Flow and wakes in complex terrain and offshore: Model development and verification in UpWind

R.J. Barthelmie University of Edinburgh (UK) and Risø National Laboratory/DTU (Denmark) r.barthelmie@ed.ac.uk
J.G. Schepers, S.P. van der Pijl ECN (Netherlands)
O. Rathmann and S.T. Frandsen Risø National Laboratory/DTU (Denmark)
D. Cabezón CENER National Renewable Energy Center (Spain)
E. Politis and J. Prospathopoulos CRES (Greece)
K. Rados, NTUA (Greece)
K. Hansen, DTU (Denmark)
W. Schlez, J. Phillips, A. Neubert Garrad Hassan and Partners (Germany)

Summary

The paper presents research conducted in the Flow workpackage of the EU funded UPWIND project which focuses on improving models for 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

As wind farms and wind turbines grow larger there is an increasing need to describe accurately the wind speed, wind shear and turbulence climate at the wind farm site. In addition, each wind turbine generates a wake and the neighbouring wind turbine in the array which is exposed to the wake will experience a lower wind speed and higher turbulence than the unobstructed turbine. In other words, the energy yield of the wind farm will be lower and the loads higher than for an equivalent number of single turbines.

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 types of models 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 EU funded UPWIND project that aims to develop the next generation of wind turbines in the 5-12 MW range.

2. Wake modelling

Models describing wind turbine wakes were developed mainly in the 1980’s e.g. [2] and were used in wind farm models to approximate losses due to wakes e.g. [3]. By necessity the wake models had to be fairly straightforward, building on relatively few wake measurements and not requiring too much computing power. However, for single wakes or small wind farms in fairly straightforward environments these tended to give results which were not strongly in disagreement with the available data (e.g. ([4]; [5]; [6]). It should be emphasised that this discussion mainly concerns power losses due to wakes. Modelling of turbulence in wakes for load calculations tends to focus on for specific cases while power loss modelling has to encompass the full range of wind speeds and directions ([7]; [8]; [9]).

It has recently become clear that wake modelling for large offshore wind farms is inadequate [10] and also that wake modelling in complex terrain needs to be significantly improved. Therefore the focus of our work is in these two areas. A major shift has occurred in terms of computing resources which means that wake modelling is no longer confined to engineering approximations and that CFD modelling of the whole wind farm can be undertaken. This brings a new dimension to wake model in terms of the detailed temporal and spatial variation that can be modelled but a new complexity to wake model evaluation since measurements are not available on a finely spaced mesh over the wind farm, nor (typically) at high time resolution. CFD also brings new detail to near-wake studies which are not (typically) considered in wind farm studies. Below we describe some of the issues involved in wake model evaluation using the range of wake/wind farm models from the most straightforward like WAsP, through the moderately complex (Ainslie based e.g. Windfarmer) to the more complex (e.g. Wakefarm based on UPM) to complete CFD models.

3. Measurements

3.1. Types of measurements

There are essentially two types of measurements; meteorological and wind farm data. Some wind farms retain the meteorological mast(s) that was/were established for the resource determination and if these data are available in addition to wind farm data it is an added bonus particularly with regard to questions such as ‘What is the wind farm power curve?’ (depending on the mast location). At few offshore wind farms such as Vindeby, Bockstigen, Horns Rev and Nysted one or more meteorological masts were added after construction to aid research.

Meteorological data can also be divided into two types – mast and remotely sensed data. Examples of wind farms supported by meteorological mast data include Nørrkær Enge, Vindeby, Horns Rev and Nysted. The advantage of meteorological mast data is that it is usually available for a long period, it is typically accurate (although this can depend on the mast structure) and wind speed, direction and turbulence profiles to hub-height are usually 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. However, wake analysis has to be made for specific directional sectors and the wake distances can vary according to the layout of the wind farm and the position of the mast. Measurements are rarely made above hub-height.

Remote sensing is providing additional types of information for use in wind energy. We exclude here satellite data although these have been used both for wind resource [11] and for wakes estimation [12]. 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. [13]. Data from both instruments requires additional processing and maybe subject to some accuracy or operational limitations but progress has been made to the point where Doppler lidar in particular may become a standard instrument. As yet, there have been limited studies using sodar or lidar in wake studies e.g. ([14]. Obviously for wake studies in large wind farms, wind farm data are needed. Parameters required would typically be the power output, nacelle direction and yaw misalignment and additional operational information such as 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.

