of the proposed method.

The manuscript has been updated to reflect the astute comments from the reviewer, shown below, in blue.

The first dataset is a near-wake high-resolution planar PIV wind tunnel experiment at a working TSR of $\lambda = 5.5$. The necessity to accurately predict the near-wake comes not only from the possible interaction with downstream turbines, but, recently, the interaction with other objects within a farm, such as transmission lines or bird clusters ([1] and [5]). As a purely near-wake focus would be limiting, two additional datasets are included in this investigation.

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An additional model, developed with the combination of the double-Guassian formulation by [3] coupled with the yaw model from [2] is proposed.

...

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...

Following this, Sect. 3 describes the proposed analytical model based on a combination of work by Keane [3] and Bastankhah and Porté-Agel [2].

...

This section proposes a wake model using a combination of existing models, developed to improve the accuracy of predictions in the near-wake under yaw misalignment.

...

Any novel modifications to the equations are highlighted in bold and described in the section below.

...

where $D_{\pm}$ is modified from work by [3] with the addition of the yaw centre y_c, and multiplication of r_{min} by $\cos(\gamma)^2$, given by

...

The equation for the wake centre y_c is dependant on the normalised length of the potential core x_0/D given below from work by Bastankhah and Porté-Agel [2]

...

Work by Keane [3] uses the actuator disc model. Keane employs work by Tennekes and Lumley [4] to show the mean momentum flux across a disk is given by

...

This study compared six analytical yaw wake models, including a proposed double-Gaussian formulation as a combination of the work by Keane [3] and Bastankhah and Porté-Agel [2]

Major comments:

1) Reproducibility of the wake data comparison / Missing information on input data.

A quantitative model comparison of models with tunable input parameters is always somehow "tricky". Dependent on the model tuning the difference to the measured reference data can be actively influenced. Here, the authors present a consistent way of model tuning by minimizing the absolute mean error of every model to the measured reference data. However, it is not transparent to which values the tunable parameters of each model have been set. For reproducibility of the presented results, the values of these parameters is required. I would suggest including an additional table:

Table 2: Analytical wake models – tuning parameters Include all the values of the tunable parameters of the different wake models for the Near-wake / Far-wake / Full-scale case for reproducibility of the presented results.

Futhermore, an overview of the main parameters of the three reference datasets is missing. Most of this information can be found in the cited original papers, while information about the turbine thrust coefficient CT is missing completely. Especially turbine's CT and the turbulence intensity in the inflow are regarded as crucial input parameters to the models. It would be interesting to see how similar/different they are for the three reference datasets.

Table 3: Comparison of the experimental datasets Include information about Turbine size, diameter, CP, CT, inflow-TI, inflow-shear ...

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We thank the reviewer for their comment regarding the clarity of model calibration and on the reproducibility of the manuscripts data. The authors agree fully with this comment and have included two additional tables (Table 1 and Table 2) within the manuscript's, shown below, in blue.

The process used to tune these parameters is outlined in Sect. 2.2 and the resulting parameters are displayed in Table 1. The results from the tuning procedure are discussed in the following section.

...

The information necessary to reproduce the results from the near-wake, far-wake and full-scale datasets are presented in Table 2. It must be noted that all yawed thrust coefficients are measured for the near- and far-wake datasets, however, for the full-scale dataset only the zero yaw angle thrust coefficient is known, hence the thrust coefficient is estimated using $\cos^2(\gamma)$, shown in Table 2

2) Experimental details/limitations.

TABLE 1: Tuned parameters for each analytical model. X_0 represents the models standard calibration.

Model	Parameter	Near Wake	Far Wake	Full Scale	X_0
BPA					
	α^*	0.733	2.05	4.16	2.32
	k	0.00560	0.0292	0.0293	0.0220
Sh					
	k_w	0.0103	0.0948	0.0644	0.0834
	σ_0/D	0.283	0.223	0.323	0.235
Bl					
	c_s	0.109	0.175	0.179	0.195
	k	0.0344	0.0301	0.0461	0.0270
	b_f	-0.354	-1.06	-0.775	-1.15
Ba					
	U^*	0.341	0.493	0.525	0.216
	α	0.629	0.248	0.695	0.600
Pr					
	α	0.0613	0.0338	0.990	-
	n	0.174	0.937	0.567	-
	r'_{min}	0.467	0.416	0.477	-
	d'_e	1.06	0.881	1.02	-

There are some important details about the wind turbine experiment missing in the paper:

(a) First of all, what was the measured thrust coefficient CT at the design tip speed ratio? This crucial input parameter for the wake models is not mentioned anywhere.

