

Modelling and measurements of wakes in large wind farms

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Abstract. The paper presents research conducted in the Flow workpackage of the EU funded UPWIND project which focuses on improving models of flow within and downwind of large wind farms in complex terrain and offshore. The main activity is modelling the behaviour of wind turbine wakes in order to improve power output predictions.

1. Introduction

The central core of most wind farm models was developed in the 1980's for small wind farms in simple or moderately complex terrain. Wind farms being developed today are larger and often in complex terrain, close to forests or offshore. Thus there is a need for further research, to examine the performance of wind farm and wake models in these more difficult environments. In ideal circumstances, wind and turbulence would be predicted on a fine mesh (horizontal and vertical) for the whole wind farm over a range of wind speeds and directions. There is a gap between engineering solutions and computational fluid dynamics (CFD) models and a bridge is needed between these in order to provide more detailed information for modelling power losses, for better wind farm and turbine design and for more sophisticated control strategies and load calculations. This is the focus of our work within the UPWIND projects that aims to develop the next generation of large wind turbines.

2. Measurements

2.1. Types of measurements

For evaluating wakes there are essentially two types of measurements; meteorological and wind farm data. Meteorological data can be divided into two types – mast and sodar/lidar data. The advantage of meteorological mast data is; it is available for a long period, it is accurate (although this can depend on the mast structure/instrumentation) and wind speed, direction and turbulence profiles to hub-height are available at a good time resolution and with high data capture. The most obvious disadvantage is that the location of the measurements is fixed so from a wake perspective the wake distance is fixed. Measurements are rarely made above hub-height. Both sodar and doppler lidar are able to measure wind speed profiles both beyond and above hub-height and may be particularly useful offshore due to the expense of erecting tall meteorological masts in this environment e.g. [1].

Obviously for wake studies in large wind farms, wind farm data are needed. Parameters include power output, nacelle direction and yaw misalignment and a status signal. These data are routinely collected using Supervisory Control And Data Acquisition (SCADA) systems although storage and retrieval of these data for research purposes may be a time consuming process. A more significant issue is that all wind farm data are typically confidential and developers are reticent to share raw data. This is a big issue in model evaluation exercises where data are necessary and also by the nature of the exercise many different groups are involved. Nevertheless it is clear that access to data is critical at this point while the wind farm model evaluation for more challenging environments is conducted.

2.2. Issues comparing models and measurements

Power loss modelling should encompass the whole range of wind speeds and directions. In general, computing requirements for CFD models means we are restricted to examining a number of specific wind speed and direction cases and only a moderate number of turbines rather than wind farms with ~100 turbines which can easily be done by wind farm models. On the other hand it can be difficult to extract reasonable simulations from some of the wind farm models for very specific cases when models are being used beyond their operational windows. In addition to this there are a number of specific issues relating to wake measurements:

- Establishing the freestream flow
- Wind direction, nacelle direction and yaw misalignment
- Wind speed gradients across the wind farm
- Accuracy of the site specific power curve and thrust
- Time averaging between models and measurements
- Natural fluctuations in the wind speed and direction in any period
- Wake transport time through the wind farm
- Turbulence intensity and atmospheric stability

3. Models

The comparison uses the full spectrum of models from whole wind farm codes which use moderately simple wake models to full CFD models. Models are listed below in approximate order of complexity from the simplest (in terms of wake modelling) to the most complex.

3.1. WAsP

The Wind Atlas Analysis and Application Program (WAsP) is based on a linearised model used in the European Wind Atlas. The WAsP program [2] uses meteorological data from a measurement station to generate a local wind climate from which the effects of obstacles, roughness and complex terrain have been removed. To produce a wind climate for a nearby wind farm or wind turbine site these local effects are reintroduced. In terms of wind farm modelling the wake model in the commercial version is based on [3]. A new wake model ('Mosaic tile') is being developed for use within WAsP which is described in [4]. The main advantage of the program is that it is fast and robust. It does not model flow in complex terrain if flow separation occurs although there are methods for improving its predictions in complex terrain [5]. Also it is not intended for single simulations. The program utilises the station data by fitting it to a two parameter Weibull distribution. For the complex terrain simulations discussed below it is important to note that the program is being used in a way which is not recommended.