3.2 Issues comparing models and measurements

There are some major issues in wind farm model validation studies which will be discussed below. As stated above we concentrate here on power loss modelling which should encompass the whole range of wind speeds and directions and we also consider that the range of wind farm/wake model extends from engineering through to full CFD models. 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 WindFarmer and WAsP. On the other hand it can be difficult to extract reasonable simulations from some of the wind farm models for very specific cases. For example, WAsP relies on having a Weibull fit to wind speed distributions and fairly large directional sectors (30°). Therefore for specific wind speeds and narrow directional bins models like WAsP are never going to produce very exact solutions because they are being used beyond their operational windows. In addition to this there are a number of specific issues:

- Establishing the freestream flow. The major issues in determining the freestream flow are the displacement of the measurement mast from the array (assuming there is a mast), adjustments in the flow over this distance especially in coastal areas and differences in height between the measurement and the turbine hub-height. If there is no mast or the mast is in the wake of turbines or subject to coastal flow then the turbine(s) in the freestream flow may be used. If power measurements are used to determine wind speed they will be subject to any errors in the site specific power curve.

- Wind direction, nacelle direction and yaw misalignment. Because of the difficulty in establishing true north when erecting wind vanes (especially offshore where landmarks may not be determinable) it can be difficult to establish a true freestream direction. Even a well maintained wind vane may have a bias of up to 5° and it is important to understand this because the total width of a wake may be of the order 10-15° at typical turbine spacing. In a large wind farm, each turbine may have a separate bias on the direction, which is very difficult to determine. Analysis must be undertaken to calibrate the maximum wake direction to within 1° and to check for bias of the yaw angle on each wind turbine in the array.

- If there is a gradient of wind speeds across the wind farm as there may be e.g. in coastal areas, near a forest or caused by topography these variations will need to be accounted for before wake calculations are undertaken.

- In terms of modelling wakes both the power curve and thrust coefficients must be known but these will vary according to the specific environment. A power curve must be calculated for the site. For modelling, the question of whether the thrust coefficient should be set to one value for the wind farm or at each individual turbine in each simulation is still an open one. The state-of-the-art is to validate the individual power and pitch curves with reference to the nacelle anemometer, which seems to be a rather robust method to determine changes in the system setup.

- Comparing the modelled standard deviation of power losses in a row with the measured standard deviation raises a number of issues. The two most important are ensuring that the time averaging is equivalent between models and measurements and taking into account that there will be natural fluctuations in the wind speed and direction in any period. Models are typically run for specific directions but it may be necessary to include the standard deviation of the wind direction in the model simulations.

- In the large wind farm context the time scale of wake transport must be considered. A large wind farm with 100 turbines in a 10 by 10 array with an 80 m diameter rotor and a space of 7 rotor diameters has a length of nearly 6 km. At a wind speed of 8 m/s the travel time through the array is more than 10 minutes. As mentioned above the wind direction will be subject to natural fluctuations in addition to possible wake deflection but there will also be natural variations in the wind speed over this time scale.
- Determining turbulence intensity and stability may be critical. Turbulence intensity is a key parameter in many models. Using either mast data to determine this information or deriving it from turbine data is subject to fairly large errors for the reasons discussed above and because the accuracy of temperature measurements used to derive stability parameters is often inadequate.

4. Wake modelling in complex terrain

4.1. Overview

Models of the engineering type have been developed and calibrated for flat terrain applications. However, in complex terrain applications, the assumptions made in those models are no longer valid. More advanced methods should be applied taking into account the effect of the atmospheric boundary layer including flow separation and streamlining. In this respect the adoption of Navier-Stokes solvers seems to be the most accurate approach and the only one capable of simulating the interaction of wind turbine wake with the wind velocity shear and the shape of the complex terrain.

There are several issues, which need to be investigated regarding wake modelling in complex terrain:

- Complex topography results in the narrowing of the wind rose and the decrease the Weibull-k values. How does the narrowing behave with the increase in the hub height? The effect on the power curve should be quantified.
- The effect of topography on the wake geometry has to be investigated. Does the wake follow the streamlines? How does the terrain affect the wake opening?
- The reference wind velocity should be correctly assigned for modelling purposes. This is not obvious for steep slopes and wind parks with machine-wake interaction. In the context of an actuator disk modelling of the wind turbines, the combination of a BEM method with a Navier-Stokes solver could overcome the issue of the reference velocity definition by directly calculating the blade forces.

By answering these issues, it is expected to develop relationships for the maximum wind velocity deficit, the turbulence intensity and the wake geometry, which would complete the wake modelling along with those existing in flat terrain.

4.2. Complex terrain cases

The Gaussian Hill

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

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

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. The simulations without the wind turbine are needed 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 machine 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, ±15^o, ±30^o) 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.

