SEVENTH FRAMEWORK PROGRAMME
THEME 3
ICT - INFORMATION AND COMMUNICATION TECHNOLOGIES

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Summary:

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Abstract

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1 Introduction

The work in Task 1.2 "Flow and load/power relation" is aimed at calculating the flow field for each subset of Task 1.1, and at deriving mechanical loads and electrical power output from the wind fields and comparing them to the corresponding measurements. More specific, the objective of Task 1.2 is:

- To compare and analyze the measured datasets prepared under Task 1.1 by using the WAKEFARM program and to classify WAKEFARM for specific flow situations (e.g. stability, ambient turbulence intensity) (deliverable D1.2), and
- To develop preliminary maps of wind fields and mechanical loads and energy (deliverable D1.3).

WAKEFARM is the wind turbine wake method of ECN which calculates the decay of the velocity deficit and some other quantities in a row or array of wind turbines. The measured data originates from the ECN Wind turbine Test site Wieringermeer (EWTW) which consists of a row of 5 wind turbines.

This report (deliverable D1.2) presents the comparison between the measured and the calculated data in the row of wind turbines, and the resulting classification of the ability of WAKEFARM to predict quantities in such a row. First, in section 2 the approach is addressed in the form of brief descriptions of the measured data and the calculation method. Next, in section 3 we present the results of the comparison and the classification, and finally, in section 4 we present the conclusion.

2 Approach

2.1 Measured data

The measured data consists of 10-minute averaged quantities obtained under conditions where all 5 turbines in the ECN Wind turbine Test site Wieringermeer EWTW operated normally during approximately 1 hour at combinations of 4 wind speed ranges and 3 wind direction ranges (see figure 1):

- Wind speed at hub height [m/s]:
  (1) 2 - 4 and 4 - 6 (near cut-in)
  (2) 8 - 10 (halfway nominal power)
  (3) 12 -14 (near nominal power)
  (4) 16 - 18 and 18 -20 (high wind speed)
- Wind direction at hub height [deg]:
  (1) 270 - 280 (aligned)
  (2) 180 - 190 (perpendicular)
  (3) 240 - 250 (misaligned)

These confidential and restricted data, which are available via a dedicated ftp site at ECN (aeolus@ftp.ecn.nl), are described in more detail in Brand et al., 2008.

The data originate from the 5 Nordex wind turbines (T5, T6, T7, T8 and T9) and the 3 meteo masts (MM1, MM2 and MM3) at the ECN wind turbine test field EWTW and were measured between 1 August 2005 and 30 April 2008. Data measured at the turbines include standard quantities (electrical power, blade pitch angle, rotor azimuth, generator speed and status), environmental quantities (wind speed and direction), and, at 2 turbines, mechanical quantities (like tower bending moments and blade root bending moments). Meteo data include wind speed, wind direction, and air temperature. Appendix A gives a short description of the EWTW.

2.2 Calculation method

WakeFarm is a wind turbine wake method which calculates the wind speed downstream of a wind turbine. To this end the turbine wake is subdivided into a near wake and a far wake. In the near wake the flow is modeled by an empirical velocity profile. In the far wake, on the other hand, the flow is modeled with the 3D RANS equations in combination with the $k\varepsilon$ turbulence model. The free stream wind field is modeled with the Panofsky-Dutton method, and the wind turbine rotor model consists of an actuator disc with an axial force coefficient which depends on the wind speed. Multiple turbine wakes and different turbine types in wind farms are treated in a straightforward way. A more detailed description of WakeFarm, based on Schepers and Van der Pijl, 2007, is presented in appendix B.

Input to WakeFarm includes upstream wind speed, wind direction, turbulence intensity and Monin-Obukhov length, plus blade pitch angle of the turbines. Calculated quantities include per turbine the wind speed deficit, the aerodynamic power, the axial force at the rotor, and the generator speed. Derived quantities include rotor shaft torque (determined from aerodynamic power and rotor speed) and tower bending moment (determined from axial force at the rotor and turbine hub height)[1].

