Beyond the Ainslie Model:

3D Navier-Stokes Simulation of Wind Flow through Large Offshore Wind Farms

V. Riedel, T. Neumann, M. Strack
Deutsches Windenergie-Institut GmbH, Wilhelmshaven, Germany
v.riedel@dewi.de

1. Abstract

A CFD model is presented that can be used for the calculation of the wind and turbulence conditions in large-scale offshore wind farms. Information on wind shear and turbulence intensity increase can be derived from the model for the purpose of fatigue load calculations. Advantages over current engineering wake models are presented and verification results are summarised related to onshore near-wake measurements and to the Horns Rev wind farm.

2. Introduction

DEWI is currently involved in the research project OWID, which stands for "Offshore Wind Design Parameter". Its aim is to evaluate wind data from the FINO1 offshore platform (see Figure 1), to calculate site parameters relevant for mechanical loads and to compare the results to current standards. Besides being the project co-ordinator, DEWI is responsible for the work package "Wake Effects", where the FINO1 data have to be extrapolated from the platform to positions deep inside large offshore wind farms in order to approximate the turbulence and wind shear conditions there. These wake effects are not easily calculated. On the one hand, there is a wide variety of wake models of very different complexity. On the other hand, the models are in general more tuned to smaller size onshore farms and they fail to reproduce the specific effects that are currently observed in large farms. In the case of large onshore wind farms, this is again confirmed in [5].

3. Requirements for an Offshore Wake Model

Precise Farm Efficiency

We demand that the model should give precise predictions of the farm efficiency. This is important for wind farm optimisation and for financial modelling.

Fatigue Load Calculation Input

The model should produce the required input for fatigue load calculations. This is the characteristic turbulence intensity that must be expected in the farm, but also information on the wind shear.

Scale Extrapolation Capabilities

The most important property is that the model must have scale extrapolation capabilities. This means that it must not be a simple fit to existing wind farm operational data, e.g. from Horns Rev. The reason is that the wind farms currently planned for the German Bight are much different from Horns Rev, regarding layout, overall size, turbine type and distance to the coast. Besides that, a wind farm optimisation for those farms will only be successful if the relevant wind farm effects are physically modelled.

Atmospheric Stability Effects

It is also important that the model should be able to incorporate atmospheric stability effects, because experience at Horns Rev has shown that stability has quite a significant effect on the wind farm performance. In particular, it drops for stable situations.

Acceptable Computation Time

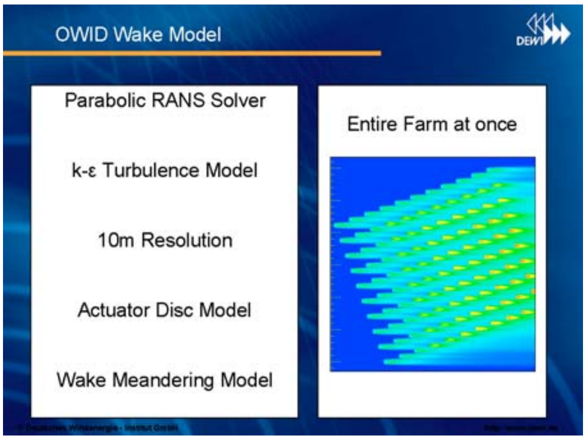
The last property is that we would like to have an acceptable computation time. This can mean at maximum that we may run a wind farm optimisation on a small computer cluster. On the other hand, this excludes the whole class of large eddy models that are currently much in fashion among modellers.

Looking at these requirements, it was necessary to set up a special model for the project, which is described below.

Figure 1: Offshore Research Platform FINO1.

4. Model Description

The "OWID Wake Model" is an application of current engineering Computational Fluid Dynamics (CFD) modelling techniques to the wake modelling problem. It is not primarily a research model, which should today at least employ a large-eddy turbulence model, but it is a model that is designed to provide the engineer with realistic input for fatigue load calculations that are carried out in the OWID project. For an overview see Figure 2. There are similarities to the model used at ECN [8]. The OWID model solves the Reynolds-Averaged Navier-Stokes Equations in parabolic mode using the commercial CFD software Phoenics [7]. The parabolic calculation instead of an elliptic one is required in order to limit computation time. Additionally, the strong parabolic nature of the problem is obvious and we do not expect any significant improvements with an elliptic calculation.