3.2. GH

The ambient wind speed distribution and boundary layer profile is calculated by an external wind flow model, WAsP is used in this project. The wind turbine wake model then makes use of this data superimposing the effect of the offshore wind farm. We use an empirical representation of the wind turbine as suggested by Ainslie [6]. The initial wake is in this model a function of the wind turbine

dimensions, thrust coefficient and local ambient wind speed and turbulence. The eddy viscosity wake model in GH WindFarmer is a CFD calculation representing the development of the velocity deficit using a finite-difference solution of the Navier-Stokes equations in axis-symmetric co-ordinates. The eddy viscosity model thus automatically observes the conservation of mass and momentum in the wake. An eddy viscosity turbulence closure scheme is used to relate the shear stress to gradients of velocity deficit. Empirical expressions are used to model the wake turbulence [7] and the superposition of several wakes that are impacting on one single location. Multiple wakes are calculated by consecutive downstream modelling of individual wakes. Due to the empirical components in GH WindFarmer it is possible to model typically 7200 wind speed and directional scenarios needed for a complete energy assessment of a wind farm in reasonable time. The model has performed well in all environments, including small offshore wind farms [8]. For very large wind farms, the boundary layer profile is modified by the presence of wind turbines. One approach to account for this is to represent the wind farm area by area of higher roughness [9].

3.3. ECN

ECN's WAKEFARM model is based on the UPMWAKE code which originally was developed by the Universidad Polytechnica de Madrid. It is based on parabolized Navier-Stokes equations. Turbulence is modelled by means of the k-epsilon turbulence model. Through the parabolization of the governing equations it is assumed that there exists a predominant direction of flow and that (among others) the downstream pressure field has little influence on the upstream flow conditions. In other words, the axial pressure gradients are neglected. These assumptions no longer hold in the near wake where additional modelling is necessary. In the ENDOW project [10] this was accomplished by excluding the near wake and the solution procedure started at a fixed distance behind the rotor. A Gaussian velocity-deficit profile was prescribed that acts as a boundary condition for the far wake. This initial profile is based on experiments. Hence the near-wake physics are not accounted for explicitly and rely on tuning with experimental data. In the present project a hybrid method is used which is still based on the WAKEFARM model but the near wake expansion and flow-deceleration is accounted for directly. This is achieved by an analogy with the boundary-layer equations. The (axial) pressure gradients are prescribed as external forces and enforce the flow to decelerate and the wake to expand in the near wake. A free vortex wake method is used to compute these pressure gradient terms a priori.

3.4. CENER

The model, based on the commercial CFD code Fluent, allows simulating the rotor effect over the flow as axial momentum sources assigned to the cells corresponding to the rotor volume. The forces are calculated as a function of the thrust coefficient, the incident wind speed and the rotor area. As input, the model needs basic wind farm data including, among others, the thrust coefficients of the wind turbines as well as the surrounding topography. For a certain wind direction, the description of the wake is obtained through the calculation over the whole domain of the general fluid equations in its RANS form with a k- ϵ turbulence closure scheme.

3.5. CRES

The governing equations are numerically integrated by means of an implicit pressure correction scheme, where wind turbines are modelled as momentum absorbers by means of their thrust coefficient. A matrix-free algorithm for pressure updating is introduced, which maintains the compatibility of the velocity and pressure field corrections, allowing for practical unlimited large time steps within the time integration process. Spatial discretization is performed on a computational domain, resulting from a body-fitted coordinate transformation, using finite difference/finite volume techniques. The convection terms in the momentum equations are handled by a second order upwind scheme bounded through a limiter. Centred second order schemes are employed for the discretization of the diffusion terms. The Cartesian velocity components are stored at grid-nodes while pressure is

computed at mid-cells. This staggering technique allows for pressure field computation without any explicit need of pressure boundary conditions. A linear fourth order dissipation term is added into the continuity equation to prevent the velocity-pressure decoupling. To accommodate the large computational grids needed in most applications for a fair discretization of the topography at hand, a multi-block version of the implicit solver has been developed. Turbulence closure is achieved using the standard $k-\omega$ model [11], suitably modified for atmospheric flows.

