LARGE OFF-SHORE WINDFARMS: LINKING WAKE MODELS WITH ATMOSPHERIC BOUNDARY LAYER MODELS

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1 INTRODUCTION

One of the main objectives of the EU-5th Framework project ENDOW (Efficient Development of Off-Shore Wind Farms) is to develop a design tool, which calculates the power production of a large off-shore wind farm. This design tool will consist of an atmospheric model coupled with a wake model. An atmospheric model is meant to calculate the free flow in off-shore conditions, taking into account terrain and meteorological effects, but usually no wind turbines and resulting wake effects are included. The wake model is then meant to fill this gap, i.e it calculates the disturbance from a wind turbine on the initial flow, where meteorological and terrain effects are usually not included in the principal wake calculations. Some wake models assume that the outer atmospheric flow remains constant over the farm and as a consequence the flow at infinity returns to the initial flow field again. Other wake models calculate a wake deficit under the assumption of a constant outer flow, and superimpose this wake deficit on a (possibly) varying outer flow.

Within the ENDOW project various candidate atmospheric and wake models are available to be incorporated into the design tool. In order to gain insight into the suitability of the various models and in the way how they can be linked, a questionnaire has been distributed between the various modelling partners. Using the response on the questionnaire an inventory of the different models has been made with emphasis on the items which determine the compatibility of the different models. Aspects, which are of importance for this compatibility are consistancy from a physical point of view, but also consistancy from an informatic point of view (i.e. input/output, platform, compiler etc.).

In the paper the first results from the questionnaire are summarized. Thereto Section 2 gives a brief description of the questionnaire. This is followed by section 3 and 4, in which the response on the wake and the atmospherice models is summarized. In section 5 some first ideas on the interfacing are proposed.

It must be noted that the present inventory is very preliminary: Many answers on the questionnaire are still lacking and the paper is mainly intended to serve as food for discussion within the project group.

2 DESCRIPTION OF THE QUESTIONNAIRE

In the questionnaire, questions are posed on the physics of the models, the input and output of the models, the grid, the platform, compiler, the computational effort, possible convergence problems, as well as many related items.

3 QUESTIONNAIRE, THE WAKE MODELS

3.1 Available wake models

Until February 2002, answers on the questionnare were only available from:

- The Energy Research Center of the Netherlands, ECN: (The WAKEFARM program)
- Robert Gordon University, RGU: (A 3D-NS program)
- University of Oldenburg (UO): (The FlaP program)
- Garrad Hassan and Partners (GH): (WindFarmer)

3.2 Wake cases, Statistics, Analysis of wind farm lay-out

In the response on the questionnaire some confusion became apparent because of the fact that participants apply the wake models differently. Basically, all participants run the wake models for separate cases, i.e. the wake is calculated for a particular (mean) ambient wind speed, turbulence intensity, wind direction, Monin-Obukhov length scale etc. However some additional processing is needed in order to determine the power production of a wind farm.

- A tool is required which determines the wake distances and the multiple wake situations from the lay-out of the wind farm. This information is used as additional input to the wake cases;
- The wake wind speeds should be processed to a rotor averaged wake wind speed from which the power of the turbine is derived using the power curve;
- Then a summation of the different wake cases should be performed, using the appropriate frequency distributions of the free stream conditions, in order to obtain the resultant annual energy production.

The summation, the calculation of power production and the analysis of the wind farm lay-out are essential parts of the design tool, but they are not considered to be part of the wake modelling itself. For the present purpose, the modelling of the separate wake cases will form the basis for the questionnaire. Note that all wake models in the ENDOW project are already integrated with a wind farm model, which determines the required wake cases and sums the wake cases over the appropriate distributions.