OWID Wake Model

Parabolic RANS Solver

k-ε Turbulence Model

10m Resolution

Actuator Disc Model

Wake Meandering Model

Entire Farm at once

Figure 2: Overview of the OWID wake model properties.

Turbulence is calculated with the k-ε turbulence model which has shown to give realistic results in many different application cases. Although there are many modifications of the k-ε model, especially for the atmospheric boundary layer, we use the model in its original standard form [6] without any modification of model constants or terms. The reason is that the model must be able to represent ambient boundary layer turbulent exchange processes as well as wake turbulence. If one would tune the model so that it may better represent the vertical variation of the ambient flow, the wake turbulence budget may be influenced in a way that is difficult to assess. The same is true for the ambient flow if one would tune the model to the wake processes. Additionally, the primary aim of our modelling efforts is to have a model that is *not* tuned to any specific wind farm, which one could not prevent if one would tune the turbulence model to e.g. Horns Rev. Therefore we decided to leave the model in its original state, which is a kind of average turbulence behaviour that is applicable to many different cases.

An important property of the model is that it considers the whole farm at once. Most of the existing models perform calculations for single wakes that are afterwards superimposed and mixed according to some rules. For large farms however, we are convinced that a separation into ambient flow and wakes is not appropriate and one must directly model the superposition and mixing of different wakes.

The whole wind farm and an area around it are covered with a 3D Cartesian grid with a resolution of 10 m in all directions. In the farm area, this resolution is used up to a height of 300 m, above that, the grid spacing expands towards the upper grid boundary at 1000 m.

The inflow boundary condition is obtained by a one-dimensional simulation of the atmospheric boundary layer during that the geostrophic wind speed is adaptively adjusted so that a specific wind speed at hub height for the situation considered is obtained. If one would specify the inflow through application of Monin-Obukhov Similarity theory, the inflow would not be in perfect equilibrium with the main domain flow. Even in the absence of any wind farm in the model domain, one would have undesired horizontal variations of the wind conditions that would have a negative impact on the precision of the wind farm calculations.

The boundary conditions at the turbines are modelled according to the actuator disc model. Wind speed is reduced in the rotor plane according to the thrust curve and the wind speed observed in the rotor area. That velocity reduction is applied in the rotor plane and adjusts the incident flow according to the energy loss at the machine. Directly behind the rotor, there is large wind shear at the boundary of the wake, leading to heavily increased turbulence production.

Additionally, a simple model for the wake meandering phenomenon is implemented. The flow field at the turbine rotors is calculated as a superposition of shifted versions of the original flow field. Different shifted versions of the flow field are, in the superposition, weighted according to a two-dimensional Gaussian distribution function. The standard deviation of this distribution function is estimated to be about 45 m on base of our analyses carried out with the 10 Hz data from the sonic anemometers at the FINO1 platform. It should be noted that during stable stratification the standard deviation of the shifting function is considerably smaller; it shrinks to about one half of its overall mean value. That should be one important reason why large-scale farms behave differently in stable situations.

5. Near Wake Verification Results

The first verification case is a high quality IEA/IEC conform onshore near wake measurement at 2 rotor diameters behind an up to date pitch controlled turbine. A reference measurement is installed also at hub height at an appropriate distance on the opposite side of the turbine.

Figure 3 shows verification results for the wind speed deficit in the wake behind the turbine, for the wind speed range 8 m/s to 10 m/s. Accordingly, the graph shows the relative wind speed in the wake versus the relative wind direction. Especially the centre line deficit is calculated very precisely.