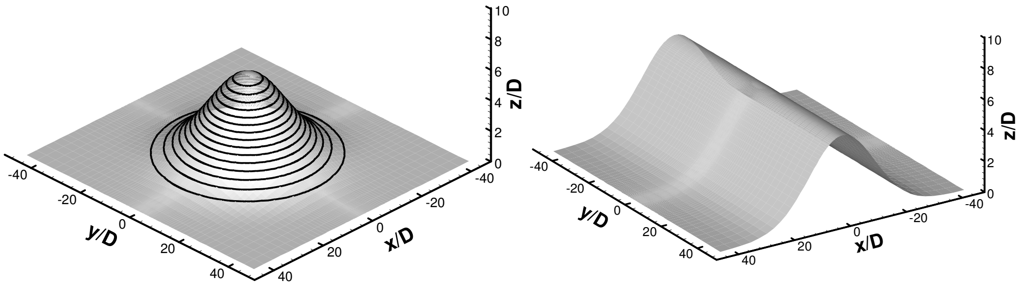

Figure 1: Terrain of the 3D and 2D Gaussian hill ($L = 1750$).

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 simulation of five subsequent wind turbines in flat terrain is considered to well cover this case. A parametric analysis will be done for different values of the distance between the wind turbines (3, 5 and 7D) and different values of Ct (0.3, 0.5 and 0.7). The level of turbulence intensity will be set equal to 13%.

The wind speed deficit and wake radius variations at hub height will indicate the significance of the wake effect of the previous wind turbines and how this effect decays as the distance from the first machine increases. The vertical and lateral profiles of the wind deficit along with the xz and yz contour plots can represent the evolution of the wake geometry.

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, installed in 2001, 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).

Two meteorological masts are located upstream of the wind farm on the wind directions mentioned above. The masts registered 10 minutes averages of wind speed, wind direction and standard deviation of wind speed at 20 m and 40 m high. In addition, the air temperature is measured at 10 m height. Regarding power data, the output energy as well as the nacelle wind speed for every wind turbine is recorded on an hourly basis. Furthermore, a specific status signal is also registered in order to filter the unavailability of the wind turbines. Overall, a 2 year period of simultaneous data (meteorological and wind farm) is available.

The location of the meteorological masts allows the upstream flow in the prevailing wind direction to be characterised in order to analyse situations of far wake. Other non-prevailing sectors (W-WSW) corresponding to near wake scenarios are known to contain enough frequency of data and some information could also be extracted. Yaw angle at the wind turbines was not registered so that only wind direction at the meteorological masts could be used at the filtering process.

The study represents a first attempt of comparing and validating the existing wake models on a real moderately complex site and according to real field data.

4.3. Models

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–ω model [15], suitably modified for atmospheric flows.

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.

WAsP

The Wind Atlas Analysis and Application Program (WAsP) is based on a linearised model used in the European Wind Atlas and is the most widely used wind resource/wind farm model in the world. The WAsP program [16] 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 [17]. A new version of the wake model is being developed (see below). 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 which are given in [18]. Also it is not intended for single simulations. The program utilises the station data by fitting it to a two parameter Weibulll 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.

4.4. Preliminary model comparison

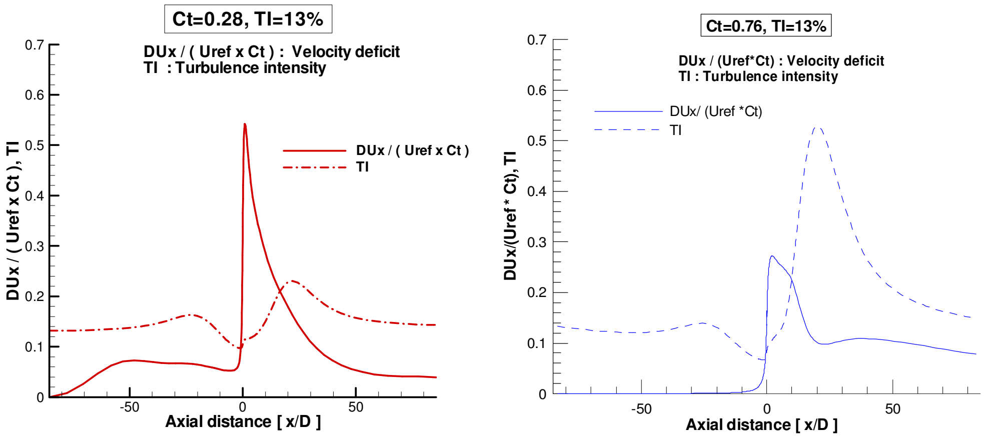

Figure 2: Preliminary results for the velocity deficit and turbulence intensity at turbine hub-height over the 2 D Gaussian hill (two different CFD models).

