New Developments in Large Wind Farm Modelling

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Abstract

Standard wake models based on the numerical solution of the RANS thin shear layer equations have been in use since the late 80's as successors to faster but simpler empirical models. These models describe the wake as the effect of individual turbines each operating in the wind flow field, independent from other turbines and without affecting the flow itself.

The work presented here details an extension to standard wake and wind flow models. Using a standard modelling approach as basis, an additional empirical correction describes the disturbance of the atmospheric flow caused by the presence of a wind farm. This breaks with the assumption that the wind flow can be treated as independent from the wind farm.

The focus of this work is to deliver an accurate, scalable and transferable model which can describe the available observed data sets and which is sufficiently fast to be used for commercial wind farm design and analysis. Validation of the new model against experimental data from two large wind farms shows that it accurately represents the losses in those wind farms with little computational cost added.

Introduction

Early wake modelling in the 1970’s concentrated on modelling the momentum deficit caused by infinite arrays of turbines, but was not able to resolve the wake flow in detail [1-4]. This changed with the advent of empirical model descriptions with the ground breaking work of Lissaman who introduced a detailed description of wind turbine wakes and introduced concepts developed for plumes and jets to the wind energy industry [5].

The next quantum leap came in 1985 to 1989 when Ainslie published a sequence of papers describing a numerical CFD solution for the wake development [6]. The model solves the RANS equations in their thin shear layer, axis-symmetric form using an eddy viscosity turbulence closure and representing the turbine by empirical boundary conditions at 2D behind a turbine.

More than 20 years have passed since Ainslie first employed standard CFD methods to describe individual wakes. The model has become the standard in wind farm design and it predicts the wake losses of most wind farms in the world with unsurpassed accuracy. However wind farms have evolved since and new challenges have arisen. In particular, the wind farm size has increased and today wind farms with hundreds up to several thousands turbines stretching over long distances are under development, onshore and offshore.

It has been shown for wind turbines more than 5 rows inside a large offshore wind farm that wake losses can be higher than predicted by standard models [7]. While the effect on the overall performance of current wind farms is small, the experimental data points to a fundamental weakness in the standard models.

With increased wind farm size the early wake work obtains new relevance. The wind farm size increased to a degree that the wind farm now affects the wind flow. We assume in this work that wind farms do not usually reach a scale where they influence the underlying processes significantly, but can be treated as independent perturbations of the wind flow.

Large wind farm model description

The modelling of wind farms is traditionally a two step process. In the first step the ambient wind flow without the presence of a wind farm is established. In a second step wind turbines are placed within this wind flow. The ambient wind flow is assumed to be independent from the wakes generated by the wind turbines. Some very simple models that are not discussed here also assume the wakes to be independent from the wind flow variation over a site.

The new large wind farm model process can be described in three steps:

- Use the wind flow model and data of choice that best describe the ambient wind flow over the potential wind farm site.
- Place the turbines in the wind flow and calculate the large wind farm correction to the ambient flow due to the presence of the turbines.
- Use a standard wake model with the corrected ambient wind speeds as boundary conditions to describe the inter-turbine wake deficits.

The model presented here is a refined version of [8], which has been available to users of the GH WindFarmer software since 2006. With an empirical correction we describe the disturbance of the atmospheric flow caused by the wind farm. This breaks with the traditional assumption that the wind flow can be treated as independent from the wind farm.

The large wind farm correction (second step above) is described by:

- Boundary layer modification – Establishes the magnitude of correction to the ambient the wind profile behind each individual turbine
- Wind turbine density – Considers relative turbine positions and decides if a correction should be applied in a particular direction sector.
- Row to row distance – The correction is applied only if the adjacent lines of turbines are closer than a threshold
- Downstream recovery – From a certain distance the wind speed recovers to ambient levels and no correction is applied.

The component models are presented in this paper in detail followed by a brief validation of the model. More details on the validation can be found in [9].

Boundary layer modification

Momentum is continuously generated on top of the boundary layer and transferred downward to the ground surface in a dynamic equilibrium. Wind turbines that take out some of this momentum are part of the dynamic equilibrium similar to trees or other roughness elements. However as the impact of the wind turbines on the boundary layer profile is not as well researched we take some guidance from forest canopy and roughness change models.

An IBL develops from each turbine location, and is displayed in Figure 1 for the first turbine.

