Development of a streamline wake model for wind farm performance predictions

Matias Sessarego¹†, Ju Feng¹, Mikkel Friis-Møller², Yun Xu³, Mengying Xu³ and Wen Zhong Shen¹

¹Fluid Mechanics Section, Department of Wind Energy, Technical University of Denmark, Nils Koppels Allé, 2800 Kgs. Lyngby, Denmark
²Wind Turbine Loads and Control Section, Department of Wind Energy, Technical University of Denmark, Frederiksbergvej 399, 4000 Roskilde, Denmark
³Shanghai Electric Wind Power Group Co., Ltd. Floor 3, J Building, No. 115 Caobao Road, Xuhui District, Shanghai, People’s Republic of China

†Present address: Ørsted Wind Power A/S, Nesa Allé 1, 2820 Gentofte, Denmark
E-mail: wzsh@dtu.dk

Abstract. In the present paper a new streamline model for wake development based on a streamline topology is applied and compared with different approaches for modeling the wind turbine wakes. The contribution of the present work is the comparison of the streamline-and straight-wake models as well as the different wake models, e.g., Jensen and Gaussian. The models have been applied to two wind farm cases. The results from the first case are compared against SCADA measurements and computational fluid dynamics simulations (CFD). The CFD simulations are performed using Reynolds-Averaged Navier Stokes (RANS) together with the actuator disc (AD) approach. The mean percent difference in power using the different wake models ranged between 19-20%. Mean percent difference in power for the AD-RANS was approximately 20%. For the second wind farm case only wake models are compared and approximately ±1% difference exists between them. The present work shows that the streamline topology of the wind turbine wake flow as well as the wake models have an effect on the performance prediction of wind farms.

1. Introduction
In response to the global energy demand and climate change, wind farm development is increasing worldwide both in onshore and offshore environments [1]. Wind farm developers are constantly evaluating the challenges and benefits for the various potential onshore and offshore sites. For onshore wind energy deployment, suitable sites in flat terrain typically provide low installation, operation and maintenance costs compared to complex terrain sites. However, many of the suitable sites in flat terrain are already occupied by wind farms, thus attracting more attention to empty complex terrain sites.

In the planning stages for the development of new onshore wind farms, various computational tools are used to predict the performance of a wind farm with different levels of fidelity. Computational fluid dynamics (CFD) is a high-fidelity approach for estimating the wind distribution over a complex terrain site. Wake models can be superimposed on the CFD flow solution to simulate the wake effects due to the presence of wind turbines in a proposed farm. The classical Jensen [2, 3] model and the Park [4, 5] model are the most popular approaches...
to predict the wake deficit of wind farms. The Jensen and Park models are also the standard implementation in commercial software for wind resource assessment such as WAsP (Wind Atlas Analysis and Application Program) [6, 7] and WindPRO [4].

In the present paper, the new streamline model based on a streamline topology [8, 9] is applied and compared with different approaches for modeling wind turbine wakes. The importance and contribution of the presented work is to assess the differences between the streamline model and the straight model as well as the different wake models, e.g., the Jensen and Gaussian wake models. The model is used to predict the performance of a wind farm with twenty-five wind turbines at a real complex terrain site. Model results are compared against SCADA measurements and CFD simulations. A second wind farm site with eight wind turbines is also evaluated using wake models only.

The current paper is organized into four sections: 1. Introduction, 2. Methodology, 3. Results, and 4. Conclusions. Section 2 contains the background regarding the streamline model and the wind farm sites. Then, results from the wind farm performance predictions will be shown in section 3. Finally, conclusions are given in section 4.

2. Methodology

The methodology section is composed of two subsections: 2.1 Description of streamline model and 2.2 Example cases. The example cases are provided to illustrate how the streamline model can be applied to predict wind turbine wakes and the wind farm performance.

2.1. Description of streamline model

The new streamline model is based on a streamline topology of the base flow at the wind turbine hub height and can be combined with any of the wake models, e.g., Jensen/Park or the Gaussian wake model proposed by Bastankhah and Porté-Agel [10]. The new engineering streamline wake model is referred to as Streamline. Streamline is suitable for complex terrain sites, since the model captures the effect of flow direction changes caused by the terrain topography. Streamline is based on the work of Brogna [8, 9] written in MATLAB and is rewritten into Python for integration into PyWake [11], which is a Python library used for wind farm performance predictions in the Technical University of Denmark (DTU)’s wind farm design tool framework TOPFARM [12]. Details regarding the model can be found in [8].