3.6. NTUA

NTUA CFD model solves the 3D Reynolds averaged incompressible Navier-Stokes equations with second order spatial accuracy. The model [12] (see also [13]) assumes Cartesian grids, uses the $k-\varepsilon$ turbulence closure model and accommodates wind turbines embedded in its grid as momentum sinks representing the force applied on the rotor disk that is in turn evaluated from the local C_t thrust coefficient. NTUA has performed preliminary offshore wake calculations for the Horns Rev Wind Farm. Due to the extensive cpu effort and memory requirements, only Case 1.8.2 (see below) was initially simulated and model results were compared with observations.

4. Model comparison

4.1. Complex terrain cases

Three model simulation types are planned to compare the performance of the CFD models with wind farm models where appropriate:

- Simple terrain (Gaussian Hill). Simulations shown below.
- Five turbines in flat terrain. In flat terrain wind parks, wind turbines are often aligned in parallel rows, which means that one machine can be partially or completely situated in the wake of a neighbouring wind turbine. In order to estimate the effect of a neighbouring wake on the wind turbine efficiency, multi-wake simulations for the worst (in terms of efficiency) case will be examined.
- The complex terrain wind farm. A real wind farm located in a moderately complex terrain is proposed for the comparison and validation of wake models. The wind farm is constituted by 43 wind turbines separated 1.5 diameters in the adjacent direction and approximately 11 diameters between rows. The layout is formed by 5 alignments oriented towards the prevailing wind directions (NW-SE). The study represents a first attempt of comparing and validating the existing wake models on a real moderately complex site and with wind farm measurements.

The idealized simulation of a single wake in the case of a Gaussian hill will constitute the basis for the comparison of the wake characteristics between flat and complex terrain. The conclusions deduced from the analysis of the 3D and 2D Gaussian hill can be extended to more complex terrain where the irregularities of the topography are seen as separate hills.

The Gaussian 2D hill geometry is defined by the relationship

$$z = h e^{\left[-0.5\left(\frac{x}{\sigma}\right)^2\right]}, \quad \sigma = L/1.1774, \quad (1)$$

here x , z are the horizontal and vertical coordinates, h is the height of the hill and L is defined as $x(z=h/2)$. In the 3D hill, $\sqrt{x^2+y^2}$ replaces x in Eq.(1). The 3D and 2D hill terrain derived from Eq.(1) for $L=1750$ are shown in Fig.1. Two configurations corresponding to different hill slopes will be examined: $h=700m$, $L=1750m$ (steep slope) and $h=700m$, $L=3000m$ (gentle slope).

The different configurations will be simulated with one wind turbine at hilltop and without the wind turbine (to provide the value of wind speed at the wind turbine position for the calculation of the actuator disk force as well as the reference velocity field for the evaluation of the wind speed deficit). The turbine is the 5 MW reference turbine used in Upwind WP2 with 126 m diameter ($D=126$ m) and 90 m hub height. Note, that the lengths in Figure 1 have been dimensionalized with the wind turbine

diameter. The input wind velocity profile is assumed logarithmic with 500 m boundary layer height and 10m/s velocity at hub height. Three different levels of turbulence intensity (5%, 13% and 15%) and six different wind directions ($0, \pm 15^\circ, \pm 30^\circ$) will be examined.

The variations of wind speed deficit and turbulence intensity at hub height above ground level and the vertical profiles behind the wind turbine must be estimated and compared to the respective ones in flat terrain, so that basic guidelines are derived for the effect of the hill on the wake characteristics.

