Improved modelling of wake aerodynamics and assessment of new farm control strategies

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Abstract. In the paper two related subjects are discussed: 1) A new approach is presented to model the wake of a turbine. Keywords in this approach are computational effectiveness and a physical sound basis. The new approach is validated with wake measurements and generally shows a good agreement. 2) A new farm control strategy is explained which aims to reduce the wake effects and the associated power losses in a wind farm. The benefits from this control strategy are assessed with measurement results from ECN’s research farm, EWTW and with calculations from the above mentioned wake model.

1. Introduction

The majority of nowadays wind turbines, both on-shore and off-shore, are located in wind farms, the size of which gets larger and larger.

In these large wind farms, most turbines are located in the wake of one or more turbines by which the flow characteristics felt by these turbines differ considerably from the free stream flow conditions. The most important wake effect is generally considered to be the lower wind speed behind the turbine(s) since this decreases the energy production and as such the economical performance of a wind farm. The overall loss of a wind farm is very much dependant on the conditions and the lay-out of the farm but it can be in the order of 5-10%. Apart from the loss in energy production an additional wake effect is formed by the increase in turbulence intensity, which leads to higher fatigue loads.

With regard to the minimisation of wake effects, two approaches can be distinguished:

• Accept the wake effects as they are and try to optimise the windfarm layout in order to suffer as little as possible from these wake effects.
• Reduce the wake effects using dedicated control concepts. At ECN two concepts are developed which are called 'Heat and Flux' and 'Controlling Wind'.

Both strategies can obviously only be applied succesfully if there is a good understanding of wake effects and with the help of an accurate wake model.

The wake model used by ECN is called WAKEFARM ([2]). This program is a slightly modified version of the UPMWAKE model developed by the Universidad Politecnica de Madrid, see [1].

The UPMWAKE/WAKEFARM model is based on the 3D Parabolized Navier Stokes equations. The model divides the wake into a near and a far wake where the turbulent processes in the far wake are modelled with a k-ε turbulence model. The parabolisation of the Navier
Stokes equations is a widely accepted technique to reduce the calculational time of wake models considerably. However, this parabolisation is only justified in the far wake. The near wake is then often covered with rough empirical approximations, see [4]. In section 2 of this paper, some of these modelling aspects are discussed in more detail. Section 3 then describes a method which has been developed at ECN and which is capable of modelling the near wake in a physical sound way, where at the same time the parabolisation remains possible. Results from the improved code are compared with wind tunnel measurements and with measurements on ECN’s Wind Turbine Test Site Wieringermeer, EWTW, see section 4.

Section 5 then explains the Heat and Flux concept in more detail. Some preliminary measurements at Heat and Flux operation have been taken in the EWTW. In section 6 these measurements are compared with calculations from the improved WAKEFARM program.

2. Original WAKEFARM modelling

The WAKEFARM methodology consists, roughly speaking, of a chain of 4 distinct models: A model for 1) the free stream wind speed, 2) the rotor, 3) the near wake and 4) the far wake.

The free stream wind field is modelled with the method from Panofsky-Dutton [6]. It models the axial wind speed and turbulence intensity as function of height using the friction velocity \( u^* \), the roughness height \( z_0 \) and the Monin-Obukhov length scale \( L \), where the ambient turbulence intensity follows from an expression for the turbulent kinetic energy \( k \) in the ambient flow which is given in i.e. [2] and assuming the anisotropy from [6].

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 function of wind speed.