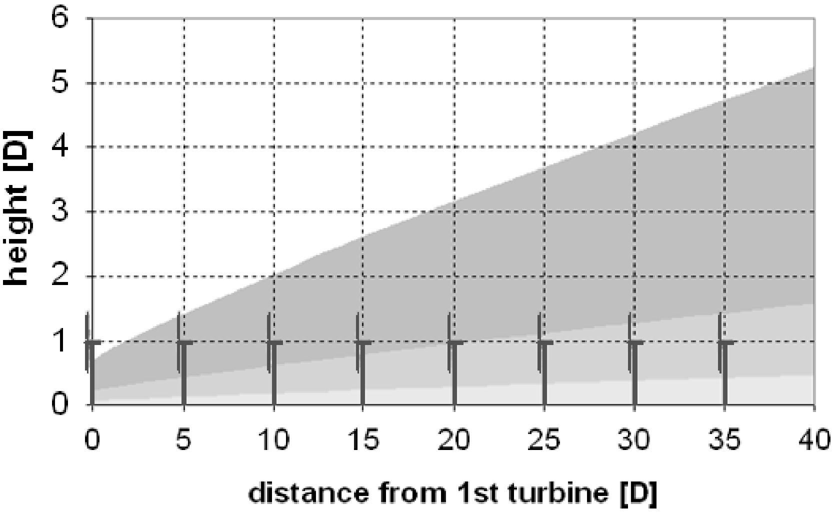

Figure 1: Internal boundary layer development after disturbance caused by first turbine. The ambient wind speed for downstream turbines is reduced.

The height h of the internal boundary layer (IBL) for a roughness change as function of the fetch (x) and (z'_0) the larger of the two roughness values (z_{01}) and (z_{02}) can be determined from [10].

$$\frac{h}{z_0^{'}}\left(\ln\frac{h}{z_0^{'}}-1\right)=0.9\frac{x}{z_0^{'}}$$

To take into account that the momentum is not extracted at ground level an offset of 2/3 hub height (z) is used leading to a new height (h'). It is further assumed that the disturbance to the ambient wind speed (u_1) felt at the lower edge of the rotor (z') is decisive for the turbine performance. The wind speed (u) is then expressed as:

$$u(z)=\begin{cases} u_1(z) \quad for\; z'\geq 0.3h' \\ \dfrac{u_1(z)}{ln\left(\dfrac{z'}{z_{01}}\right)}\left[\dfrac{ln\left(\dfrac{h'}{z_{01}}\right)}{ln\left(\dfrac{h'}{z_{02}}\right)}\cdot ln\left(\dfrac{0.09h'}{z_{02}}\right)\left\{1-\dfrac{ln\left(\dfrac{z'}{0.09h'}\right)}{ln\left(\dfrac{0.3}{0.09}\right)}\right\}+ln\left(\dfrac{0.3h'}{z_{01}}\right)\cdot\dfrac{ln\left(\dfrac{z'}{0.09h'}\right)}{ln\left(\dfrac{0.3}{0.09}\right)}\right] \quad for\; 0.09h'<z'<0.3h' \\ u_1(z)\left[ln\left(\dfrac{h'}{z_{01}}\right)\cdot ln\left(\dfrac{z'}{z_{02}}\right)\right]\Big/\left[ln\left(\dfrac{h'}{z_{02}}\right)\cdot ln\left(\dfrac{z'}{z_{01}}\right)\right] \quad for\; z'\leq 0.09h' \end{cases}$$

Wind Turbine Density

The momentum extracted per given area is increasing with the number of wind turbines in that area. Changing the area roughness to achieve this is an option, but it is impractical for wind farm design purposes as the distribution of wind turbines may be irregular and is subject to iterative change and no fixed relationship with roughness can be established. Instead a geometric measure of turbine density is used.

