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Flow and wakes in large wind farms in complex terrain and offshore

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Abstract

Power losses due to wind turbine wakes are of the order of 10- 20% of total power output in large offshore wind farms. The focus of this research is wind speed and turbulence modelling for large wind farms/wind turbines in order to optimise wind farm layouts to reduce wake losses and loads. This research is part of the EC funded UPWIND project which aims to radically improve wind turbine and wind farm models in order to continue to improve the costs of wind energy. The first part of this work is to assess the state of the art in wake and flow modelling. For complex terrain, a set of three evaluations is underway. The first is a model comparison for a Gaussian Hill where CFD models and wind farm models are being compared for the case of one hill-top wind turbine. The next case where observations will be available is for the case of five turbines in flat terrain. Finally a complex terrain wind farm will be modelled and compared with observations. For offshore wind farms, the focus so far has been cases at the Horns Rev wind farm which indicate wind farm models require modification to reduce under-prediction of wake losses while CFD models typically over-predict wake losses. Further investigation is underway to determine the causes of these discrepancies. The project therefore represents a set of unique evaluations of models with observations in different environments. Progress towards improving wind farm models will be described.

1. Complex terrain

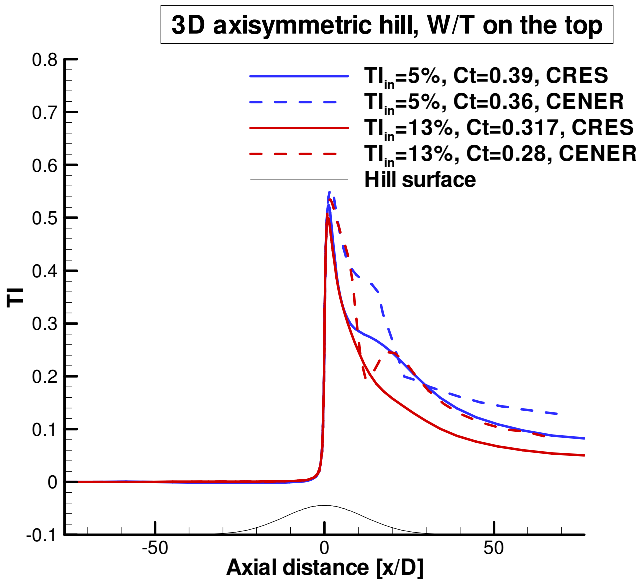
Three model simulation types are planned to compare the performance of the CFD models with wind farm models where appropriate:

- Simple terrain (Gaussian Hill). Simulations shown below.
- Five turbines in flat terrain. Initial model simulations are shown below.
- The complex terrain wind farm. This work is not yet complete.

1.1 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 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, ±15^{o}, ±30^{o}) are 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.



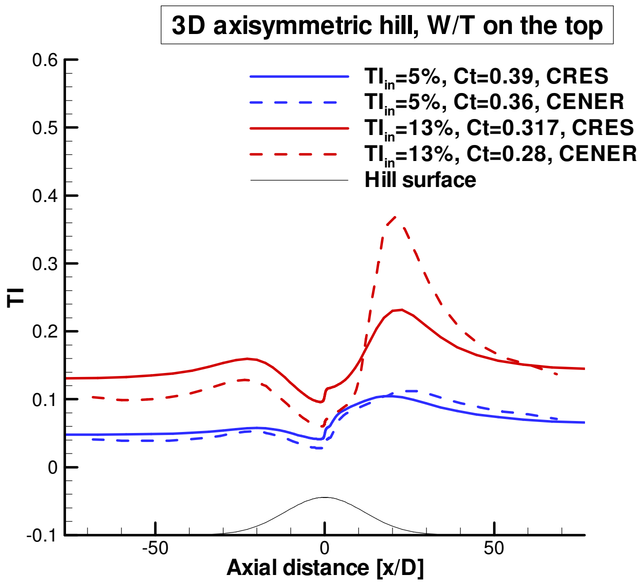


Figure 1: Preliminary results for the velocity deficit (top) and turbulence intensity (bottom) at turbine hub-height over the 2 D Gaussian hill (two different CFD models).

As shown in Figure 1 there are major differences in the simulations undertaken with two different CFD models which are being explored. In this Figure, two cases are depicted: The initial turbulence TI_in=5% and TI_in=13% cases. The predicted Ct values are also shown on the figures. Regarding the velocity deficit predictions, it is observed that CRES predicts a faster decay rate which is a result of the higher Ct predicted value or equivalently of the lower predicted velocity at the hill top. Regarding the turbulence intensity predictions, small differences are observed for the TI_in=5% case; however, these differences are enhanced for the TI_in =13% case. The pattern (positions of minimum and maximum turbulence) is similar for CRES and CENER calculations. The differences in the velocity predictions can be attributed to a different roughness length estimation, whereas the differences in the turbulence intensity can be attributed to the different turbulence model (k omega vs. k-epsilon) and/or a different initial turbulence intensity profile. These issues are under investigation and a final comparison between CRES and CENER predictions is in progress.