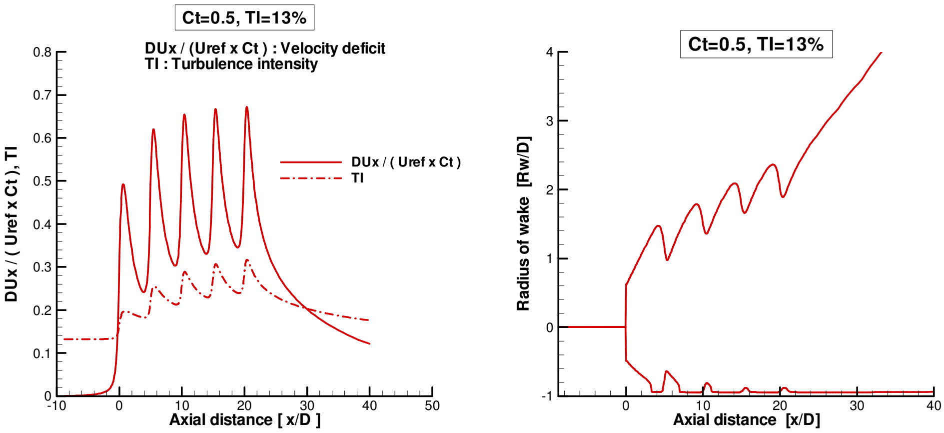

Figure 3: Preliminary results for the velocity deficit and turbulence intensity for the expansion of the wake for five turbines in flat terrain.

5. Wake modelling offshore

5.1. Overview

A comparison of the main wake/wind farm models was undertaken as part of the ENDOW project (e.g. [19], [20]) for small offshore wind farms. From this and a further experiment at Vindeby [4, 14] 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 [21] and those in large multi-row wind farms where current wind farm models appear to under-predict wake losses [10]. It can be postulated that this is due to the interaction of turbulence generated by wind turbines wakes with the overlying atmosphere [22] and that a new generation of models is required to deal with this complex interaction of wakes with each other and the boundary-layer [23]. 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.

5.2. Definition of flow cases for offshore wind farms based on Horns Rev data

A number of flow cases have been defined for the Horns Rev offshore wind farm. The Horns Rev wind farm is a Danish 160 MW wind farm, 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 4. See [24] for more detail about the wind farm and wake measurements.

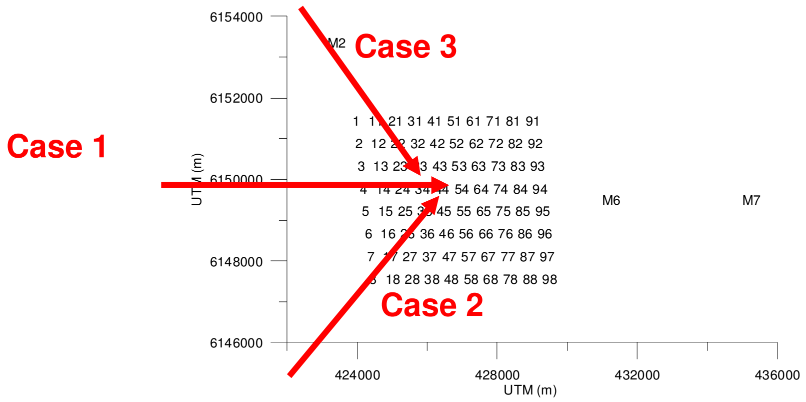

Figure 4: Horns Rev layout including definition of 7D, 9.4D and 10.5D flow directions.

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 5 for 3 different spacings.

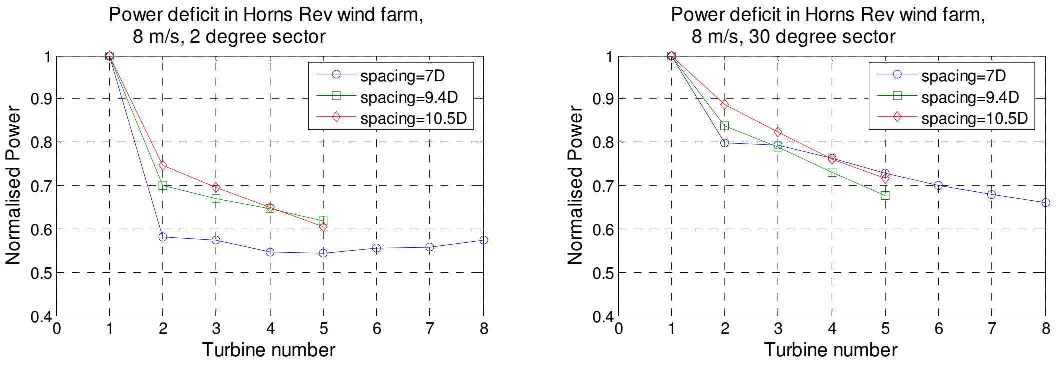

Figure 5: Power deficit inside Horns Rev wind farm for V=8±0.5 m/s inflow for different spacing.