(b) Secondly, were power and thrust of the turbine measured for different tip speed ratios, i.e. CP-TSR and CT-TSR curves? Did the power peak for the tip speed ratio it was designed for? (TSR = 5.7)?

(c) What was the chord-based Reynolds number for your turbine at the inflow wind speed of Uinf = 7.8 m/s? From the information given in Table A1, the chord-based Reynolds number should be around Rec,root = 26000 at the innermost blade element and Rec,tip = 74000 at the blade tip. According to Giguere and Selig (1998), the airfoil was designed for Rec = 250 000, while the lowest Reynolds number the polars were measured for was Rec = 100 000. A Reynolds-number independent performance of the turbine should be shown for these low Re-numbers (i.e. by Reynolds-number independent CP-TSR curves measured at different inflow speeds) or the mismatch at least discussed.

TABLE 2: Flow and turbine characteristics.

Dataset	Yaw angle [°]	C_T	U_∞ [ms^{-1}]	TI [%]	D [m]	λ
Near-wake						
	-30	0.542	7.8	5.3	0.5	5.5
	-25	0.579	7.8	5.3	0.5	5.5
	-20	0.618	7.8	5.3	0.5	5.5
	-15	0.632	7.8	5.3	0.5	5.5
	-10	0.657	7.8	5.3	0.5	5.5
	-5	0.674	7.8	5.3	0.5	5.5
	0	0.682	7.8	5.3	0.5	5.5
	5	0.672	7.8	5.3	0.5	5.5
	10	0.653	7.8	5.3	0.5	5.5
	15	0.628	7.8	5.3	0.5	5.5
	20	0.602	7.8	5.3	0.5	5.5
	25	0.557	7.8	5.3	0.5	5.5
	30	0.508	7.8	5.3	0.5	5.5
Far-wake						
	0	0.820	4.88	7.5	0.15	3.8
	10	0.780	4.88	7.5	0.15	3.8
	20	0.730	4.88	7.5	0.15	3.8
Full-scale						
	0	0.780	8.6	12.5	131	7
	11	$0.750 = 0.78\cos(11)^2$	8.6	12.5	131	7

(d) What was the wind tunnel blockage ratio in your experiment? It seems to be low enough, but could the wake deflection be influenced by the side walls of the wind tunnel? At least a basic discussion of this should be included in the description of the experimental setup.

(e) The measured near-wake distances at x/D=2.7 +- 0.6 are very similar. If near-wake measurements are deemed important for this model comparison, why were not measurements closer to the turbine, i.e. x/D ¡ 2, performed? Please justify that in the paper.

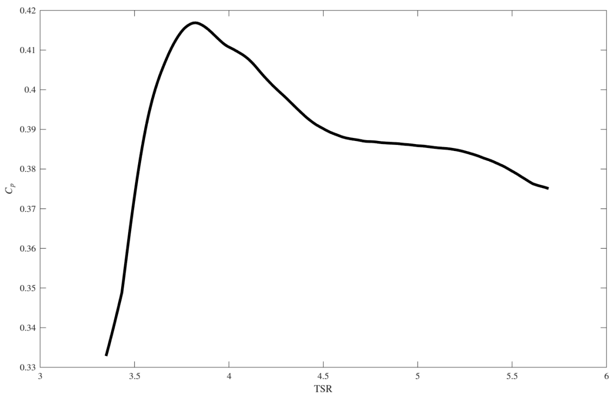

FIGURE 1: Power coefficient vs TSR.