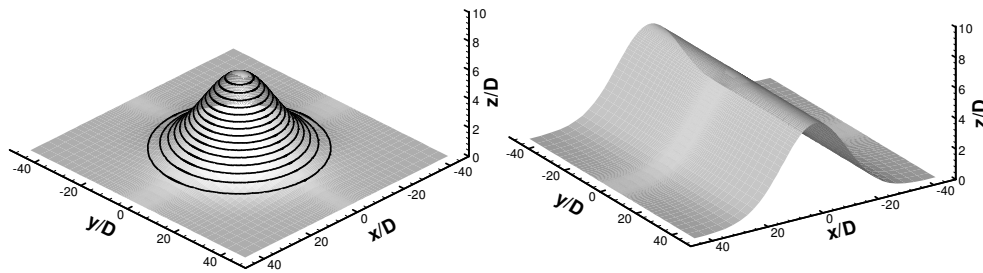


Figure 1: Terrain of the 3D and 2D Gaussian hill ($L = 1750$).

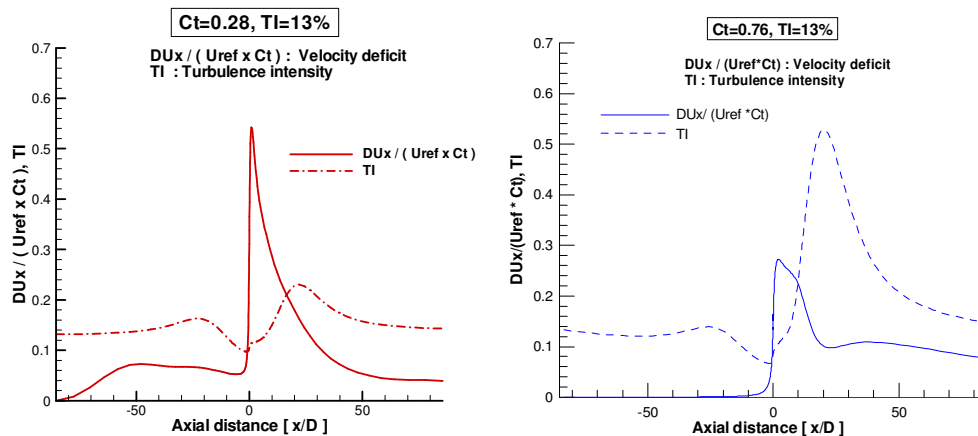


Figure 2: Preliminary results for the velocity deficit and turbulence intensity at turbine hub-height over the 2D Gaussian hill (two different CFD models).

4.2. Wake modelling offshore

A comparison of the main wake/wind farm models was undertaken as part of the ENDOW project (e.g. [14], [13]) for small offshore wind farms. From this and a further experiment at Vindeby [15, 16] it was not possible to distinguish any particular model or group of models as outperforming the others in terms of the accuracy of prediction of single wakes. The main issue for the current project is that there appears to be a fundamental difference between the behaviour of wakes in small wind farms where standard models perform adequately [17] and those in large multi-row wind farms where current wind farm models appear to under-predict wake losses [18]. It can be postulated that this is due to the interaction of turbulence generated by wind turbines wakes with the overlying atmosphere [19] and that a new generation of models is required to deal with this complex interaction of wakes with each other and the boundary-layer [20]. The main objective of our research in this regard is to evaluate and improve wake/wind farm models in comparison with data from large (multi-row) offshore wind farms. A number of flow cases have been defined for the Danish offshore wind farm Horns Rev that is owned by DONG Energy A/S and Vattenfall AB, consisting of 80 Vestas V80 wind turbines located in a 8 by 10 grid, with a basic spacing of $7D$ as shown in Figure 3 [21].