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.

5.3. Models used in the comparison

ECN

ECN's WAKEFARM model is based on the UPMWAKE code which originally was developed by the Universidad Polytecnica de Madrid. It is based on the 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 are plausible some distance away from the turbine and allows for a rapid numerical solution procedure. In the near wake, however, the wake expands, the flow decelerates and pressure gradients are eminent. Obviously, the assumptions no longer hold in the near wake and additional modelling is necessary to account for the near wake.

In the ENDOW project [25] 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.

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 [2]. 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 [8] 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 [26].

WAsP

As described in Section 4.2 the WAsP model is designed to use the Weibull distribution of wind speeds in a number of direction sectors. To perform specific simulations for small wind speed and directions bins approximations have to be made which limits the accuracy of the results. For example, here a Weibull distribution for wind speeds was assumed with a shape factor of 2 which is reasonable offshore and with the scale parameter adjusted to give the required mean wind speed. However, a large number of wind speeds will be above or below the mean, giving quite different results from performing a simulation at one specific wind speed. Similarly, the wind speed distribution by direction cannot be limited to having all wind speeds in one sector. Results are shown here to give a general guide as to how WAsP performs. A new wake model is being developed for WAsP and this is described below.

The new WAsP wake model

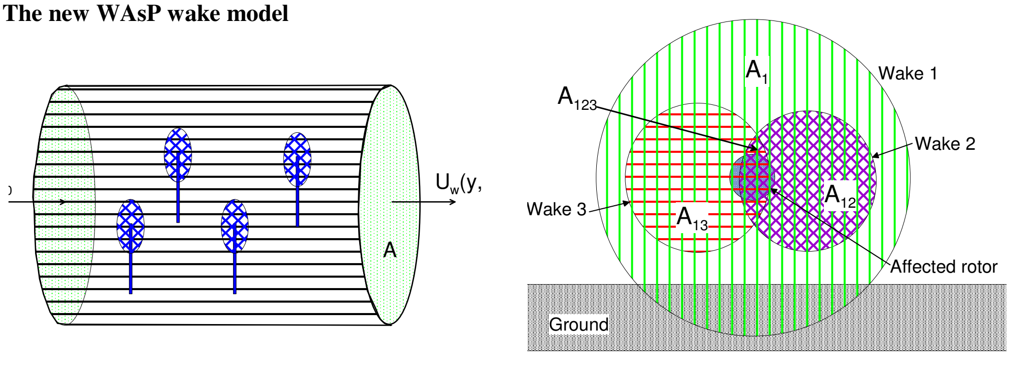

Figure 6: Left. Cylindrical control volume around a set of turbines. Cut-off of the control volume at the ground level has been left out for graphical reasons. Right: Overlapping wakes example. The wake structure is composed of a number of “mosaic tiles”, each with one or more overlapping individual wakes.

The model aims at wind farm production estimates in engineering software like WAsP. Thus the wake model must be computationally fast while having the most important wind flow features adequately represented. The model is based on balance equations for volume and momentum in a control-volume as illustrated in Figure 6. The relative speed deficit $\delta \equiv (U_w - U_0)/U_0$ at the exit plane of the control volume is then related to the thrusts on the turbine rotors. The individual wakes are assumed to develop according to a power-law expansion with an exponent of 1/3 to 1/2. In the model, the speed deficit distribution at a certain downwind (turbine) position is assumed to be a pattern of one or more overlapping wakes areas, “mosaic tiles” as illustrated in Figure 6, each assumed to have constant relative speed deficit. The wake model will be calibrated and tested against relevant off-shore wind farm data [27].

NTUA

NTUA CFD model solves the 3D Reynolds averaged incompressible Navier-Stokes equations with second order spatial accuracy. The model [28] (see also [20]) assumes Cartesian grids, uses the k-ε 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 Ct thrust coefficient. NTUA has performed preliminary offshore wake calculations for the Horns Rev Wind Farm. Due to the extensive cpu effort end memory requirements, only Case1.8.2 (see below) was initially simulated and model results were compared with observations.

5.4. Comparison of models and measurements

The preliminary evaluation shown in Figure 7 is for a westerly wind direction with flow exactly along the rows as shown in Figure 7. 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.