3.3 Wake models: Physical description

- ECN: ECN's program is a slightly modified version of the UPMWAKE program [1], which has been developed by the Universidad Politecnica de Madrid. It is a parabolic method in which the turbulent processes in the far wake are modelled through a k-ε model. The wake is initialised at 2D. The near wake is modelled with the standard momentum theory, to which empirical corrections are added.
- RGU has developed a fully elliptic turbulent 3D Navier-Stokes numerical solver (3D-NS) with k- ε turbulence closure based on a previous axisymmetric model [6]. Initial data required to start the 3D-NS calculations are the velocity and turbulence intensity profiles in the atmospheric boundary layer upstream the rotor (ambient atmospheric conditions). The computational domain includes the rotor of the wind turbine(s), which is approximated by means of a semi-permeable disk to simulate the pressure drop across a real rotor disk (thrust).
- UO: The wind farm model FLaP of UO uses an implementation of the wake model proposed by Ainslie, 1988 [2]. It is a two-dimensional (axi-symmetrical) model solving the momentum and continuity equations with an eddy-viscosity closure. The eddy-viscosity is modelled as a combination of contributions from the ambient turbulence of the free flow and the shear generated turbulence in the wake. The wake model starts at a distance of 2D behind the rotor with an empirical wake profile as boundary condition.
- GH: Similar to the UO model

3.4 Wake models: Grid

- ECN: Output is generated in an orhogonal grid:

  - Size in flow direction: 0.25D
  - Size in lateral direction: Approximately D/7
  - Size in vertical direction: Approximately D/7

  Note that grid-sizes in lateral and vertical direction are thrust dependant, because they are related to the so-called expanded diameter.

- RGU: Output is generated in a non-uniform orthogonal grid:

  - Flow direction: D/10 grid length at the turbine locations.
  - Lateral direction: Approximately D/10 at the rotor tip (minimum).
  - Vertical direction: Approximately D/50 minimum close to the ground/sea and D/10 at the rotor tip

  Note: The orthogonal grid is dense close to the turbines and the ground/sea plane

- UO

  - Axi-symmetric 2-dimensional grid
  - Typical grid distances: radial 0.033D, axial 0.5D

- GH

  - Axi-symmetric 2-dimensional grid
  - Typical grid distances: radial 0.1D, axial 0.2D

3.5 Wake models, Input of atmospheric conditions

- ECN: Friction velocity, roughness height (z_0) and Monin-Obukhov length scale L (Or wind speed U(z), turbulence intensity I(z) and L), wind direction. For the wind farm model [4], frequency distributions are needed as well.

- RGU: Wind speed, $U(z_{ref})$, turbulence intensity $I(z_{ref})$ at a reference height and Richardson number or equivalently Monin-Obukhov length scale, wind direction

- OU:

  - In time series mode (case studies): Wind speed $U(z_{ref})$, wind direction, turbulence intensity $I(z_{ref})$, Monin-Obukhov-length scale
  - In climatology mode: wind direction dependent frequency distributions of wind speed, mean turbulence intensity and stability

- GH: Frequency distributions (P,A,k) of wind and ambient turbulence intensity

3.6 Wake models, Input of wind farm lay-out

Several formats are apparent, but basically the positions of the turbines are defined by means of the x,y coordinates of the turbines.

3.7 Wake models, Description of Turbine

Basically all wake models describe the wind turbines by means of diameter, hub height and thrust curve of every turbine (and power curve if power of downwind turbines is to be calculated).

3.8 Wake models, Unequal spacing and different turbines:

The question was posed whether it is possible to model wind farms with unequal spacing between the turbines and with different turbine types. This is possible for all wake models. In ECN's, GH's and OU's wake model, the minimum distance between the turbines should be approximately 2D (due to the initialisation of the wake).

3.9 Wake models, Output

- ECN: For every x-position a file can be generated with data on the y_{lat}, z_{vert} grid points: u,v,w,k, ε,T (Turbulence intensity and turbulent length scales can be derived). Hence the output which is generated are statistical, averaged, data. In the windfarm model [4], a summation to power output is performed, using approprate frequency distributions of the different wake cases;

- RGU: For every cell of the computational domain a file can be generated with data on the x-flowdirection, y_{lat}, z_{vert} grid points: u,v,w,k,ε (Turbulence intensity and turbulent length scales can be derived). Power is obtained indirectly from the rotor averaged wind speed and a power curve.