We appreciate the reviewer's careful and insightful feedback on the experimental details/limitations. The authors have commented on the points (a-e) below:
(a) The measured thrust coefficients are shown in Table 2.
(b) Yes the Cp-TSR and Ct-TSR curves were measured however, to ensure the turbine was operating at the TSR and Cp of the comparison Senvion 6M126 turbine, the TSR is not at the peak Cp, shown in Fig. 1. Additionally, the gradient of Cp-TSR at the location of operation is far shallower than at the peak, therefore changes in TSR with T_i did not cause major changes in the turbines power.
(c) A Cp-TSR at different wind speeds has been completed for this blade and it is observed that a 30% change in Re causes a 10% change in Ct and a 20% change in Cp at the design TSR, however this is taken into account when tuning the models with input parameters of U and Ct. A discussion regarding the Reynolds dependency of the turbine is added to the manuscript, shown below, in blue.
(d) The blockage ratio is 4 % and the transverse deflection of the wake is less than 0.5D, hence the distance from the centre of the wake to the far walls of the tunnel at maximum deflection is over 2D. A discussion on these points are reflected in the manuscript, shown below, in blue.
(e) Due to the length of the turbine nacelle, to avoid unwanted reflections when conducting PIV, the closest FOV the authors could achieve was $\approx 2D$. A discussion regarding the experimental limitations are included in the manuscript, shown below, in blue.

As a result of the low Reynolds numbers associated with scale wind turbine experiments, a study into the Reynolds dependency of the blade is conducted. It is observed that a 30 % change in Reynolds number causes a 10 % change in thrust coefficient C_T and a 20 % change in power coefficient C_p at the design TSR.

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The wind tunnel geometric blockage due to the wind turbine is $< 4\%$ and is accounted for in the free-stream velocity. The maximum transverse deflection of the wake is less than $0.5D$, hence the distance from the centre of the wake to the far walls of the tunnel at maximum deflection is over $2D$.

...

Due to the length of the turbine nacelle, to avoid unwanted reflections when conducting PIV, the FOV was limited to $\approx 2D$ behind the turbine.

> 3) Discussion/conclusions on "model flexibility" vs "model complexity" of additional tuning parameters in the proposed wake model.
>
> Also, a critical discussion about the interplay of model tuning and error reduction should be included in the paper. Section 5 closes with "the model's flexibility resulting from having tunable parameters". Isn't it somehow expectable that the MAE is reduced when additional tuning parameters are introduced? How does that make the model more complex to handle on the other hand? Include some lines of discussing that.
>
> In the abstract/conclusions it is mentioned: "The proposed double-Gaussian model achieves the lowest absolute mean error across all datasets." This is correct but not surprising as the model has the highest number of tunable parameters. Also, the main contributor to the lowest absolute mean error across all datasets mainly stems from the near-wake results, that some of the other models are not designed for. I propose another, more realistic conclusion along the lines of "The proposed double-Gaussian model shows improved modelling of the near-wake".

We thank the reviewer for their comments, expanding on the necessity for additional discussion regarding the flexibility and complexity of the models used. The authors agree that the introduction of additional tuning parameters can lead to a reduction in error, and that this effect must be interpreted with care. However, the improvement of the near-wake prediction of the proposed model is not just a consequence of the increased tuning parameters, but rather the use of a double-Gaussian formulation [3]. A discussion on the improved flexibility with model complexity has been added to the manuscript, shown below, in blue.
The authors agree that the more realistic abstract/conclusion the reviewer has suggested gives a logical understanding of the proposed findings. Please see the additional changes to the manuscript in blue below.

The proposed double-Gaussian model shows improved modelling of the near-wake.

...

The reasoning for the greater accuracy of the methods is a consequence of their more complex representation of the near-wake profile, alongside the greater number of tuning parameters, thereby allowing the models greater flexibility for differing turbine operating conditions. An unwanted result of the increased tuning parameters of the super- (Bl) and double-Gaussian (Pr) models is an increase in the complexity of the models. When tuning each model, it took an order of magnitude more iterations for the super- (Bl) and double-Gaussian (Pr) wake models to converge to a local minimum, when compared to the single-Gaussian formulations.

...

The double-Gaussian model (Pr) consistently demonstrates the highest accuracy, achieving an average MAE of 2.6 %, akin to the model's more complex representation of the near-wake profile, alongside the greater number of tuning parameters, thereby allowing the model greater flexibility for differing turbine operating conditions.

...

Overall the proposed double-Gaussian model shows improved modelling of the near-wake.