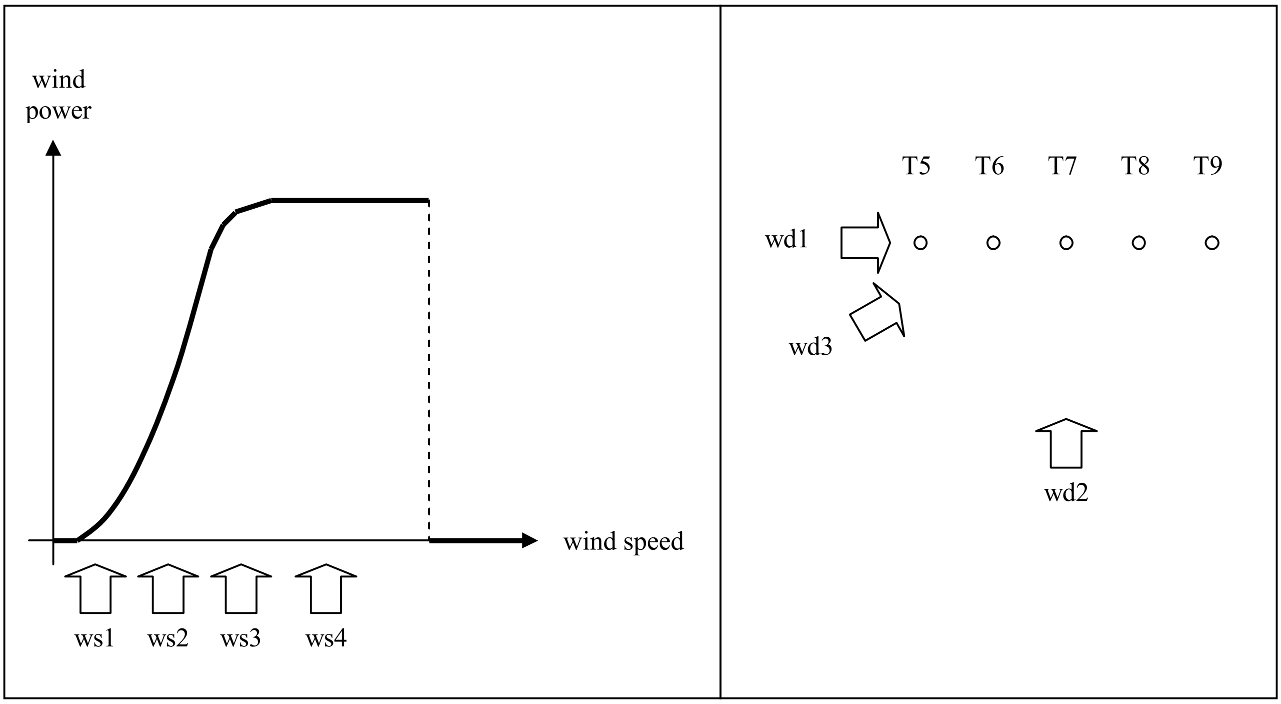

Figure 1 *Description of the wind speed ranges (left) and the wind direction ranges (right)*

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[1] Note blade bending moment is not calculated by WakeFarm

3 Results

3.1 Comparison between calculated and measured data

3.1.1 Inflow aligned with turbine row (case wd1)

The comparison between measurements in the EWTW and calculations with WAKEFARM is based on the wind speed, the wind power, the rotor shaft torque, the tower bending moment and the blade bending moment at the five wind turbines, plus the upstream wind speed at the meteo mast(s). Wind direction is not considered separately because in the calculation wind direction is assumed to be the same everywhere. This section addresses an inflow which is aligned with the row of turbines. In the calculations turbulence intensity and Monin-Obukhov length are set to the standard values for the EWTW, which standard values were estimated from these and other measurements in the EWTW.

Figure 2 shows the wind speed as a function of the distance along the row of turbines, plus the upstream wind speed as measured at the meteo mast(s). The measured wind speed is found to decrease with distance along the row until a minimum is reached at the second or third turbine. Further along the row the measured wind speed is found either to remain the same or to increase somewhat - the data is not clear on that. Apart from the near cut-in case the calculated wind speed is too high and the calculated decay is too gradual.