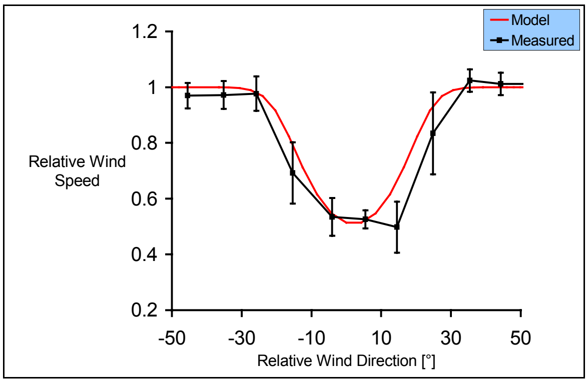


Figure 3: Measured an simulated relative wind speed in the wake of the turbine.

Figure 4 shows results for the same site regarding the turbulence intensity increase, depending on the wind speed. The turbulence intensity increase is considered at the centre of the wake in a 10 degree sector. The average increase is modelled very well, also the decrease towards higher wind speeds. For low wind speeds, the increase is calculated slightly too high, but in terms of mechanical loads and actual relative frequency of these low wind speeds offshore, this is quite unimportant.

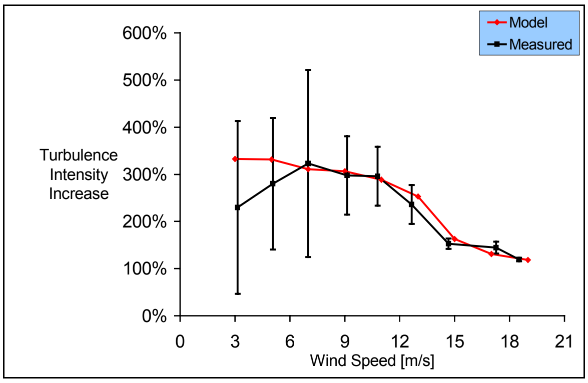


Figure 4: Measured and simulated turbulence intensity increase in the turbine wake.

6. Horns Rev Verification Results

The Horns Rev wind farm is a large offshore wind farm installed close to the west coast of Denmark in the North Sea. It consists of 80 Vestas V80 wind turbines that are arranged in a slightly sheared grid (see Figure 5). The power and thrust curve of the turbine is taken from [1].

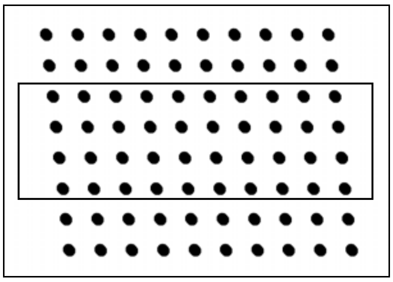


Figure 5: Sketch of Horns Rev wind farm layout.

For this verification, averaged energy output data were kindly provided by Dong Energy. The energy output given for individual turbines is averaged in columns for the four centre rows and then considered relative to the front turbines. The situation considered includes wind from a 30 degree wind direction sector centred at 270 degree, while wind speed remains in the range from 7.5 m/s to 8.5 m/s. In total, 341 10 minute average values were considered in the averaging process. For comparison, wake calculations were also conducted using the Ainslie model [3].

In Figure 6 the measured and averaged power output of the turbines is shown relative to the front turbine versus the row number. It is observed that there is, starting at the 3rd column, a continuous power output decrease. This decrease is not modelled by the Ainslie model. The reason lies in its many simplifying assumptions, its treatment of the superposition and mixing of wakes and in the definition of the initial velocity deficit.

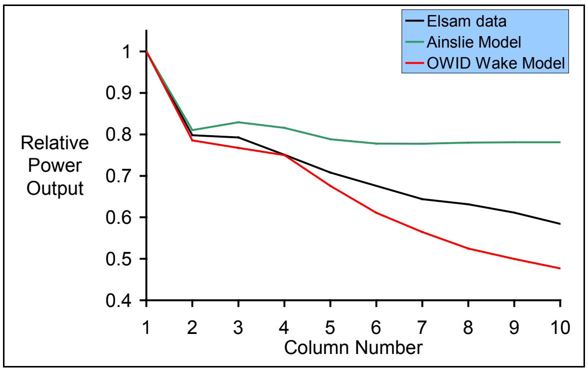


Figure 6: Measurements and calculation results for Horns Rev.