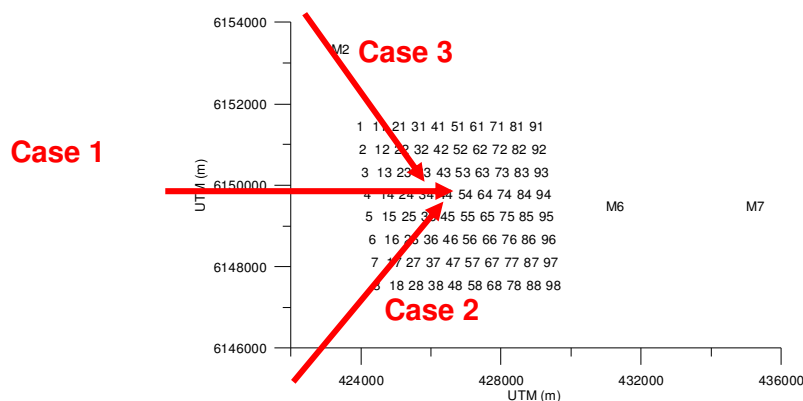


Figure 3: Horns Rev layout including definition of 7D, 9.4D and 10.5D flow directions.

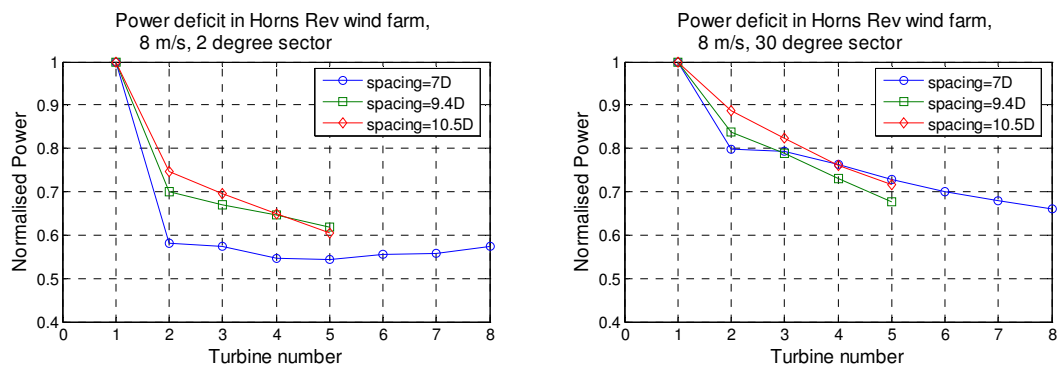


Figure 4: Power deficit inside Horns Rev wind farm for $V=8\pm 0.5$ m/s inflow for different spacing.

Electrical power, nacelle position and wind turbine status signals have been extracted from the SCADA system with a reference period of 10-minutes and merged with meteorological measurements from three masts (M2, M6 and M7). The undisturbed power values are used to define 3x3 flow cases, corresponding to wind speeds levels of 6 ± 0.5 , 8 ± 0.5 and 10 ± 0.5 m/s, which are combined with three different spacings 7 D, 9.4 D and 10.5 D. The mean deficit along a row of turbines has been calculated and presented on Figure 4 for 3 different spacings. The offshore wind farm at Horns Rev is characterized with low turbulence (<8%) and many operational hours in near neutral stability. The major findings are an almost constant deficit of 55-60% which is identified during pure wake situation for a very small sector of 2 degrees, furthermore the deficit decreases down wind with an increasing sector size. The preliminary evaluation shown in Figure 5 is for a westerly wind direction with flow exactly along the rows as shown in Figure 4. The wind speed bins shown are for 6, 8 and 10 m/s. At these low to moderate wind speeds, the thrust coefficient is relatively high. Thus the wake losses shown are likely to be the most severe but wind directions in the relatively narrow wind direction bins will also occur relatively seldom.

It has become apparent that standard wind farm models are lacking one or more components which account for the modification of the overlying boundary-layer by the reduced wind speed, high turbulence atmosphere generated by large wind farms. This effect is likely to be particularly important offshore due to the low ambient turbulence. This will be the subject of future work.