Figure 3a presents the wind power as a function of the distance along the row of turbines. Apart from the near cut-in case (where power already is low) and the beyond nominal case (where power is nominal), the calculated wind power is found to be too high and the calculated decay too gradual. At the first turbine, on the other hand, the calculated wind power is found to be in agreement with the measured value. The same holds for the rotor shaft torque which is presented in figure 3b.

From figure 4a it is clear that tower bending is poorly calculated: trends let alone values are not in agreement with the measurements. As to the blade bending moment in figure 4b the information is inconclusive because of lacking measured data from another turbine and lacking calculated data.

3.1.2 Approximately 30 deg misaligned to turbine row (case wd3)

In this section an inflow is considered which is misaligned with the row of turbines at an angle of 30 deg. The figures 5, 6 and 7 display that for a given wind speed case the level of a quantity remains the same with position along the row. This implies that measured as well as calculated wakes do not reach another turbine, or, in other words, that each turbine acts as the first one in a row. In agreement with what was found in section 3.1.1, the calculated wind power and rotor shaft torque are in agreement with the measured values.

3.1.3 Inflow perpendicular to turbine row (case wd2)

The case with an inflow perpendicular to the row of turbines was not considered because with an inflow angle of 30 deg already the wakes do not reach another wind turbine.

3.2 Classification of WAKEFARM for specific flow cases

Wind power and rotor shaft torque for the *upstream* turbine in a row are well predicted in the sense that these correspond to the measured values. Wind speed, wind power and rotor shaft torque for the *other* turbines in the row are reasonably predicted in the sense that the predictions are good for near cut-in and near/beyond nominal but are too optimistic and too gradual otherwise.

Tower bending moment on the other hand is poorly predicted in the sense that values as well as trends do not correspond to the measurements. As to blade blending moment the information is inconclusive because calculated blade bending moment is not available.

Together this means that WAKEFARM's ability to predict quantities in a row of wind turbines is limited.

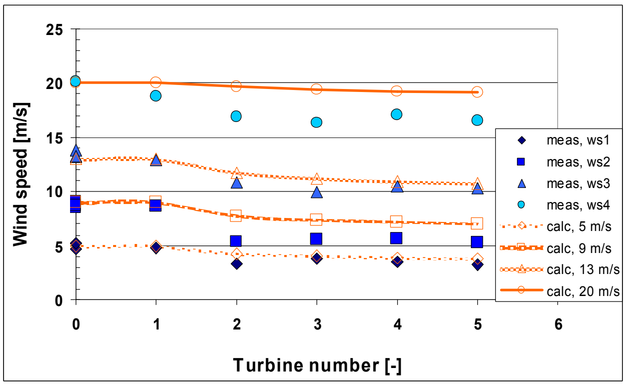

Figure 2 *Wind speed as measured and calculated for the four wind speed cases; inflow aligned with turbine row. Turbine #0 indicates a meteo mast*

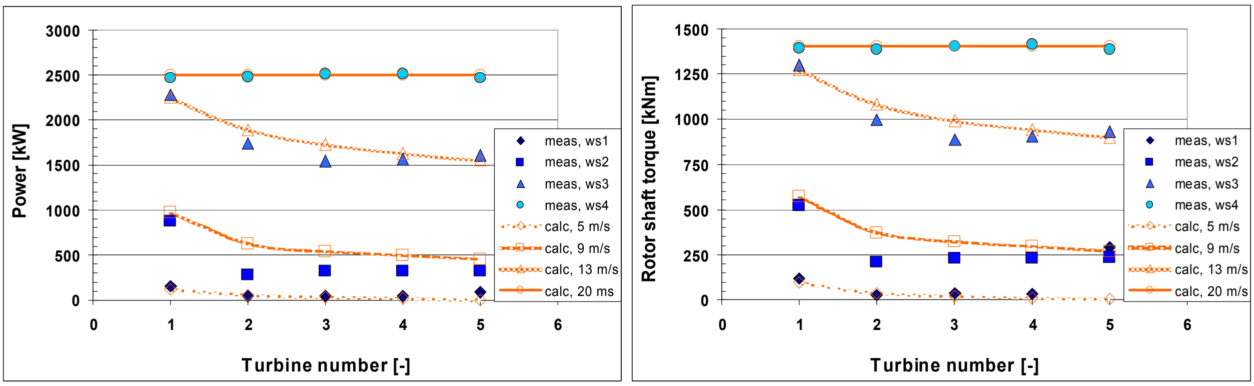

Figure 3 *Power (left) and rotor shaft torque (right) as measured and calculated for the four wind speed cases; inflow aligned with turbine row*