- UO:

  - Gaussian wind profile and mean I at specified x-position or:

  - (Wind farm model) Wind speed at specified points or;

  - (Climatology mode) Annual mean wind speeds at specified points.

  - Power

- GH: Wind speed, turbulence, energy production

3.10 Wake models: Platform

- ECN: Unix Workstation or PC;

- RGU: Unix Workstation or PC with Linux

- OU and GH: PC with MS-Windows-xx

3.11 Wake models: Compiler

- ECN and RGU: Fortran 77(90)

- OU: Borland Pascal and C++

- GH: C++

3.12 Wake models: Calculational time

- ECN: Order of 1 minute for a quintuple 9.5D calculation on a Unix work station comparable to a 500 MHz PC

- RGU: Order of 12 hours for a single wake calculation on a Unix work station comparable to a 500 MHz PC

- OU and GH: Seconds

3.13 Wake models: Convergence

- ECN: In 99 % of the cases. The program may crash at low wind speeds near the cut-in wind speed in combination with low turbulence intensities.

- RGU, OU and GH: Always

4 QUESTIONNAIRE, ATMOSPHERIC MODELS

4.1 Available atmospheric model

Until February 2002, answers on the questionnaire were received from

- RISOE: Coastal Discontinuity Model (CDM)

- RISOE: Wind Atlas Analysis and Application Program (WAsP)

- RISOE: WAsP Engineering

4.2 Atmospheric models: physical description

- CDM: This is a very simple model based on stability and roughness changes to a wind speed profile moving offshore. An earlier version was described in [3] and more recently it is described in the report to the EC from the POWER project (forthcoming).

- WAsP: see http:// www.wasp.dk/Program_Features.htm. WAsP constitutes a complete analysis and application package. Wind data, whether in the form of a time series or a climatological table, can be transformed into regional wind atlases. Such data may be the users own measurements or general climatological data. The program can be applied directly for estimation of wind climate with wind atlas data from the Danish and the European Wind Atlases and corresponding data collections from other countries - all over the world. WAsP has a number of sub-models for correcting the wind flow behind obstacles, in complex terrain and for roughness changes. The wake model in Park uses momentum deficit theory where the wake is assumed to expand linearly behind the model.

- WAsP-engineering: http://www.waspengineering.dk The mean flow model at the heart of WAsP Engineering has been used at Risoe for more than 15 years (LINCOM). It has been used in many different contexts and a modified version is the central algorithm in WAsP. In addition, WAsP Engineering incorporated various new algorithms: A model for the description of roughness over water (Charnock), a component to model the effect of roughness changes and orography on turbulence, and a procedure to estimate the 50-year storm over complex terrain. The base of this version of the code, giving the influence of the topography on the flow of a neutrally stratified atmosphere, has been extended by Astrup et al (1997) with a model for the influence of varying surface roughness. This extension was based on the assumption that close to the ground the flow is in equilibrium with the local surface roughness, and on a complicated model for the vertical extent of this equilibrium zone. Later the model has been extended to calculate spatial derivatives of the mean wind field, such as the vertical shear dU/dz, which is used in the turbulence modeling. LINCOM is based on an analytical solution in Fourier space to a set of linear equations derived from the normal non-linear mass- and momentum equations for incompressible fluid flows. The linear equations describe the perturbations in velocity and pressure, which the real terrain induces in an equilibrium flow corresponding to a flat terrain with uniform surface roughness. The perturbations caused by horizontal gradients in ground elevation and surface roughness are determined separately and added as a first order approximation to the combined perturbation. Another difference from WAsP is that LINCOM has a more realistic treatment of the inner layer, i.e. the layer close to the ground where perturbations in the turbulent momentum transport are important.