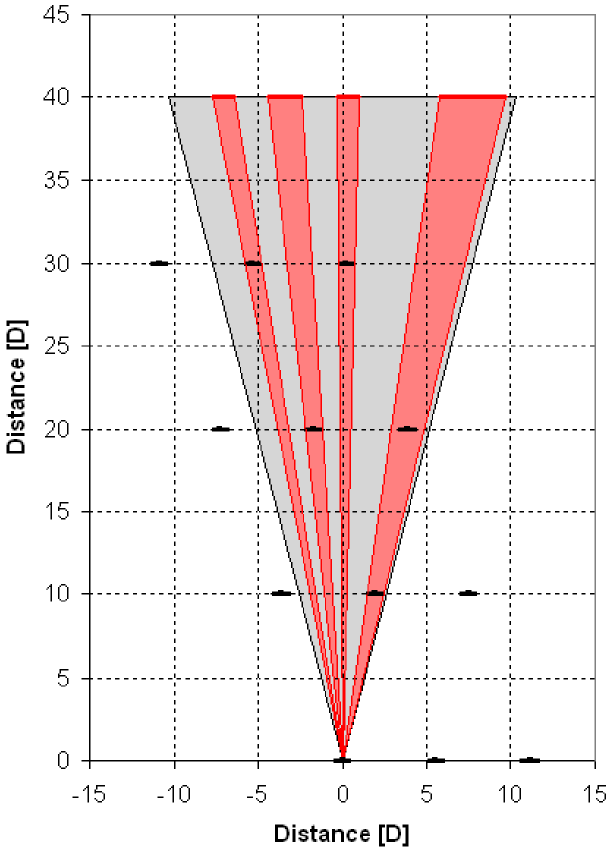

Figure 2: Geometric model to consider the turbine density for a 30 degree sector. The large wind farm correction to ambient wind speed is applied for wind arriving from the red sectors.

For each small direction sector the horizon is scanned and the presence of upstream turbines detected. The ambient wind speed correction is applied if and only if such a turbine is present (Figure 2) in the sector.

The consequences of the geometric model is that the overall impact of the correction is reduced with distance to turbines due to a smaller aspect ratio and increased for a fixed distance with increased turbine density due to more turbines contributing.

The geometric model is considering how much of the horizon is filled with turbines. No wake expansion is considered in this step. This is not needed because this model is to be used in conjunction with standard wake models that already consider the effect of wake expansion and consequential wake recovery.

Wind blows along wind farm geometry axis

When for any wind direction the cross wind spacing between two rows of wind turbines is more than a fixed number of turbine diameters, then the wind turbine wakes in each row are considered to develop independent from other rows (Figure 3). Experimental evidence suggests that no large wind farm correction should be applied for this narrow wind direction sector.

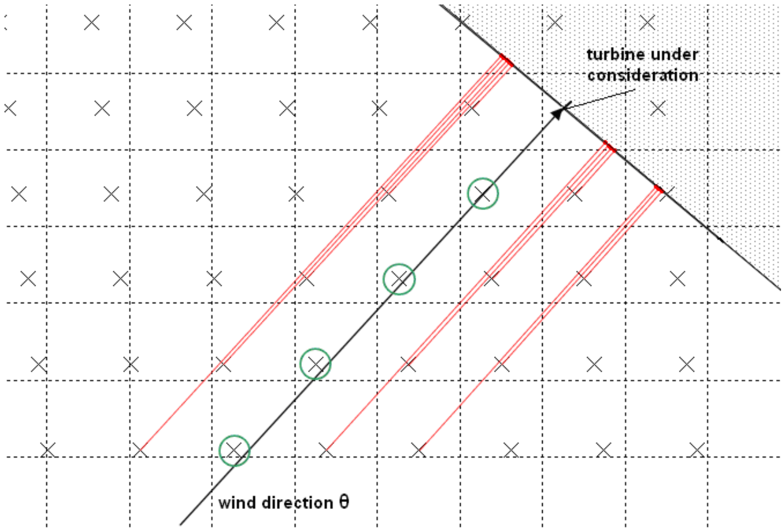

Figure 3: The crosswind distance is determined by projection of upstream turbines onto a plane perpendicular to the flow direction.

Downstream recovery

The disturbance of the wind profile caused by a wind turbine is expected to subside after a certain distance. Investigation is ongoing to establish details of the processes and relevant scales. However as a first approximation, this recovery can be modelled as linear (Figure 4).