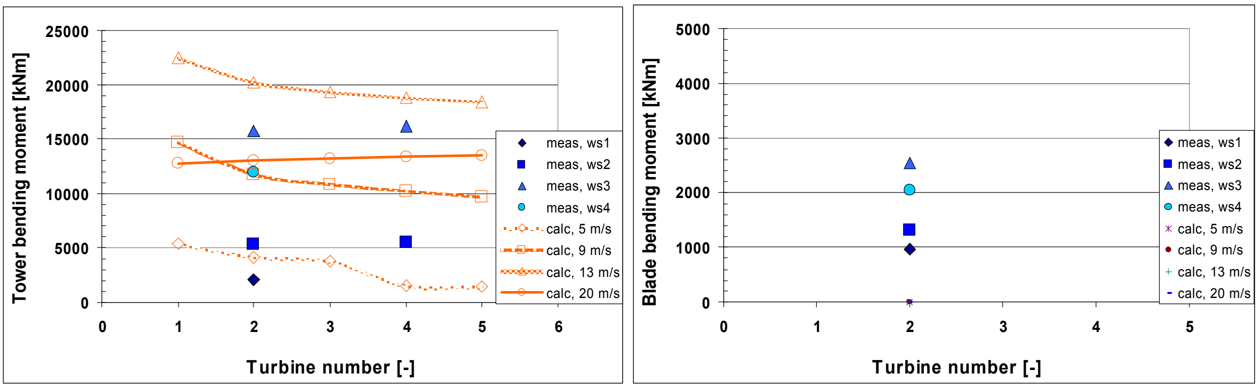

Figure 4 *Tower bending moment (left) and blade 1 bending moment (right) as measured and calculated for the four wind speed cases; inflow aligned with turbine row*

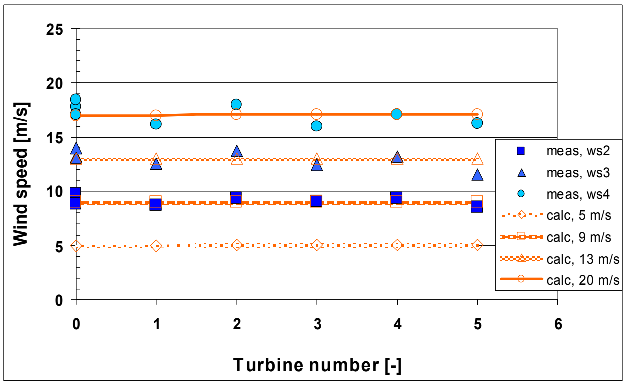

Figure 5 *Wind speed as measured and calculated for the four wind speed cases; inflow misaligned ~30 deg with turbine row. Turbine #0 indicates a meteo mast*