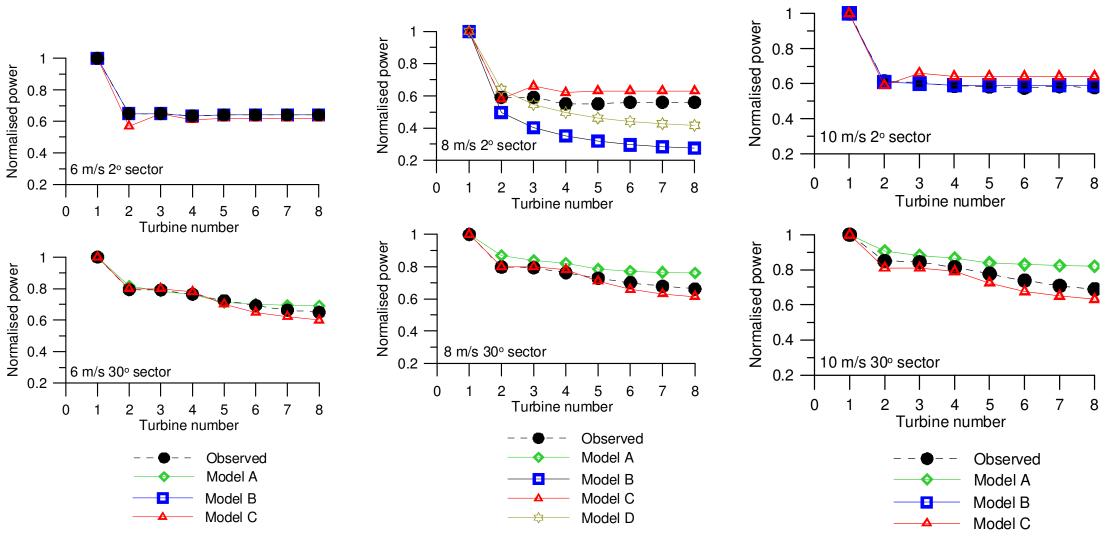

Figure 7: Preliminary comparison of models and measurements for three wind speed scenarios at Horns Rev (direction 270°, case 1 in Figure 4).

6. Large offshore wind farms

6.1. Overview

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. Here we discuss some of the ongoing work to address this issue.

GH

The general description of the WindFarmer model is given in section 5.3 above. Modelling the Horns Rev wind farm the good performance of the Eddy Viscosity Model was again visible for the first few rows of turbines. However further downwind, deeper into the wind farm, the modeling turned out to be increasingly less accurate. As the effect seen in the data from Horns Rev and other offshore wind farms is not visible in onshore wind farms we need to identify what effects that are specific to offshore could be the cause for the discrepancy. The most plausible explanation for this effect has indeed been under discussion since the dawn of the wind energy industry, e.g. [29]: The wind turbine does not only react passively to the wind regime but at the same time is part of it. Weather systems are not considered to be affected significantly at the scale of developments considered. However locally, by the presence of wind turbines, the boundary layer profile is modified.

A wind farm area can in this model be represented by an area of higher roughness. Due to the lower roughness offshore such an area of increased roughness has a pronounced effect, similar to a forest onshore. Onshore, on the other hand, such effect would be masked by the higher terrain roughness.

Based on this explanation we have developed a model that does not require the wind farm to have a particular shape. Instead of modelling an area of increased roughness we model the disturbance caused by each individual turbine. This allows us to consider the effect for a wider variation of wind farm layouts during the design phase and optimisation of a wind farm layout.

The model comprises simply of two components

- Calculation of internal boundary layer height
- Vertical offset of the boundary layer

On the basis of this model the ambient wind speed is corrected. The wake model itself stays unchanged. The model results are presented in Figure 8. The model reproduces well the results from Horns Rev for different wind speeds and directions.

Extreme caution is required with regards to the application of the offshore correction for large wind farms. The model has not yet been validated against multiple wind farms. As soon as data from such wind farms become available, an update of the model is likely and therefore the current model results should be seen as preliminary.