Minor comments:

> 1) dU/Uinf axis in wake profile plots: Although the figure text describes that the distance between two vertical lines corresponds to dU/Uinf = 0.25 or 0.50, additional dU/Uinf axes on top of the profile plots would be helpful to quantify the differences in the predictions.

We thank the reviewer for their comment and agree it would be helpful to have additional axis, this has been modified in the manuscript, and shown below in Fig. 2,3,4,5,7,8.

> 2) Figures 5 and 10: Is it necessary to show all distances between x/D=4 and x/D=11 in these plots? A reduction to x/D = 4,7,9,11 (or similar) would show the same main trends and be more manageable for the reader.

The authors agree, and are thankful to the reviewer for pointing out where figure 5 and 10 may be overwhelming, this has been changed within the manuscript, shown below in Fig. 3,7.

> 3) Analysis of both the Mean Absolute Error (MAE) and Root Mean Square Error (RMSE): It is very important to quantify the deviations of the model predictions from the measured velocity data. However, the MAE and the RMSE show the absolute same trends for all comparisons made in this article. Wouldn't it be enough to focus on one error quantification method?

We appreciate the reviewer's thoughtful and constructive comment. The authors agree that, for the cases presented in this study, both metrics exhibit similar overall trends across the models. Nevertheless, It is of the authors opinion that the MAE and RMSE are both important metrics when representing the error of each model. As the MAE offers a robust measure of the general prediction error and the RMSE shows where larger deviations of particular points are present, both are necessary when model predictions are evaluated against planar PIV and single point velocity data. For these reasons, we have retained both MAE and RMSE in the manuscript.

Side note: Figure 9 includes 8x2 error comparisons, which is a lot of information for little variation in the conclusions to be drawn from the error comparison. In my opinion error comparisons of three yaw angles, e.g. for gamma = 10, 20, 30 degrees, would be sufficient here.

We thank the reviewer for this helpful and astute observation, as such Fig. 6 has been updated within the manuscript.

Technical comments:

p. 1, Title of the paper. I suggest to extend the title of the paper to "Analytical yaw models for wind turbine wakes: a two-dimensional comparison". The original title seems incomplete and will make it more difficult to find the paper in search engines.

The authors thank the reviewer for their comments regarding the title of the manuscript and agree with the proposed change.

p. 3, L.67: The acronym "FOV" is not defined yet. Include the full "field of view (FOV)".

We thank the reviewer for their comment and have corrected the manuscript, shown below in blue.

Field Of View (FOV)

p. 5, L.119: "A non time-resolved dataset of 3000 snapshots taken (. . .) To ensure the velocity snapshots are synchronous with the turbine measurements". In this text section there are two points that are not clear to me: (1) Why is the dataset "non time-resolved"? (2) Why do the velocity measurements need to be synchronized with the turbine measurements when only mean values are presented?

We thank the reviewer for their comments. The measurements need to be non-time resolved to ensure the velocity fields are statistically uncorrelated. The comment of the synchronization of the velocity measurements has been omitted.

p. 10, L.192: "3.1 Model procedure". If there is the numbering "3.1", there should also be "3.2".

We thank the reviewer for their comment and have updated the manuscript accordingly.

Mathematical formulation

p. 10-15, chapters 4 and 5: it is sometime difficult to recall what the "super-Gaussian", "double-Gaussian", ... models are. Could it be better to use the acronyms defined in Table 1 in the text, e.g. "super-Gaussian Bl", "Double-Gaussian Pr" model?

The authors agree it may be difficult to recall the models based on how they are currently presented in the manuscript. Therefore all comments regarding the models within the manuscript have an additional acronym consistent with Table 1.

p. 11, Figure 4, and P.14 Figure 8. The figure text of both figures refers to downstream distances x/D= 1.05, 1.65 and 3. From the figures itself and the exp. setup presented earlier in Figure 2, downstream distances somewhere around x/D = 2.1, 2.7 and 3.3 seem to be more correct?

The authors apologise for the oversight on this matter and thank the reviewer for their comment. The modifications to Figure 4 and 8 have been made, shown below in blue.

$x/D = 2.1$, 2.7 and 3.3

p. 14, L.264: "... overpredict the wake deficit." It looks to me like they "overpredict the wake deflection", and accurately predict the wake deficit.