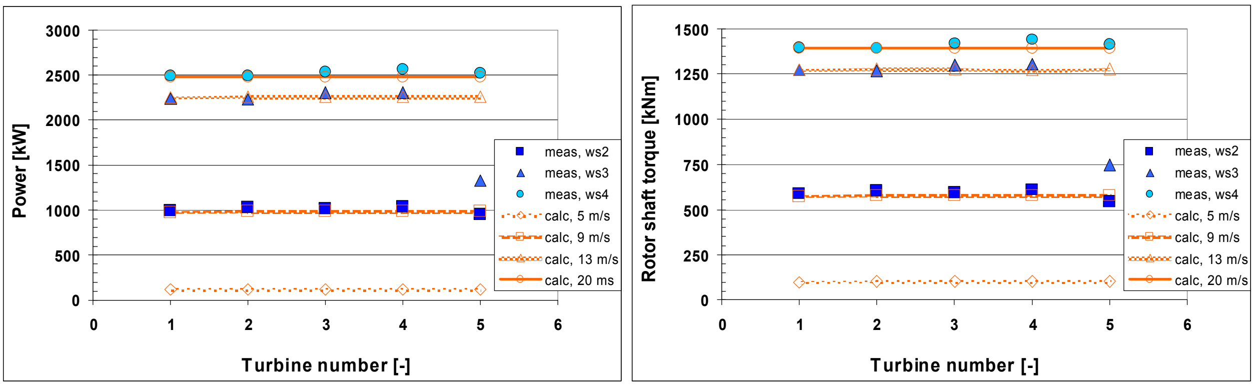

Figure 6 *Power (left) and rotor shaft torque (right) as measured and calculated for the four wind speed cases; inflow misaligned ~30 deg with turbine row*

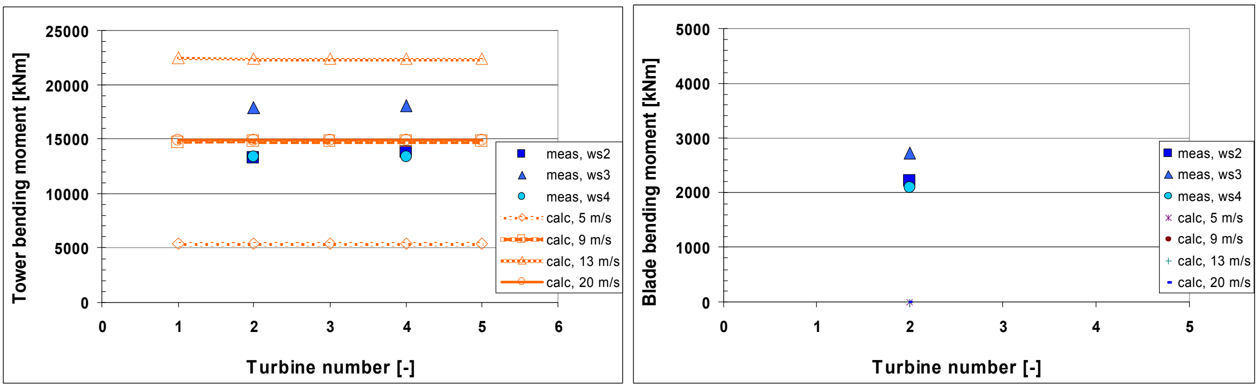

Figure 7 *Tower bending moment (left) and blade 1 bending moment (right) as measured and calculated for the four wind speed cases; inflow misaligned ~30 deg with turbine row*

4 Conclusion

The measured datasets prepared under Task 1.1 have been compared to the outcome of calculations with the WAKEFARM program in terms of 10-minute averaged wind speeds, mechanical loads (rotor shaft torque, tower bending moment, and blade bending moment) and electrical power, and have been analyzed in order to classify WAKEFARM for specific flow cases. It has been shown that wind speed, wind power and rotor shaft torque for the upstream turbine in a row are reasonably to well predicted, but further downstream in the row in general are too optimistic and too gradual. In addition it has been shown that tower bending moment is poorly predicted, and that no conclusions can be drawn on the predictability of blade bending moment.

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Appendix A Description of EWTW

The EWTW consists of 5 Nordex N80 wind turbines with a hub height of 80 m, a rotor diameter of 80 m and a nominal power of 2.5 MW; together with 3 meteo masts with a height of 108 m which are instrumented at various levels between 25 m and 108 m. Figure A.1 shows a map of the location of the 5 wind turbines and the 3 measurement masts in the EWTW, and the tables A.1 and A.2 show their relative distances and directions. More information is available in the public reports on the EWTW, for example Eecen et al, 2005, and Eecen and Verhoef, 2007.