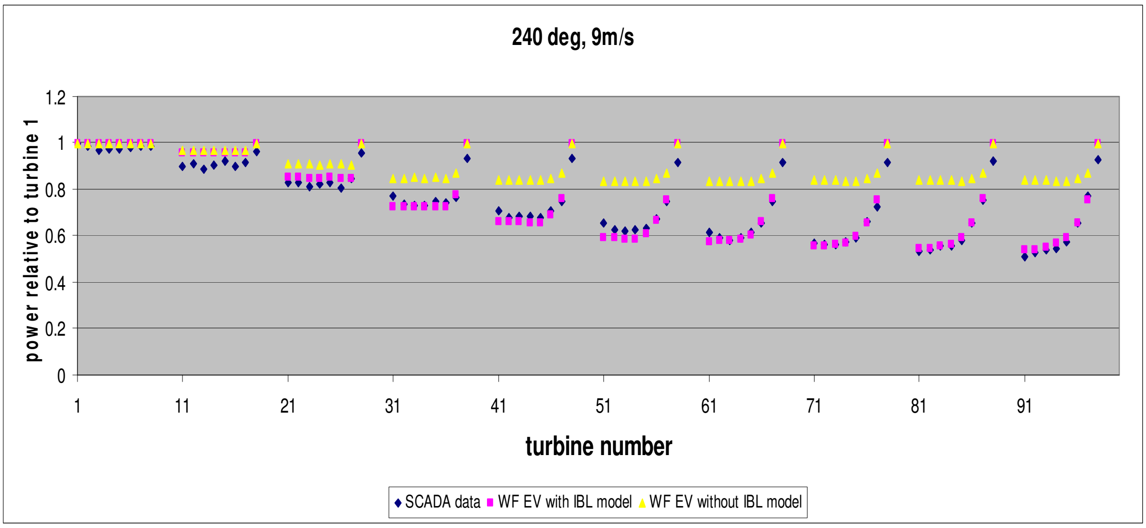

Figure 8: Energy yield at Horns Rev (240 deg 9 m/s) data compared with new and old model from [30].

6.2. RISOE

Added roughness models are based on the representation of a wind farm as a roughness element causing an internal boundary layer (IBL) to grow over the wind farm. Thus in a simple 2D model the development of the IBL, roughness and wind recovery can be calculated according to the spacing and thrust coefficient, height of turbines and ambient turbulence intensity. As shown in Figure 9, the velocity deficit can be advected >10 km downwind [1]. This idea based on [5] has been further expanded to include specific wake development, wake merging and wake interaction with the boundary layer in [23].

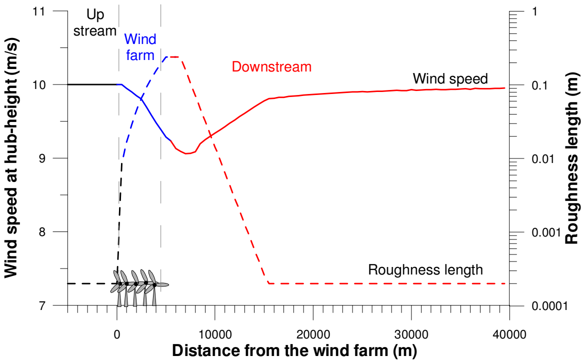

Figure 9: Representation of the wind farm as a roughness element [1]

7. 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.

8. Acknowledgements

Research funded in part by EU project UPWIND reference SES6 019945. RB acknowledges the Scottish Funding Council for their support of the Joint Research Institute with the Heriot-Watt University as a component part of the Edinburgh Research Partnership. We would like to acknowledge DONG Energy A/S and Vattenfall AB, owners of the Horns Rev wind farm for allowing use of Horns Rev data.