4.3 Atmospheric models: Grid

- CDM: Of the order 100-500 m;

- WAsP: The program has a high-resolution, zooming, polar grid. In the centre of the region of interest the grid resolution is of the order 4m. WAsP can be applied to generate wind fields with varying grids. However, WAsP is a local to mesoscale model - the central assumption is that the regional wind climate is valid for the area of interest which gives its maximum domain of 50-100 km;

- WAsP-eng: The size of the domain should be approximately 100 times the height above the ground in which modelling required. Grid sizes of more than 200 by 200 points requires a very fast computer with vast memory resources and are not recommended. LINCOM calculates the wind vector by Fourier techniques in every mesh point of a rectangular grid. This is appropriate for WAsP Engineering for two reasons. Firstly, to model a wind speed (and fetch) dependent roughness at sea it is necessary to know the wind speed over the entire body of water. Secondly, the turbulence model uses the flow field upwind from the point of interest as input.

4.4 Atmospheric models: Input of atmospheric conditions

- CDM: Either a wind speed profile at the coast or a geostrophic wind speed together with a temperature profile or air-sea temperature difference.

- WAsP: Wind speed and direction

4.5 Atmospheric models: Input of wind farm lay-out

It is reminded that atmospheric models generally do not include the effect of wind turbines. The exception is in the WAsP model, which does include a wake model. The input for this program is basically given by x and y coordinates.

4.6 Atmospheric models: Description of turbine

This question is again only relevant for the WAsP program. This program needs diameter, hub height, power curve and thrust curve (if wake effects are to be calculated).

4.7 Atmospheric models, Unequal spacing and different turbines:

The question was posed whether it is possible to model wind farms with unequal spacing between the turbines and with different turbine types. Again this question is only relevant for the wake model in the WAsP program. In the current version of WAsP, only one wind turbine type can be modelled, with a minimum distance between the turbines of approximately 4D.

4.8 Atmospheric models, Output

- CDM: Usually a wind speed profile, turbulence, Monin-Obukhov length scale and the wind direction.
- WAsP: Wind speed, wind direction distribution
- WAsP-eng: WAsP Engineering 1.0 has five different reports:
  - Extreme wind report: 50 year winds for all sites and all heights.
  - Site report: The mean wind speed for the selected site for all winds and heights.
  - Detailed site report: Various mean flow parameters and turbulence intensities for a single wind at a single height.
  - Turbulence for winds report: Horizontal wind, velocity tilt and horizontal turbulence intensity for all defined winds for a chosen height and site.
  - Turbulence transect report: Wind speed, direction, velocity tilt and the two horizontal turbulence intensities.

In summary the most relevant output of the WasP engineering model for the present purposes is then the wind speed, the turbulence intensity and the wind direction at a particular height.

4.9 Atmospheric models: Platform

- CDM: PC or UNIX
- WAsP: PC
- WAsP-eng: PC Windows 98, Windows NT 4.0 and Windows 2000. Needs Word for the reporting tool.

4.10 Atmospheric models: Compiler

- CDM: Fortran 77- or LF95
- WAsP: Not relevant
- WAsP-eng: Not relevant

4.11 Atmospheric models: Calculational time

- CDM: Depends on the input and model version. Can be fast (minutes) or slow (hours) depending how many iterations are needed. Thus this depends on the number of grids and the type input data available.
- WAsP: Minutes
- WAsP-eng: Minutes, but under all the windows there is some computationally demanding code which really stretches the limits of what most of today's desktop

computers can support. For a normal size project with a full 12 sector extreme wind climate analysis, then the program may well need about 300 MB of memory, and could keep the machine very busy for about five minutes. A machine with at least 128MB physical RAM and a processor of at least 500 MHz is recommended.

4.12 Atmospheric models: Convergence

- CDM: Not always. Sometimes no solution is found for the stability part although it could probably be forced to a reasonable value.