Streamline requires flow data from a CFD simulation as input. Within the context of the framework, the flow data can be obtained from WAsP CFD [13]. WAsP CFD uses the CFD software EllipSys3D [14, 15, 16] to calculate the wind velocity perturbations induced by complex terrain with roughness changes. In WAsP, EllipSys3D solves the RANS equations. Python scripts in PyWake read the data files outputted by WAsP. The flow simulation is without the presence of the wind turbines and is referred to as “base flow”. See subsection 2.2 for two examples of base flows. Wake effects are modeled analytically using the Jensen or Gaussian wake models and are superimposed on the base flow.

The streamline model calculates streamlines based on the flow field from WAsP CFD. To reduce the amount of data input, the flow field from WAsP CFD should be provided only for an iso-surface at wind turbine hub height from the terrain surface. Velocity components perpendicular (or normal), and parallel to the iso-surface are derived from the WAsP flow field and are used to calculate the streamlines. Since a normal velocity component exists, the deviation of the streamlines above or below the iso-surface is taken into account, see Figure 1. Figure 1 shows a line from the iso-surface (solid line) and the new streamline (dashed line) after the normal velocities (arrows) are applied where a) and b) are with and without the terrain map, respectively. Figure 1 is from example case 1 described in subsection 2.2 with a wind direction of 270°. In separated flow regions, streamlines roll-up and terminate. For the example cases in
this work, wind turbines have logically been placed on flatter regions at elevated heights away from areas susceptible to separated flows, e.g., pits, valleys, and steep hills.

![Image](image.png)

Figure 1: Iso-surface (solid line) and new streamline (dashed line) after the normal velocities (arrows) are applied for example case 1 and a wind direction of 270° where (a) and (b) are with and without the terrain map, respectively. Replicated from [8].

2.2. Example cases

Example case 1 is a real wind farm with twenty-five wind turbines located on a complex terrain site. Figure 2(a) depicts the domain, terrain elevation and wind turbine setup for example case 1. Figure 1(a) also shows the terrain topography for example case 1. The domain is 6 km (longitudinal) by 4 km (latitudinal) with an elevation that varies between 1.37 km and 1.72 km. The difference in elevation between the highest and lowest points in the domain is 350 m. Most of the domain is relatively flat and the twenty-five wind turbines have been placed on the flat regions with some wind turbines near the cliff edges. The wind turbine hub height for all wind turbines is 67 m and therefore the flow field from WAsP CFD is used for an iso-surface at 67 m height from the terrain surface. The reference roughness used in WAsP CFD is 0.03 m. Additional details regarding the wind turbines, site location, terrain topography, etc., are available in reference [17].

In this example, the Gaussian wake model is used with and without the streamline capability to estimate the power production of all wind turbines in the wind farm. The Gaussian wake model without streamlines will have straight wakes. With streamlines, the wakes will follow the flow field. Computations with the Jensen straight-wake model are also performed. SCADA and CFD simulations are included in the comparisons. The CFD simulations were performed using Reynolds-Averaged Navier Stokes (RANS) using EllipSys3D [14, 15, 16] together with the actuator disc (AD) approach as described in [18]. The SCADA values and AD-RANS simulation results are retrieved from reference [17]. Figure 3(a) depicts the base flow from WAsP CFD including streamline computations shown on top of the terrain topography and wind turbine locations for a wind direction of 330° in example case 1.
Example case 2 is a fictitious wind farm with eight wind turbines based on a complex terrain site in Southern Europe. Exact site details cannot be revealed. Figure 2(b) depicts the domain, terrain elevation and wind turbine setup for example case 2. The domain is 1.95 km (longitudinal) by 1.98 km (latitudinal) with an elevation that varies between 0.2 km and 0.6 km. The difference in elevation between the highest and lowest points in the domain is 396 m. In this example, the Gaussian wake model is used with and without the streamline capability to estimate the Annual Energy Production (AEP) of the wind farm. Computations with the Jensen wake model with streamline- and straight-wake path are also performed. SCADA and CFD simulations are not included in the comparisons. Figure 3(b) depicts the base flow from WAsP CFD including streamline computations shown on top of the terrain topography and wind turbine locations for a wind direction of 330° in example case 2.