The authors agree they slightly over-predict the wake deflection, which is mentioned in the subsequent paragraph "a slight overprediction is observed". Additionally, the sentence "At a yaw angle of 20°, aside from at $x/D = 4$, all yaw models slightly overpredict the wake deficit." has been removed from the manuscript. The manuscript has been modified to make this point clearer shown below, in blue.

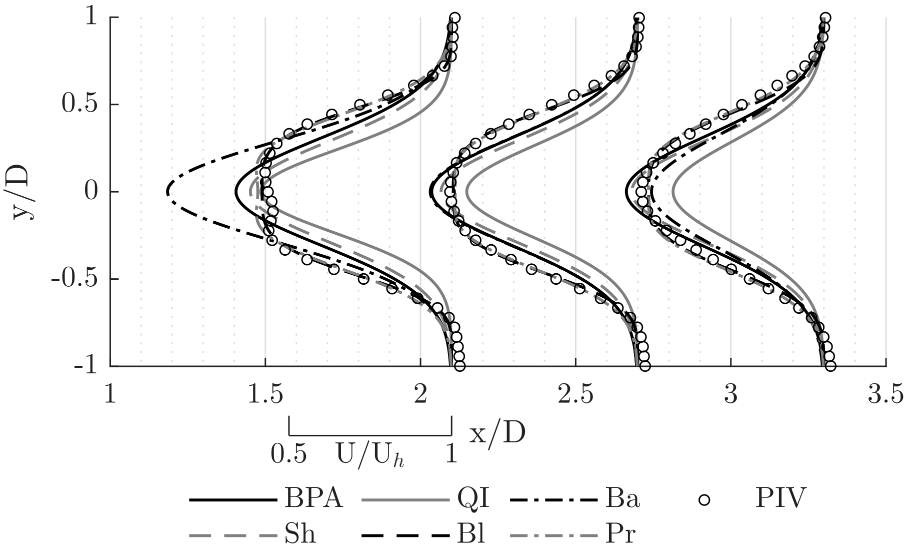

FIGURE 2: Spanwise profiles of the normalised streamwise velocity at $x/D = 2.1, 2.7$ and 3.3, comparing near-wake experimental data with tuned models at a yaw angle of zero degrees. The solid vertical grey lines indicate $U/U_\infty = 0.5$.

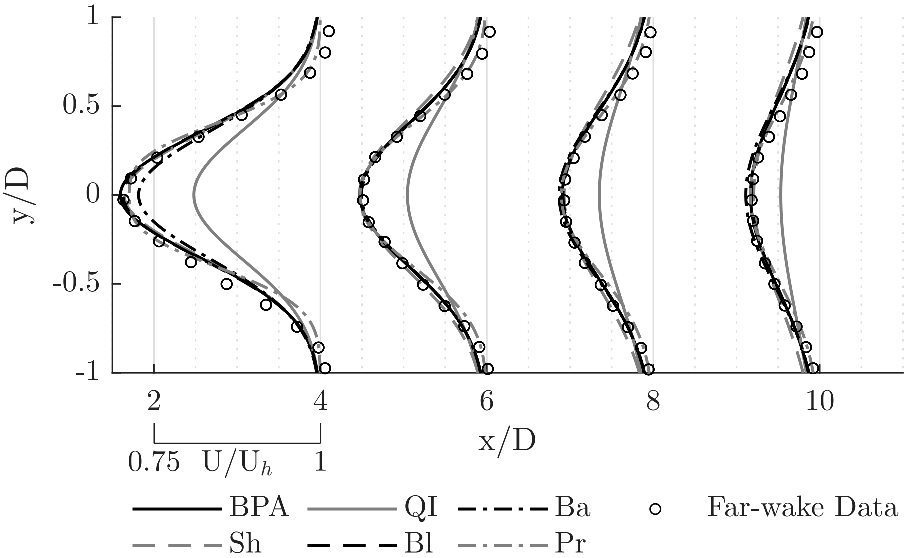

FIGURE 3: Spanwise profiles of the normalised streamwise velocity from $x/D = 4$ to 11, comparing far-wake experimental data with tuned models at a yaw angle of zero degrees. The solid vertical grey lines indicate $U/U_\infty = 0.25$.

All other models generally maintain good agreement with the measured wake centre, although a slight overprediction is observed at 20°.