On the other hand, the OWID wake model predicts the power decrease, although it overestimates that effect.

There are ways to modify the Ainslie model so that it is able to predict the power decrease [4]. However, those empirical ad-hoc corrections to the Ainslie model neglect the fact that the exact form of the power decrease depends on a number of external parameters like farm layout, ambient turbulence intensity, atmospheric stability and turbine type.

For the same wind situation, Figure 7 shows verification results related to the cross-stream variation of the energy output in the 5th column. The observed relative increase of energy output for the upper and lower row, which is sometimes called the “edge effect”, is approximated well by the model.

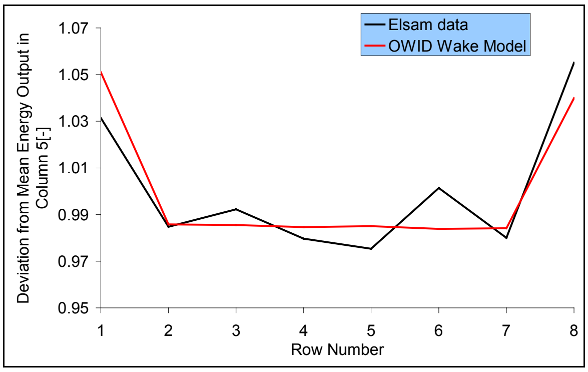


Figure 7: Cross-stream variation of energy output for Horns-Rev (5th column).

7. Conclusions

The most important conclusions of our work can be summarised as follows:

CFD Models are recommended for large offshore farms

For large offshore wind farms one has to use CFD models and cannot make the simplifying assumption of independent single wakes that are superimposed. The scope of application of simple empirical correction models is left for large scale offshore wind farms. It is not any more appropriate to separate into ambient flow and wakes.

Ad-hoc empirical corrections to the Ainslie model are questionable

The modelling of large wind farms with a locally increased roughness or similar corrections [4] is very questionable, because the model and its constants will depend on the specific farm layout and meteorological conditions. It is not expected that reliable large-scale farm optimisations can be done with those correction models.

Overdue consideration of CFD in IEC standards

Lastly, CFD methods must be more considered in IEC standards. This is because these models are now standard engineering tools and one must take advantage of their potential for precision wind modelling. It is possible to have well defined technical standards for the CFD models and their application. Additionally, Round-Robin Tests, that are common in many other technical areas, are well applicable to CFD wake modelling techniques.

8. Acknowledgements

This research is sponsored by the Federal Ministry of Environment, Nature Conservation and Nuclear Safety and by the wind turbine manufacturers GE, Multibrid, Enercon and REpower.

9. References

[1] Jensen, L.E. et al.: Wake measurements from the Horns Rev wind farm, Proceedings of the European Wind Energy Conference, London, 2004.

[2] ELSAM Engineering A/S: SCADA VIEW - A visualisation tool for Horns Rev data, Report, 25.10.2005.

[3] Ainslie, J. F.: Calculating the flowfield in the wake of wind turbines, Journal of Wind Engineering and Industrial Aerodynamics vol. 27; 213-224, 1988.

[4] Schlez, W. et al.: New Developments in Precision Wind Farm Modelling, Presentation given at the German Wind Energy Conference 2006, Bremen.

[5] Zigras, D., Mönnich, K.: Farm Efficiencies in Large Wind Farms, Presentation given at the German Wind Energy Conference 2006, Bremen.

[6] Launder, B.E., Spalding, D.B.: The numerical computation of turbulent flows, Comp. Meth. in Appl. Mech. & Eng., Vol.3, pp269, 1974.

[7] Phoenics Software, www.cham.co.uk.

[8] Van der Pijl, S.P., Schepers, J.G.: Improvements of the WAKEFARM Wake Model, Presentation given at the Workshop on wake modelling and benchmarking of models, Annex XXIII: Offshore wind energy technology and deployment, Billund, September 6-7, 2006.