Figure 2: The domain, terrain elevation and wind turbine setup for (a) example case 1 and (b) example case 2.

Figure 3: Base flow from WAsP CFD including streamline computations shown on top of the terrain topography and wind turbine locations for a wind direction of 330° in (a) example case 1 and (b) example case 2.
3. Results
The results section is divided into two subsections: 3.1 Example case 1 and 3.2 Example case 2, which are based on the descriptions provided in subsection 2.2. Example case 1 compares Streamline with measurements and CFD. Example case 2 compares Streamline with the different wake models only.

3.1. Example case 1
Figures 4 and 5 depict the power predictions from all twenty-five wind turbines (WTs) using the different wake models and are compared against SCADA measurements and AD-RANS. There are a total of nine flow cases (FC) numbered from FC1.1 to FC1.9. Recall that the SCADA measurements and AD-RANS results are from [17] and are labelled as SCADA and AD, respectively, in Figures 4 and 5. The SCADA measurements represent averaged values in ±5° bins. The standard error (SE) in the legend label SE SCADA is equal to SCADA ±5° but includes the error bars. The AD-RANS results labelled as “AD wd ±5°” represent the average results from three simulations at +5°, 0° and −5° of the main wind direction (wd) and should more closely represent the SCADA results. Independent AD simulations at the main wind directions are labelled as “AD wd” in Figures 4 and 5. Stream represents the streamline model with Gaussian wake, BGau is the Gaussian straight-wake model, and NOJ is the Jensen straight-wake model.

Percent differences in power relative to SCADA for Stream varied between 0.25% (FC 1.6, WT7) and 76.5% (FC 1.7, WT7). For BGau, 0.28% (FC 1.8, WT23) and 76.5% (FC 1.7, WT7) and for NOJ, 0.28% (FC 1.8, WT23) and 76.5% (FC 1.7, WT7). For Stream, the mean percent difference for power from all twenty-five wind turbines varied between 12.28% (FC 1.8) and 35.75% (FC 1.1). For BGau, 11.4% (FC 1.8) and 36.52% (FC 1.1) and for NOJ, 11.03% (FC 1.8) and 36.70% (FC 1.1). In summary, FC1.8 had the smallest differences while FC1.1 had the largest differences for all wake models.

Percent differences in power for AD±5° varied between 0.1% (FC 1.3, WT3) and 73.4% (FC 1.1, WT16). The minimum and maximum values for AD# are 0.1% (FC 1.7, WT12) and 78.4% (FC 1.1, WT16), respectively. The mean percent difference in power from all twenty-five wind turbines varied between 9.6% (FC 1.8) and 42.1% (FC 1.1) for AD±5°, and 10.1% (FC 1.8) and 40.9% (FC 1.1) for AD#. Therefore, averaging RANS simulations in the 5 degree range may reduce extreme percent differences slightly, e.g., 78.4% down to 73.4% for FC 1.1, WT16, but does not necessarily reduce the mean percent difference.

The mean percent difference in power from all flow cases is 20.5%, 20.0%, 19.1%, 19.8% and 19.4% for AD±5°, AD#, streamline Gaussian, straight Gaussian, and Jensen, respectively. All simulation approaches have the largest differences in FC1.1 for all wind turbines. As explained in [17], a possible explanation is that for the south wind, i.e., 180°, at a small wind speed of 4 m/s, the wind distribution over the terrain may be non-uniform. Large variations in wind speed is captured in the SCADA but not in the simulations. The percent difference for the wake models are lower than the RANS for FC1.1, but this is biased because all WTs have a slightly higher power output and is closer to the higher power output seen in the SCADA. This also affects the mean percent difference in power from all flow cases.