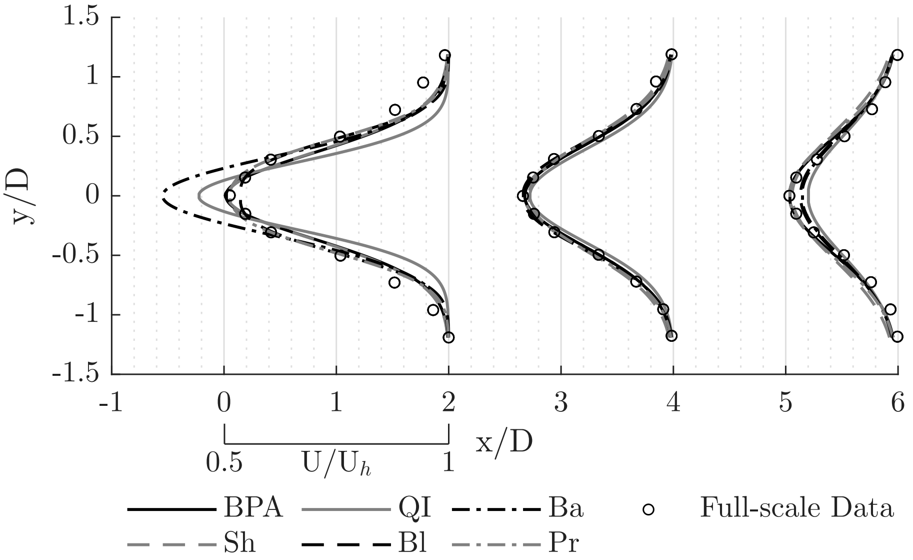

FIGURE 4: Spanwise profiles of the normalised streamwise velocity at $x/D = 2$, 4 and 6, comparing full-scale experimental data with tuned models at a yaw angle of zero degrees. The solid vertical grey lines indicate $U/U_\infty = 0.25$.

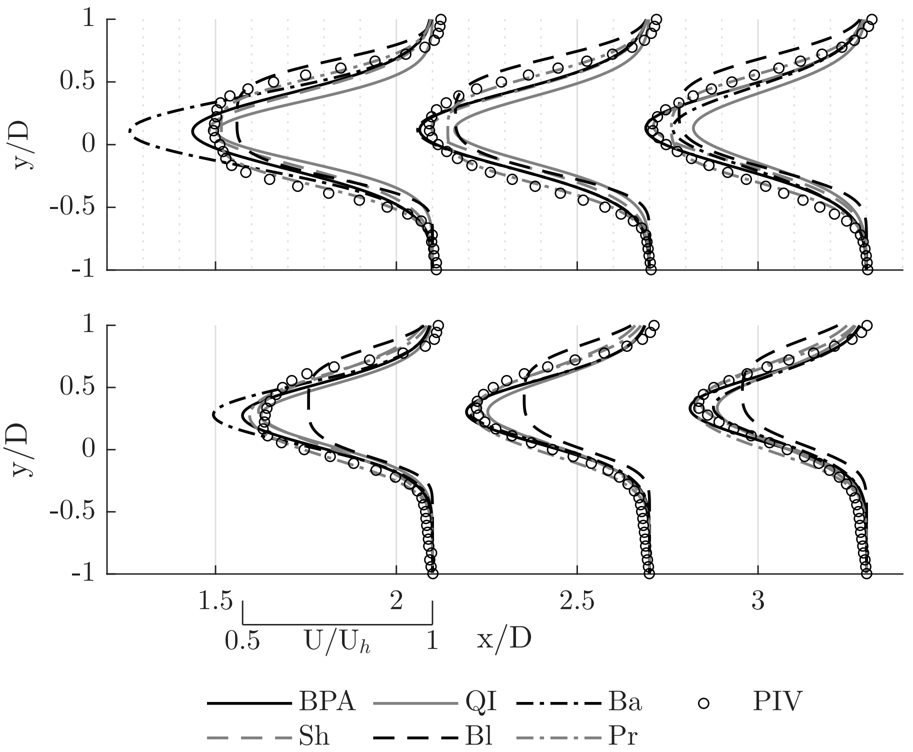

FIGURE 5: Spanwise profiles of normalised streamwise velocity at $x/D = 2.1$, 2.7 and 3.3, comparing near-wake experimental data with tuned models at (Top) $\gamma = 10°$, and (Bottom) $\gamma = 30°$. The solid vertical grey line marks $U/U_\infty = 0.5$.