1.2 Five turbines in a row

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 neighboring wind turbine. In order to estimate the effect of a neighboring wake on the wind turbine efficiency, multi-wake simulations are needed.

Eventually simulations will be compared with observations. Initially, however, simulations were made to evaluate the impact of the thrust coefficient C_t and turbulence intensity *TI*. One multi-wake case, probably the worst in terms of efficiency, is simulated: Five subsequent wind turbines positioned one behind the other. A parametric analysis is done for different values of the distance between the wind turbines (3, 5 and $7D$, with D being the wind turbine diameter) and different values of C_t (*0.3, 0.5* and *0.7*). The level of inlet turbulence intensity at hub height is set equal to *13%*. In this manner, the effects of the intermediate distance and the C_t are assessed.

It is noted that the velocity deficit at a (x,y,z) point is expressed in dimensionless form as:

$$\frac{DU}{U_{ref} \times C_t} = \frac{U_{ref}(z) - U_x(x,y,z)}{U_{ref}(z) \times C_t},$$

where U_x is the local axial velocity and U_{ref} is the inlet velocity at height z.

In Figure 2, the axial variation of the velocity deficit at hub height is represented for the case of five wind turbines with the distance between the machines given as an example here for 5D. The inlet turbulence intensity level is set to 13%. For high values of C_t ($C_t = 0.7$) the increase of the velocity deficit at the following (2^{nd}-5^{th}) wind turbines is not significant even when the distance between the machines is small ($3D$). However, for lower values of C_t there is a significant increase in the deficit of the second wind turbine which becomes greater as the wind turbines move close to each other ($w = 3D$). In general, there is no significant increase in the velocity deficit after the third wind turbine. High values of the turbulence intensity for the five wind turbines case are observed. In comparison to the one wind turbine case, the level of maximum turbulence intensity has been almost doubled.

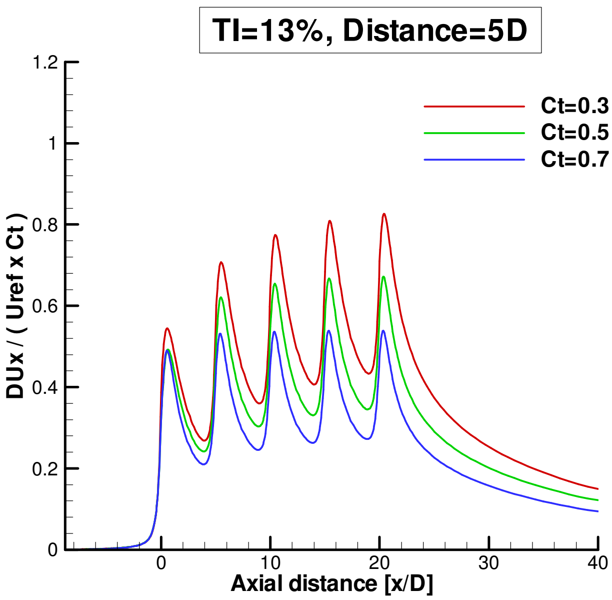


Figure 2: CFD simulations of five wind turbines in flat terrain - Effect of C_t on velocity deficit at hub height. Distance between wind turbines is 5D and inlet turbulence intensity at hub height is 13%

2. Wake modelling offshore

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 (Barthelmie et al. 2007) and those in large multi-row wind farms where current wind farm models appear to under-predict wake losses (Mechali et al. 2006). 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 (Jensen 2004).

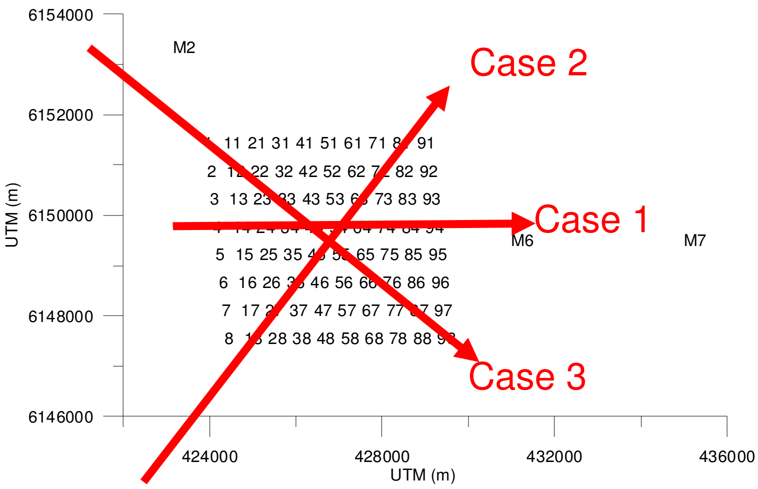


Figure 3: Horns Rev layout including definition of Case 1 (7D), Case 2 (9.4D) and Case 3 (10.5D) flow directions. Turbine locations are given by numbers and the location of the downstream masts are marked with M6 and M7.