Table A.1 *Relative distances in the EWTW in meter. Source: Report ECN-E--07-041*

[m]	**M1**	**M2**	**M3**	**T5**	**T6**	**T7**	**T8**	**T9**
M1		752	1531	1725	1713	1754	1844	1982
M2	752		1728	1988	1858	1771	1732	1751
M3	1531	1728		282	201	433	722	1022
T5	1725	1988	282		305	610	917	1223
T6	1713	1858	201	305		305	612	918
T7	1754	1771	433	610	305		306	612
T8	1844	1732	722	917	612	306		306
T9	1982	1751	1022	1223	918	612	306	

Table A.2 *Relative directions in the EWTW in degree with respect to North. Source: Report ECN-E--07-041*

[deg]	**M1**	**M2**	**M3**	**T5**	**T6**	**T7**	**T8**	**T9**
M1		277	185	178	188	198	207	215
M2	97		159	156	164	173	183	193
M3	5	339		135	211	251	261	265
T5	358	336	315		275	275	275	275
T6	8	344	31	95		275	275	275
T7	18	353	71	95		95	276	275
T8	27	3	81	95	95		96	275
T9	35	13	85	95	95	95	95	

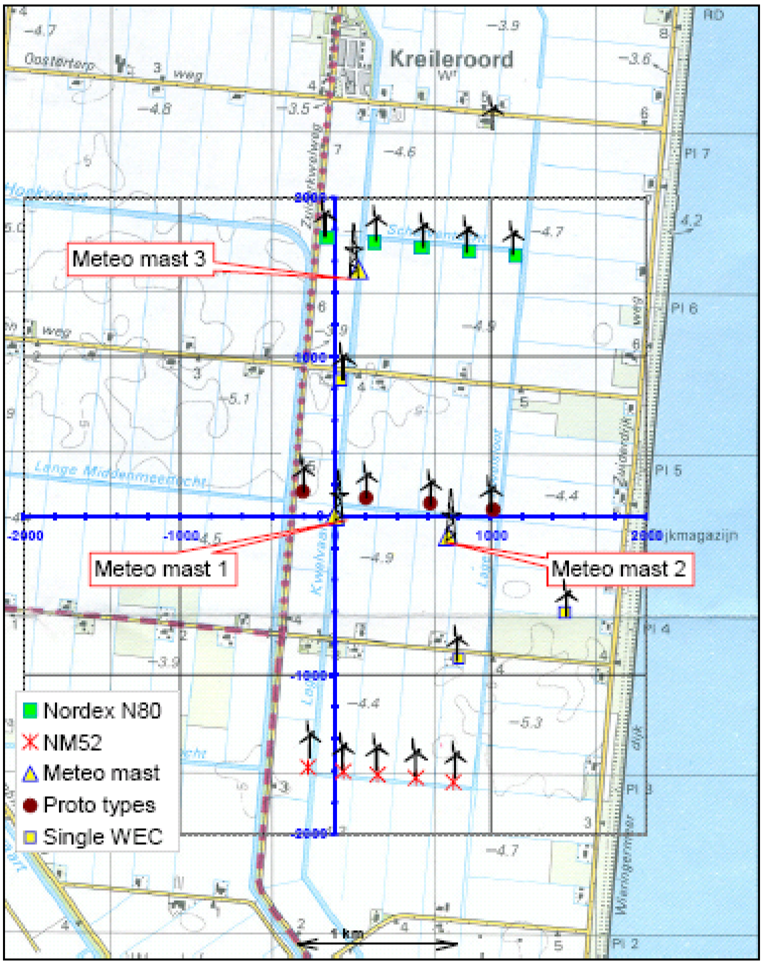

Figure A.1 *Map of the location of the 5 Nordex wind turbines (T5, T6, T7, T8 and T9; from west to east) and the measurement mast (MM1, MM2 and MM3) in the EWTW. Source: Report ECN-E--07-041*

Appendix B Description of WAKEFARM

B.1 Original WAKEFARM modeling

The WAKEFARM methodology originates from Crespo and Hernandez, 1986. It consists, roughly speaking, of a chain of four distinct models:

1) The free stream wind speed,
2) The rotor,
3) The near wake. and
4) The far wake.

The same approach is present in the program FLUXFARM, see Bot, 2006.

The free stream wind field is modeled with the method from Panofsky and Dutton, 1984. It models the axial wind speed and turbulence intensity as a function of height using the friction velocity (u_*), the surface roughness height (z_0) and the Monin-Obukhov length (L), where the ambient turbulence intensity follows from the expression for the turbulent kinetic energy (k) in the ambient flow which is given in Schepers, 2003, and assuming the anisotropy from Panofsky and Dutton, 1984. The incoming wind field is then fed to the rotor. The rotor model consists of an actuator disc with an axial force coefficient $C_{D,ax}$. This axial force coefficient should be known as a function of the wind speed.