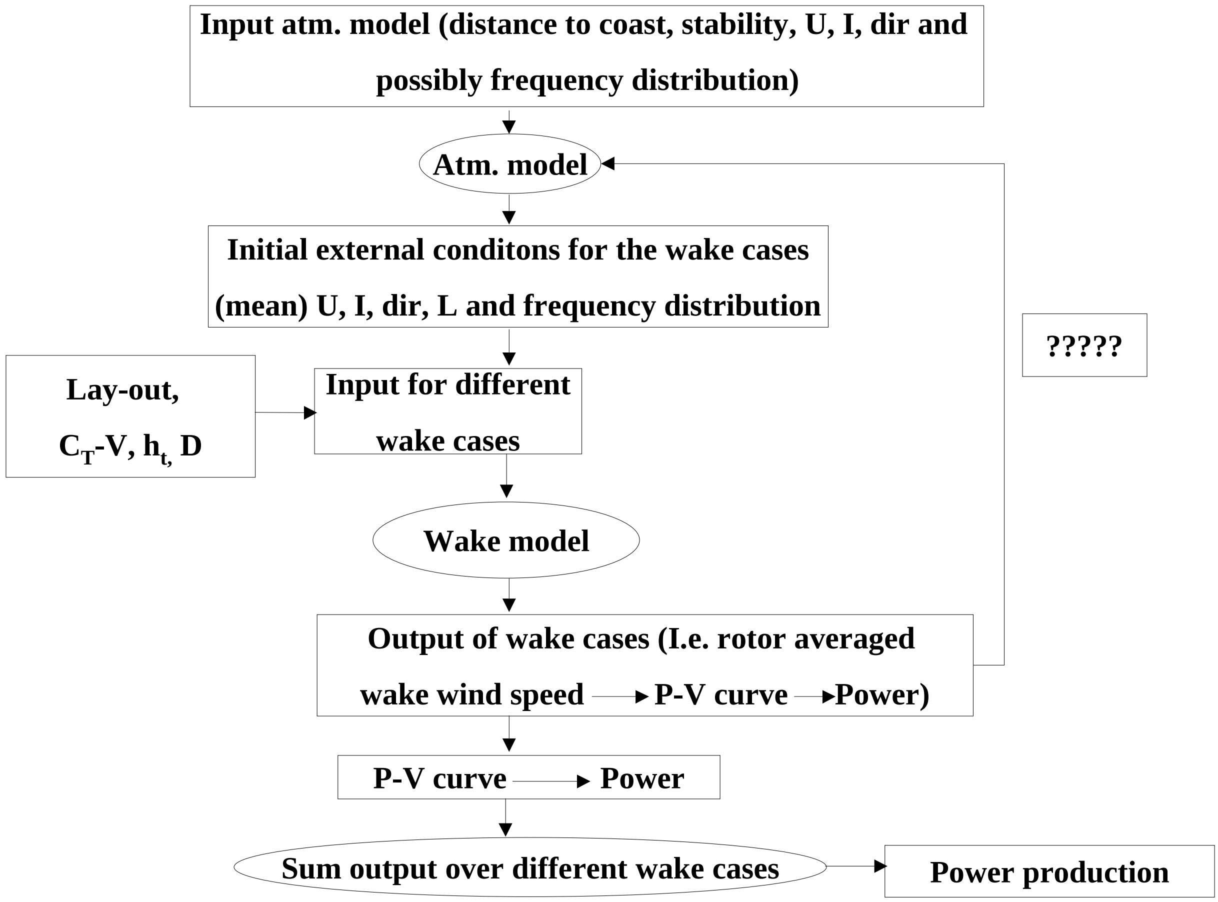
- WAsP: Always.

- WAsP-eng: No definite conclusion on this subject yet, but it seems stable.

5 INTERFACING, SOME IDEAS

An important aspect which has to reminded is that all wake models assume a constant outer atmosphere over the farm, when calculating the wake effects itself (although some participants superimpose the wake deficit on the varying outer atmopsheric flow). As such, the variations predicted by the atmospheric models on a scale, which is smaller than the size of the farm are ignored in the modelling of the wake itself.

It is proposed to make a modular set-up for the design tool. The coupling between the atmospheric model and the wake model is



established by means of input/output files with a prescribed format

The modular approach makes it possible to 'plug-in' different atmospheric and wake models, where only compatibility of the input/output files should be assured.