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 in Figure 4 for case 1 with different wake widths. The wind speed calculated from the power output of the first turbine is 8±0.5 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 infrequently. The major finding is an almost constant power deficit of around 40% which is identified during pure wake situation for a very small sector of 2°. If larger wake widths are considered the deficit decreases downwind.
In general, the CFD type models appear to be over-predicting wake losses in these narrow sectors while the wind farm models without additional modification under-predict wake losses. Clearly there are a number of possible causes of these discrepancies which might include turbulence levels in the wake, wake combination, turbulence in the boundary-layer and/or wake meandering. Model discrepancies have to be examined further in order to try to further understanding of the behaviour of multiple wakes in large wind farms.

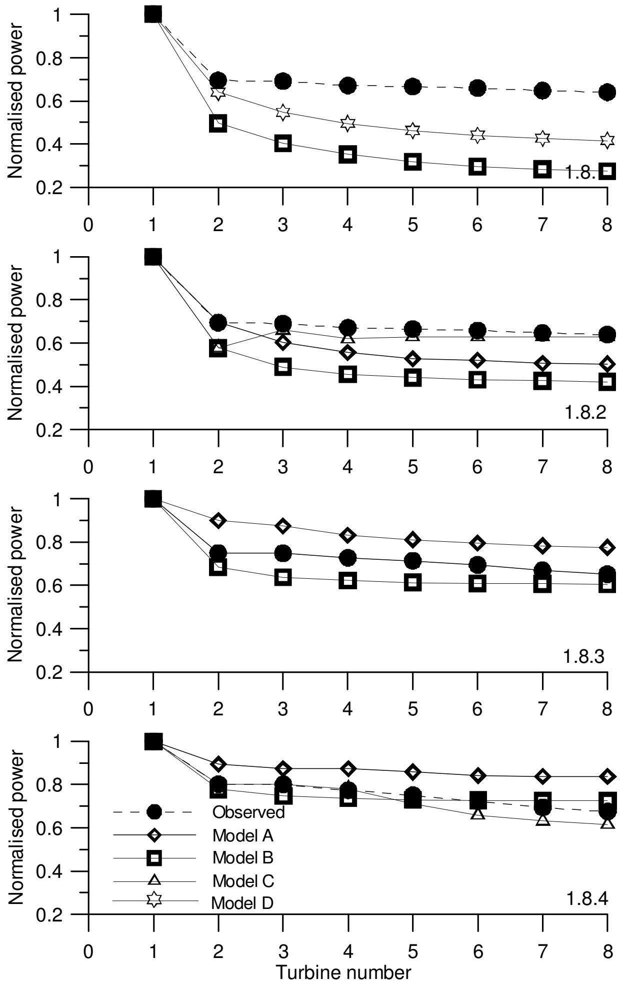


Figure 4: Comparison of models and measurements for Horns Rev (direction 270°, case 1 in Figure 4). The initial wind speed calculated from the power output of the first turbine is 8±0.5 m/s. From the top down the width of the wake sectors considered in the four panels are ±1°, ±5°,±10° and ±15°.

3 Large offshore wind farms

It has become apparent that power losses from wakes exceed those predicted using standard wind farm models. GH have made an additional feature available in their WindFarmer model to allow assessment of these effects according to the current state of knowledge. RISOE have taken several approaches including the development of a new analytical model (Frandsen et al. 2006), modifications to the WAsP model (Rathmann et al. 2006), modification of added roughness models and development of a canopy type model (Frandsen et al. 2007). In all, seven models were compared with data from the offshore wind farms at Horns Rev and Nysted in Denmark. As yet it has not been possible to undertake a full model comparison using a years data from the wind farm. This is more straightforward with the parameterised models than with the CFD models which are intensive in terms of their computing resource requirements. Comparisons have therefore tended to focus on a limited range of wind speeds with high thrust coefficient for westerly winds which are well-represented in the database, have flow directly down rows of wind turbines and have downstream masts at distances between 4 and 11 km for comparison with models. In general, models where some tuning of the turbulence intensity has been applied (either directly or through increased roughness) show good agreement with measurements. The wind speed determined from power output within the wind farm can drop to less than 80% of its freestream value (according to the initial wind speed and direction angles considered). Recovery to approximately 90% of the freestream value appears to occur with the first 5 km downwind of the last turbine in the wind farm. However, further recovery is more gradual and appears to extend for an additional 15-20 km downwind. Considerable work remains to be done in terms of model evaluation and this also relies on additional data from large offshore wind farms becoming available in order that the impact of a range of wind turbine types and wind farm configurations can be determined.

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. Significant work remains to be done including developing a physical understanding of the causes of over- or under-prediction of wake losses in large offshore wind farms by the different types of models. A cross-cutting theme is the introduction of CFD models in both complex terrain and offshore and in their representation of multiple wind turbines.

Acknowledgements

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