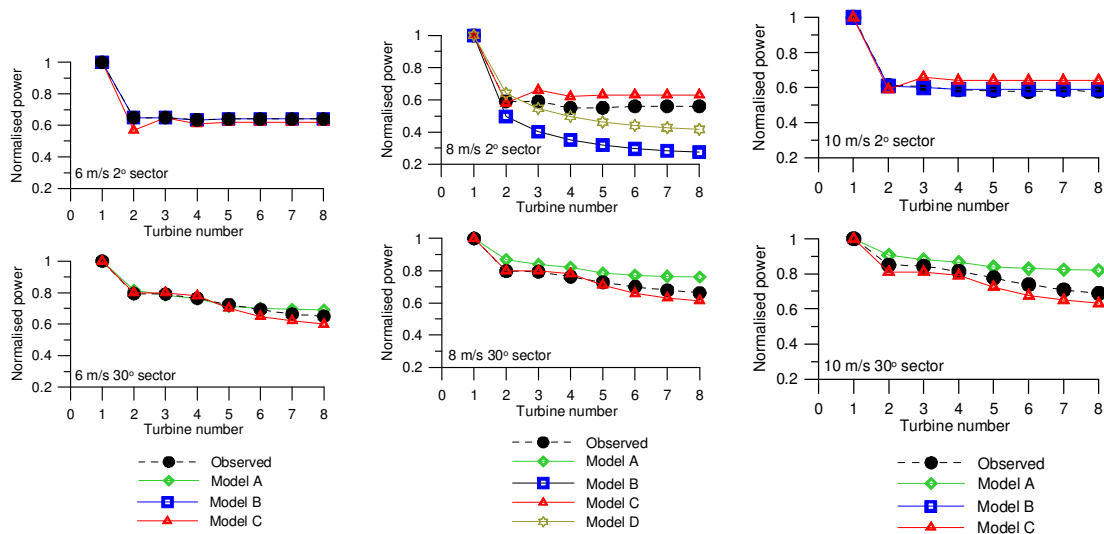


Figure 5: Preliminary comparison of models and measurements for three wind speed scenarios at Horns Rev (direction 270°, case 1 in Figure 4).

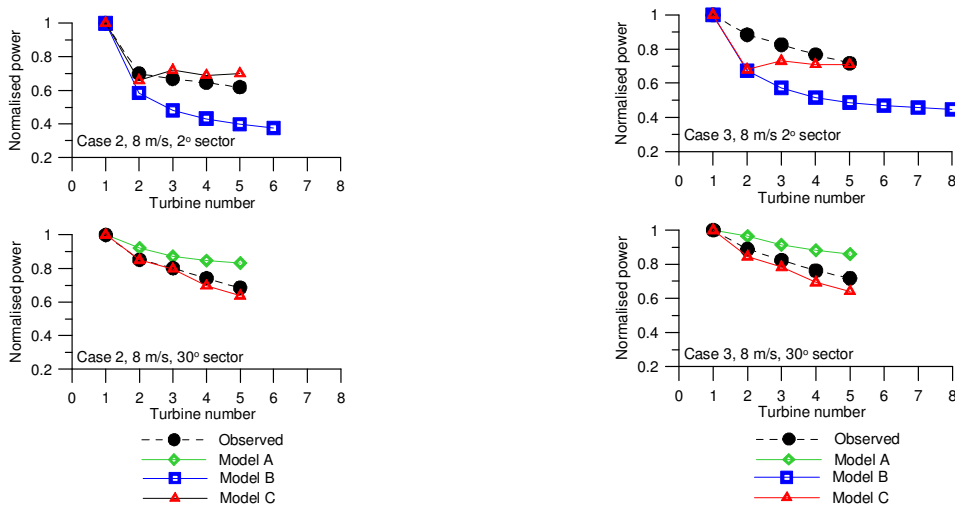


Figure 6: Preliminary comparison of models and measurements for two cases (Case 2 and Case 3 in Figure 4) and 8 m/s at Horns Rev

5. Conclusions

Within the Upwind project research in support of upscaling of wind turbines to the 12 MW size and beyond is underway. The research presented in this paper focuses on special issues relating to the development of large wind farms both in complex terrain and offshore. The results presented here are preliminary focusing on the comparison of different complexities of wake model in a number of scenarios. A cross-cutting theme is the introduction of CFD models in both complex terrain and offshore and in their representation of multiple wind turbines.

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