The most simple coupling is then given by a '1 way route': The output from an atmospheric model is used as input for a wake model. Hence it is only the output from the atmospheric models which should be made compatible to the input of the wake models, i.e. the initial external conditions for the different wake cases to be calculated by the wake models, should be provided by the atmospheric models. Basically the following atmospheric input is needed by the wake models (See section 3.5):

- (Mean) Wind speed at a particular height (or wind profile);
- (Mean) Turbulence intensity at a particular height (or profile);
- (Mean) Monin-Obukhov length scale (for most models);
- (Mean) Wind direction

Note that the frequency distributions of the above given quantities are also required. These frequency distributions should either be provided by the atmospheric models, or the atmospheric models are ran for particular cases which are summed over their frequency distribution. Additional input for the wake models should be provided by a wind farm tool, which translates the lay-out of the farm to the appropriate input data for the different wake cases.

Hence the design tool is merely a script which subsequently calls the atmospheric model and the wake model. It is anticipated that executables of the atmospheric and wake models will be used, in order to overcome, at least partly, the problem of property rights. After the wake cases have been calculated, the power production of the wind farm can easily be calculated by summation over the above mentioned frequency distributions.

However, when the required input data for the wake models are compared with the output data of the atmospheric models (compare section 4.8 with section 3.4) some incompatibilities become apparent. Most wake models require the Monin-Obukhov length scale as input parameter, which is not provided by WAsP and WAsP Engineering. Furthermore, WAsP does not produce a turbulence intensity which is needed by the wake models. The output from the CDM program seems to be most compatible to the required input of the wake models. On the other hand this model may suffer from convergence problems, and it is considered to be much less sophisticated compared to the other atmospheric models. The compatibility between wake and atmospheric models is at present being further investigated, but most likely the atmospheric model will be a combination of the WasP and the CDM model.

Apart from the one-way route coupling, a more elaborate coupling could be formed by an iteration, where information from the wake models is fed into a revised atmospheric run. The appropriateness of this option is at present still investigated. Among others, the possible influence from the wake model results on the atmospheric models needs to be investigated. It is anyhow clear that such coupling will increase complexity and computational effort of the design tool considerably, where on the other hand it is expected that the gain in accuracy is only limited. Therefore such iteration is not the most likely option to be chosen. Nevertheless a sensitivity study on the importance of this feedback will be conducted, using the CDM model and/or the mesoscale MIUU model from the University of Uppsala.

A third option would be to integrate wind turbine effects directly into an atmospheric model. Thereto the windfarm can be considered as a surface roughness [5] or as a "momentum sink". Another solution would be to include the turbines as pressure drops (where the pressure drop is known from momentum considerations). This is by far the most elegant option but also an option which is most time consuming and for which the resources in the present project are not sufficient. This is among others caused by the fact that a multi-nest meshing is needed with a higher resolution near the turbines.

6 CONCLUSIONS

- An inventory has been made of various wake models and atmospheric models, which are used in the ENDOW project. The inventory is based on a questionnaire, which has been distributed between the modelling partners;

- On the basis of the inventory some preliminary suggestions are made about the coupling between the atmospheric and wake models which is needed to develop the design tool;

- The most suitable interfacing is probably a ‘1-way coupling’ in which output from the atmospheric models is used as input for the wake models. Thereto the format of the output/input files should be prescribed. A modular approach is suggested in which different wake models and atmospheric models can be plugged in as executables. Alternatives may be an iterative coupling or the full integration of wind turbines into an atmospheric model. Most likely these options cannot be established within the scope of the project, but a sensitivity study on the importance of the feedback loop will be performed within the project;

- Some of the remaining questions are:

  - How compatible is the output of the atmospheric models to the input of the wake models?

  - Which atmospheric and wake models will be included in the design tool. This will among others depend on the Operating System, under which the design tool will be developed.

  - Property rights of the atmospheric and wake models.

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