Results in Figures 4 and 5 show that all the wake models produce similar results to the AD-RANS simulations. The percent difference relative to AD# for all wake models is 10-11%. The closer similarity between the wake model results and AD-RANS in comparison to SCADA is likely because both use similar methodologies. For example, both approaches use EllipSys3D RANS for the flow field computations. One of the differences between the wake-model approaches and the AD-RANS is how the wind turbine power is calculated. The former reads the value from a wind speed-power relation, while the AD calculates the torque and power from blade geometry and airfoil lift and drag data. The reference wind speed and wind direction used in
the simulation approaches may also not be exactly the same. These differences might explain the higher power output for all wind turbines in FC1.1 from the wake-model approaches.

![Graphs showing power predictions for various wind speeds and wake models](image)

Figure 4: Power predictions for 4 m/s and 7 m/s wind speeds using the streamline Gaussian (Stream), straight Gaussian (BGau), and straight Jensen (NOJ) wake models compared with SCADA measurements and AD-RANS (AD) simulations.
Figure 5: Power predictions for 10 m/s wind speeds using the streamline Gaussian (Stream), straight Gaussian (BGau), and straight Jensen (NOJ) wake models compared with SCADA measurements and AD-RANS (AD) simulations.

The SCADA represents averaged values over an extended measurement period. During the measurement period, the wind directions and wind speeds are always changing in the wind farm, and this cannot be measured precisely into a single reference wind speed and direction for input to simulations. The AD-RANS or simple wake-model results do not contain such dynamic behaviour. Comparison of the wake-model approaches and RANS simulations with the measurements is not straight forward. Nevertheless, the margins of differences between the different wake-model results and the SCADA measurements are not that significant.

Figure 6 depicts the top view of (a) the computed streamlines and (b) the wind velocity and wind turbine wake map with the streamline Gaussian wake model for example case 1. Most of the streamlines shown in Figure 6(a) are straight and observing that the curved streamlines only influence one or two turbines might explain why the streamline wake-model results do not differ significantly from the straight-wake in Figures 4 and 5.
3.2. Example case 2

Calculations are performed using flow fields at 8 m/s wind speed for 12 sectors, i.e., wind directions: 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, and 330°. The wind farm site considered is called Parque Ficticio. In this example, eight 2 MW wind turbines with a rated wind speed of 12 m/s are used. Figure 7 depicts the wind velocity and wind turbine wake maps with (a) streamline Gaussian, (b) streamline Jensen, (c) straight Gaussian and (d) straight Jensen wake models for a wind direction of 270°. Streamline calculations show flow separation towards the east in Figure 7(e).

Table 1 shows a comparison of the annual energy production (AEP) between the different wake models and the relative difference (Rel. Diff) in percent with the straight Gaussian model. From the table, it is shown that the streamline topology of the wind turbine wake flow as well as the wake models have an effect on the performance prediction of wind farms. For this simple wind farm case, approximately ±1% difference exists between the different wake models. More differences are expected for complex wind farms.

Table 1: Comparison of the annual energy production (AEP) between the different wake models and the relative difference (Rel. Diff) in percent with the straight Gaussian model.

| Wake Model            | Rel. Diff (%) | AEP (MWh) |
|-----------------------|---------------|-----------|
| Streamline Gaussian   | 0.20          | 5871.6    |
| Streamline Jensen     | -0.17         | 5849.9    |
| Straight Gaussian     | 0.00          | 5859.7    |
| Straight Jensen       | -0.84         | 5810.5    |
4. Conclusions

In the present paper, a new streamline model for wake development based on a streamline topology is applied and compared with different approaches for modeling the wind turbine wakes. The contribution of the present work is the comparison of the streamline- and straight-wake
models as well as the different wake models, e.g., Jensen and Gaussian. The models have been applied to two wind farm cases. The results from the first case was compared against SCADA measurements and computational fluid dynamics simulations. Relative to the measurements, the mean percent difference in power using the different wake models ranged between 19-20%. Mean percent difference in power for the AD-RANS was approximately 20%. For the second wind farm case considered, approximately ±1% difference exists between the different wake models. The present work shows that the streamline topology of the wind turbine wake flow as well as the wake models have an effect on the performance prediction of wind farms. The analysis shows that the streamline model can predict the wake flow of wind farms in complex terrain with decent accuracy in a short time, thus making it suitable for applications in layout optimization.

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