Next, the wake behind the turbine is divided into a near wake with empirical velocity profiles, and a far wake where the turbulent processes are modeled with the 3-dimensional Reynolds Averaged Navier-Stokes equations. The RANS equations comprise the continuity equation, three momentum equations in three directions and the energy equation for the adiabatic temperature and contain the unknown kinematic eddy viscosity which is assumed to be proportional to k^2/ε, where ε is the dissipation rate of turbulent kinetic energy k. The RANS equations are closed with an additional transport equation for k and an equation for ε, see e.g. Wilcox, 1998, for details. In this way, the wake profile (i.e. the mean wind speeds in three directions) is calculated. Furthermore the turbulent kinetic energy is calculated from which the turbulence intensities are derived under the assumption that the anisotropy in the wake is similar to the anisotropy in the free stream. The numerical aspects of the WAKEFARM model are discussed in much detail in Henneman, 2003. The solution procedure is based on the SIMPLE method of Patankar and Spalding, 1972. The governing equations are discretized by finite differences on a Cartesian mesh in a rectangular domain and are solved by an ADI method.

A very important simplification is then formed by the neglect of the axial pressure gradient in the equations. This enables the parabolisation of the model by which the calculation effort is reduced considerable compared to a full elliptic approach. For this reason parabolised wake models are applied widely, (see i.e. Rados et al, 2002). The neglect of the axial pressure gradient is however only justified some distance behind the turbine in the far wake. In the near wake this assumption does not hold, since the presence of the rotor leads to a strong deceleration and a large axial pressure gradient. Consequently a separate modeling for the near wake is required. As a matter of fact the near wake is usually excluded from the 'real' wake modeling and it is then covered by an empirical velocity profile which is applied some distance behind the rotor. (In the WAKEFARM program this initial velocity profile is derived from wind tunnel measurements and applied at 2.25 rotor diameters behind the rotor.) As such the near wake is only modeled implicitly in the form of an initial condition for the far wake applied some distance behind the rotor. Starting at this location the flow equations are then solved in a space marching procedure. However, the fact that this initial velocity profile relies on a data fit, puts doubt on the general validity of the modeling.

B.2 Improved WAKEFARM modeling

As mentioned in appendix B.1, a weak link in a parabolised wake method is formed by the near wake model which is usually covered by some empiricism with limited general validity. Therefore an alternative approach was seeked which retains the parabolisation (and the resulting saving of computational effort) but which is based on a more physical sound method. The adopted approach was inspired by the procedure which is commonly followed to solve the boundary layer equations along a flat plate. Such boundary layers can be solved by prescribing a streamwise pressure gradient as a source term to the flow equations, where the streamwise pressure gradient is obtained separately from an inviscid calculation.

In the improved WAKEFARM program, see Schepers and Van der Pijl, 2007, a similar procedure is followed. Hence the streamwise pressure gradient is no longer neglected but it is prescribed a-priori in the form of a source term in the flow equations. The prescribed pressure gradient is calculated from a free vortex wake method under the following assumptions:

- The flow is inviscid,
- The rotor is modeled as an actuator disc with axial force coefficient $C_{D.ax}$, and
- The condition is axisymmetric.

At first sight one might think that such hybrid method, i.e. a combination of an inviscid free vortex wake method and a viscous far wake method is very time consuming. It is then important to realize that the resulting pressure gradient, obtained with the above mentioned free wake method, is only a function of the axial force coefficient. This makes it possible to store the pressure gradient a-priori into a database for a large number of axial induction factors (i.e. axial force coefficients). This database is delivered along with the WAKEFARM program and the program then finds the appropriate pressure gradient from interpolation between the two nearest axial induction factors in the database. This leads to an enormous saving of computational effort, where the near wake is properly included in the flow equations without the need for an empirical wake profile. Instead, a hat-like velocity-deficit profile is prescribed at the rotor-plane, that corresponds to the actual flow induction. The pressure gradient term then causes a further flow deceleration and wake expansion.

B.3 References

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