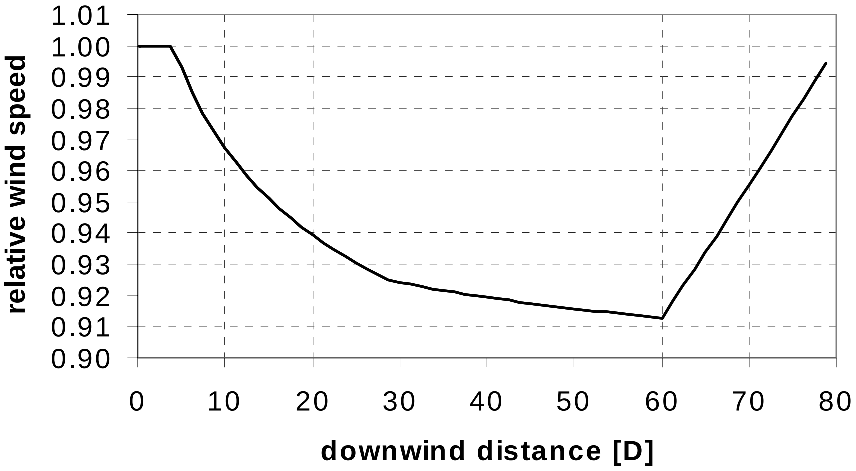

Figure 4: Corrected ambient wind speed (u) and linear recovery to ambient level.

Validation Cases

Two wind farms have been identified that show deviations from standard models that are, for selected flow cases, significant enough to support model development and validation. The model presented in this paper has been designed and calibrated with data from Horns Rev. Without major changes it was then compared to more detailed data from both Horns Rev and Nysted wind farms. Wind farm configuration and further cases are presented in [9].

The comparison with Horns Rev data averaged over a 30 degree sector shows the performance of the standard wake model is greatly improved by the correction and then also models feature details (Figure 4).

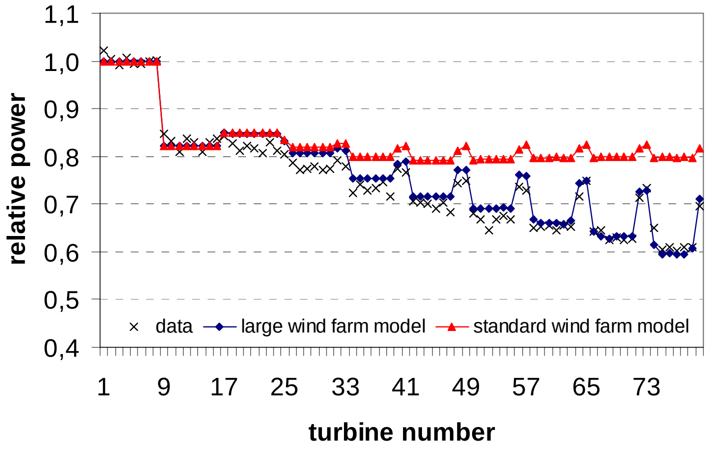

Figure 4: Normalised power for Horns Rev (7 D spacing, 255-285 deg, 8 m/s) compared with standard model (red) and same model including large wind farm correction (blue).

The comparison with Nysted data, also averaged over a 30 degree sector shows a similar improvement of the model as in Horns Rev (Figure 5).

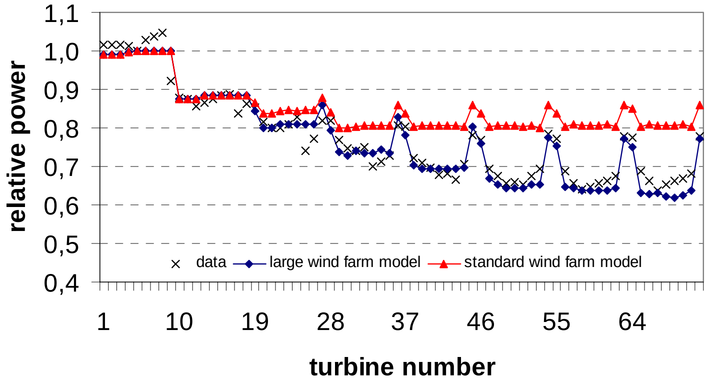

Figure 5: Normalised power for Nysted (12 D spacing, 255-285 deg, 8 m/s) compared with standard model (red) and same model including large wind farm correction (blue).

Conclusions

A simple correction to the classic wind farm wake model is presented that allows the disturbance of the ambient flow field caused by large wind farms to be modelled. The model update is made available to the industry within the GH WindFarmer wind farm design software (v4.0). The correction has been validated with success for two offshore wind farms [9] and solves a complex flow problem with little computational cost.

The model is based on fundamental physics of the boundary layer and designed to scale to wind farm layouts both onshore and offshore. However given the limited set of validation cases there is still a considerable uncertainty in such extrapolation and should therefore be undertaken with extreme caution.

Further validation cases are needed and users should be aware that the model will be adjusted when these become available.

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