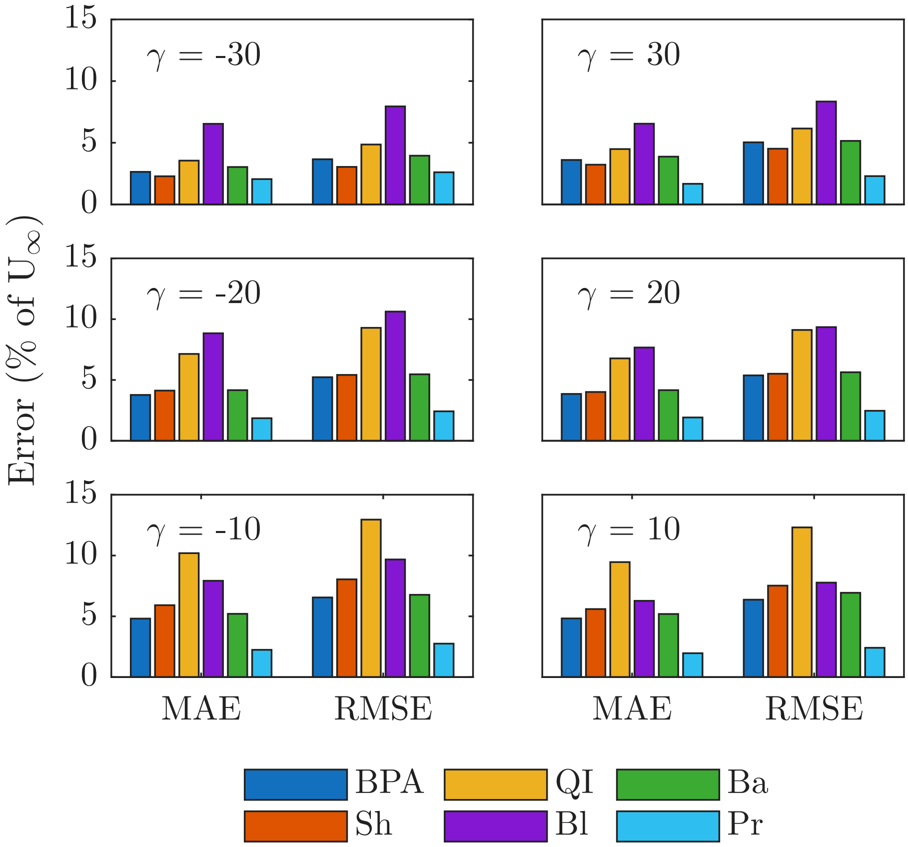

FIGURE 6: MAE and RMSE, expressed as percentages of the free-stream velocity, for each analytical model compared with near-wake velocity data at yaw angles ranging from $\gamma = -30^{\circ}$ to $\gamma = 30^{\circ}$