9. References

1. Barthelmie, R.J., S.C. Pryor, S. Frandsen, et al. *Analytical and empirical modelling of flow downwind of large wind farm clusters*. in *The science of making torque from wind*. 2004. Delft.
2. Ainslie, J.F., *Calculating the flow field in the wake of wind turbines.* Journal of Wind Engineering and Industrial Aerodynamics, 1988. **27**: p. 213-224.
3. Mortensen, N.G., D. Heathfield, L. Landberg, et al. (2000) *Getting started with WASP 7.0*. Risø-I-1532(EN). p. 60. http://www.wasp.dk/Download/DownloadFiles/WAsP/WAsP7/Getting%20Started%20with%20WAsP%207.pdf.
4. Barthelmie, R.J., L. Folkerts, K. Rados, et al., *Comparison of wake model simulations with offshore wind turbine wake profiles measured by sodar.* Journal of Atmospheric and Oceanic Technology, 2006. **23(7)**: p. 888-901.
5. Crespo, A., J. Hernandez, and S. Frandsen, *Survey and modelling methods for wind turbine wakes and wind farms.* Wind Energy, 1999. **2**: p. 1-24.
6. Magnusson, M. and A.S. Smedman, *Air flow behind wind turbines.* Journal of Wind Engineering and Industrial Aerodynamics, 1999. **80**: p. 169-189.
7. Frandsen, S. and M.L. Thøgersen, *Integrated fatigue loading for wind turbines in wind farms by combining ambient turbulence and wakes.* Wind Engineering, 1999. **23**: p. 327-339.
8. Quarton, D. and J. Ainslie, *Turbulence in wind turbine wakes.* Wind Engineering, 1990. **14**(1).
9. Thomsen, K. and P. Sørensen, *Fatigue loads for wind turbines operating in wakes.* Journal of Wind Engineering and Industrial Aerodynamics, 1999. **80**(121-136).
10. Mechali, M., L. Jensen, R. Barthelmie, et al. *Wake effects at Horns Rev and their influence on energy production*. in *European Wind Energy Conference and Exhibition*. 2006. Athens, Greece: p. 10.
11. Hasager, C.B., R. Barthelmie, M. Christiansen, et al., *Quantifying offshore wind resources from satellite maps: study area the North Sea.* Wind Energy, 2006. **9**(1-2): p. 63-74.
12. Christiansen, M.B. and C. Hasager, *Wake effects of large offshore wind farms identified from SAR.* Remote Sensing of Environment, 2005. **98**: p. 251-268.
13. Antoniou, I., H. Jørgensen, T. Mikkelsen, et al. *Offshore wind profile measurements from remote sensing instruments*. in *European Wind Energy Association Conference*. 2006. Athens, Greece, February 2006: 10 pp.
14. Barthelmie, R.J., L. Folkerts, F. Ormel, et al., *Offshore wind turbine wakes measured by SODAR.* Journal of Atmospheric and Oceanic Technology, 2003. **30**: p. 466-477.
15. Wilcox, D.C. (1993) *Turbulence modelling for CFD*. DCW Industries Inc., IBSN 0-9636051-0-0.
16. Mortensen, N.G., D.N. Heathfield, L. Myllerup, et al. (2005) *Wind Atlas Analysis and Application Program: WAsP 8 Help Facility*. Risø National Laboratory, Roskilde, Denmark. 335 topics. ISBN 87-550-3457-8. http://www.risoe.dk/vea/projects/nimo/WAsPHelp/Wasp8.htm.
17. Katic, I., J. Højstrup, and N.O. Jensen. *A simple model for cluster efficiency*. in *European Wind Energy Association*. 1986. Rome: p. 407-409.
18. Bowen, A.J. and N.G. Mortensen. *Exploring the limits of WASP: the wind analysis and application programme.* in *European Union Wind Energy Conference*. 1996. Goteborg: H.S. Stephens and Associates, Bedford, UK.
19. Schlez, W., A.E. Umaña, R. Barthelmie, et al., *ENDOW: Improvement of wake models within offshore windfarms.* Wind Engineering, 2002. **25**: p. 281-287.
20. Rados, K., G. Larsen, R. Barthelmie, et al., *Comparison of wake models with data for offshore windfarms.* Wind Engineering, 2002. **25**: p. 271-280.
21. Barthelmie, R.J., S.T. Frandsen, M.N. Nielsen, et al., *Modelling and measurements of power losses and turbulence intensity in wind turbine wakes at Middelgrunden offshore wind farm.* Wind Energy (in review), 2007.
22. Frandsen, S. (2005) *Turbulence and turbulence-generated fatigue loading in wind turbine clusters*. Risø-R-1188(EN). p. 128 http://www.risoe.dk/rispubl/VEA/ris-r-1188.htm.
23. Frandsen, S., R. Barthelmie, S. Pryor, et al., *Analytical modelling of wind speed deficit in large offshore wind farms.* Wind Energy 2006. **9**(1-2): p. 39-53.
24. Jensen, L. *Wake measurements from the Horns Rev wind farm*. in *European Wind Energy Conference*. 2004: EWEA (on CD): 9 pp.
25. Schepers, J.G. (2003) *ENDOW: Validation and improvement of ECN's wake model*. ECN, ECN-C--03-034 (March 2003): p. 113.
26. Barthelmie, R.J., G.C. Larsen, S.C. Pryor, et al. (2003) *Efficient development of offshore windfarms (ENDOW): Final report to the European Commission.*, Risø National Laboratory, Risø-R-1407(EN): 30 pp.
27. Rathmann, O., S.T. Frandsen, and R.J. Barthelmie. *Wake modelling for intermediate and large wind farms.* in *European Wind Energy Conference and Exhibition*. 2007. Milan.
28. Magnusson, M., K.G. Rados, and S.G. Voutsinas, *A study of the flow down stream of a wind turbine using measurements and simulations.* Wind Engineering, 1996. **20**(2): p. 389-403.
29. Tetzlaff G. et al. (1984) *Meteorologische Messungen zur Standortwahl für Windenergieanlagen im Küstengebiet.*, Institut für Meteorologie und Klimatologie der Universität Hannover: p. BMFT-FB-T 84-017.
30. Schlez, W., A. Neubert, and G. Smith. *New developments in precision wind farm modelling*. in *Deutsche Windenergie Konferenz*. 2006. Bremen: 5 pp.