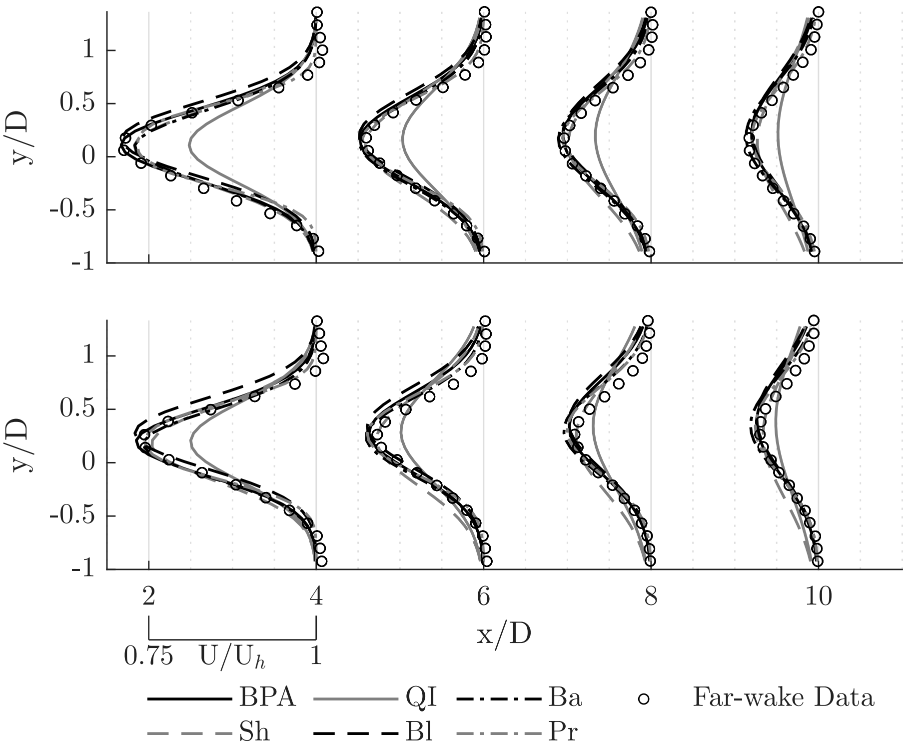

FIGURE 7: Spanwise profiles of normalised streamwise velocity from $x/D = 4$ to 11, comparing far-wake experimental data with tuned models at (Top) $\gamma = 10°$, and (Bottom) $\gamma = 20°$. The solid vertical grey line marks $U/U_\infty = 0.25$.

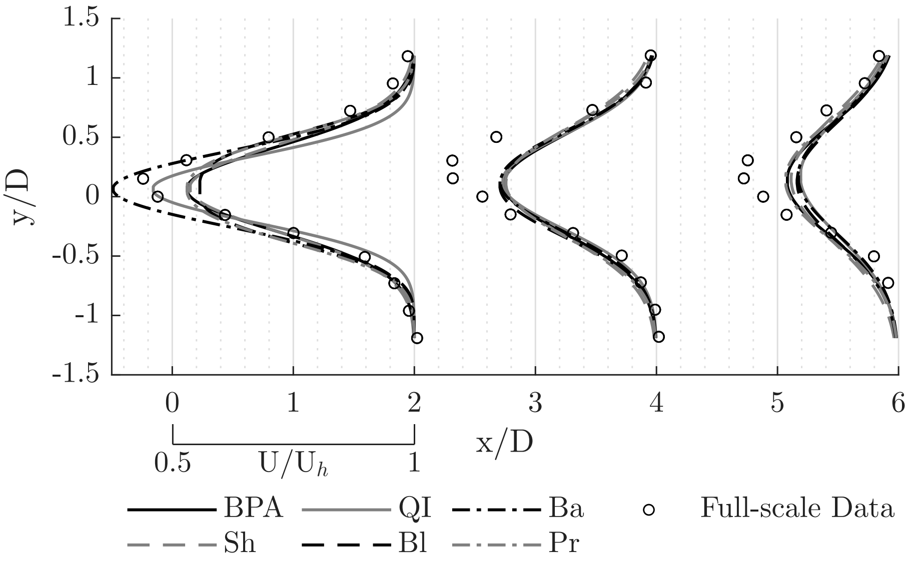

FIGURE 8: Spanwise profiles of normalised streamwise velocity at $x/D = 2$, 4 and 6, comparing full-scale experimental data with tuned models at $\gamma = 11°$. The solid vertical grey line marks $U/U_\infty = 0.25$.

References

[1] Bs en 50341-2-4:2019 Overhead electrical lines exceeding ac 1 kv – part 2-4: National Normative Aspects (NNA) for the United Kingdom, 2019.

[2] Majid Bastankhah and Fernando Porté-Agel. Experimental and theoretical study of wind turbine wakes in yawed conditions. *Journal of Fluid Mechanics*, 806: 506–541, 2016. .

[3] Aidan Keane. Advancement of an analytical double-gaussian full wind turbine wake model. *Renewable Energy*, 171:687–708, 2021. .

[4] Hendrik Tennekes and John Leask Lumley. *A first course in turbulence*. MIT press, 1972.

[5] Xuefeng Yang, Lifan Zhou, Yi Sui, Zhengru Ren, and Shengli Chen. Effects of wind turbine wakes on bird gliding aerodynamic performance. *Scientific Reports*, 2025. .