Next, the wake behind the turbine is divided in a 'near wake' and a 'far wake', where the turbulent processes in the far wake are modelled with the 3D RANS equations. These equations comprise the continuity equation, 3 momentum equations in three directions and the energy equation for adiabatic temperature. The equations contain the unknown kinematic eddy viscosity which is assumed to be proportional to \( k^2/\epsilon \), where \( \epsilon \) is the dissipation rate of turbulent kinetic energy \( k \). The equations are closed with an additional transport equation for \( k \) and an equation for \( \epsilon \), see e.g. [5] for details. In this way, the wake profile (i.e. the mean wind speeds in 3 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 [7]. The solution procedure is based on the SIMPLE method of Patankar and Spalding [8]. The governing equations are discretized by finite differences on a Cartesian mesh in a rectangular domain and 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 calculational effort is reduced considerable compared to a full elliptic approach. For this reason parabolised wake models are applied widely, (see i.e. [4]). 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 modelling for the near wake is required. As a matter of fact the near wake is usually excluded from the ‘real’ wake modelling 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 D behind the rotor). As such the near wake is only modelled 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 modelling.

3. Improved WAKEFARM modelling
As mentioned in section 2, 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 sought 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 WAKEFARM program 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:
- Inviscid flow conditions;
- The rotor is modelled as an actuator disc with axial force coefficient $C_{D,\text{ax}}$;
- Axisymmetric conditions

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 realise 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.

4. Comparison of WAKEFARM results with measured data
In this section, results from the updated WAKEFARM code as described in section 3, are compared with wind tunnel measurements and with field measurements. The wind tunnel measurements are taken by Garrad Hassan and Partners on a model rotor with a diameter of 27 cm, under conditions which more or less represent the atmospheric boundary layer, see [10] for more details. The results of the vertical wake deficits and added turbulence at 5D behind the model turbine are shown in the figures 1 and 2. The figures 3 and 4 show the results in double wake, where the second turbine is placed 7.5 D behind the first turbine. Calculations are shown for the original WAKEFARM version (with the empirical initial velocity profile as described in section 2 and for the new WAKEFARM version as described in section 3. Generally speaking the differences between the two WAKEFARM versions are small where both WAKEFARM versions reproduce the experiments well. As a matter of fact the new WAKEFARM version does show a slightly better agreement with the experiments but the main importance of the modifications lies in the wider general validity of the modelling.

In figure 6 a comparison is shown with wake measurements which are taken in ECN’s Wind Turbine Test Site Wieringermeer, EWTW. The EWTW, see figure 5 and [9] consists of 4
prototype locations for commercial testing (the 'southern' row in figure 5) and a research farm which consists of five 2.5 MW turbines (the 'northern' row). The research turbines are located in a line set-up with a mutual distance of 3.8 D. Furthermore a 108 m high meteorological mast is available with sonic anemometers at hub height ($h_t$) and $h_t +\sim 0.7$ R. This meteorological mast is located at 2.5D behind the most westerly turbine and 3.5D behind the second turbine (see figure 5). Figure 6 shows the resulting wake profiles at 2.5D and 3.5D (at hub height as function of wind direction) in comparison with the WAKEFARM results (Note that results from the improved model are shown only). The figures show a peculiar discrepancy at 2.5D where the measured deficit is very constant and the calculated deficit is more or less Gaussian. It would be expected that this deviation is ‘transferred’ to more downstream positions, but it is then surprising to see a good agreement at 3.5 D behind the turbine.

Figure 1. Single wake: Vertical wake velocity profile measured at 5D behind a model turbine in the wind tunnel

Figure 2. Single wake: Vertical added turbulence intensity profile measured at 5D behind a model turbine in the wind tunnel

5. Heat and Flux concept

The work on the Heat and Flux (H+F) principle builds on previous work on the patented concept from [3]. In the Heat and Flux concept, the pitch angle of the upstream turbine(s) in a farm is set to a less optimal value. This obviously reduces the performance of the upstream turbine but it also reduces the axial force coefficient and the resulting momentum loss in the wake. The loss in performance on the upstream turbine may then be compensated by the reduced wake effects and as such the combined performance of both the upstream and downstream turbine can be increased. This is illustrated in figure 7. The figure shows the power coefficient and axial force coefficient as function of the axial induction factor, according to the well known relations:

$$C_{D,ax} = 4a(1 - a)$$

$$C_P = 4a(1 - a)^2$$

Since the axial induction factor decreases with pitch angle, the figure can also be interpreted as the $C_P$ and the $C_{D,ax}$ as function of the minus pitch angle. The figure shows the $C_P$ to be optimal (i.e. maximum) in normal operation but this high value of $C_P$ is accompanied by a high value of $C_{D,ax}$ and considerable wake losses. In the Heat and Flux operation the pitch angle is decreased. This obviously leads to a lower $C_P$. However, the behaviour of the $C_P$ is very flat.
Figure 3. Single wake: Vertical wake velocity profile measured at 5D behind a model turbine in the wind tunnel.

Figure 4. Single wake: Vertical added turbulence intensity profile measured at 5D behind a model turbine in the wind tunnel.

Figure 5. ECN wind turbine test site EWTW, where the northern row of wind turbines consists of the research farm.

Figure 6. Single wake: Calculated and measured velocity deficits in EWTW at 2.5D and 3.5D (free stream wind speed between 10 and 12 m/s).

around its optimum by which the loss in $C_P$ is limited. On the other hand, the $C_{D,ax}$ – a curve shows a steep behaviour by which the $C_{D,ax}$ (and the resulting wake effects) decrease strongly with pitch angle. The lower wake effects may then compensate the slight loss in performance of the upstream turbine and increase the overall performance. Moreover, as a side effect, the increase in turbulence intensity in the wake, will be reduced.

In order to find a more firm confirmation of the potential for Heat and Flux, optimisations have been carried out with the program Fluxfarm ([11]. The Fluxfarm program is based on the WAKEFARM program, see section 3, and it contains an optimisation module to find the
optimal settings for Heat and Flux. The optimisations were performed on the EWTW wind farm, which is described in section 4. The difference in energy production of the EWTW between the normal operation and the resulting optimal Heat and Flux operation is presented in figure 8. The results are given as function of wind speed and the misalignment between wind farm line and wind direction. Most important is that these results do show a gain in energy production indeed. Furthermore the figure shows a rapid decreasing gain with wind speed: The gain is in the order of 40% at the lower wind speeds and it reduces to zero at above rated conditions. Furthermore the gain decreases with the misalignment between wind direction and farm line, but it is encouraging to see that even a 12 degrees misalignment still produces a gain.

It must be noted that the large relative increase at low wind speeds contribute little to the absolute overall gain: It is mainly a result of the fact that the H+F operation keeps the wake wind speeds just above the cut-in wind speed, where they fall below the cut-in wind speed at normal operation.

The overall gain is then found from the summation over all wind speeds and wind directions. As such it is very much dependant on the wind speed and wind direction distribution but it will generally be 0.5% or even less. At first sight, such gain may appear disappointing but most important is that this gain can be reached at very little additional cost. As a matter of fact, the only costs lie in the modification of the control algorithm, which should be made wind direction dependant and which should assure that the H+F settings only appear at wake conditions (in non-wake conditions, the H+F settings lead to a loss in production). In view of the uncertain and fluctuating wind direction this obviously requires some safety margin in the wind direction. As already mentioned above, a 12 degrees misalignment still produces a gain in energy production.

6. EWTW Measurements on the Heat and Flux effect
In the previous chapter an overall gain of 0.5% is mentioned. One might think that such low number is difficult to verify under atmospheric conditions. It should be realised however, that this overall gain is a summation over all wind directions, where the verification only needs to consider the ‘wake wind directions’. Under these conditions the much higher (and measurable) gain from figure 8 is expected. Since the power production at the ‘non-wake wind directions’ remains unaffected, a gain at the ‘wake wind directions’ then anyhow leads to an overall gain.

In order to find an experimental validation of the Heat and Flux concept, some preliminary measurements have been performed in ECN’s Wind Turbine Test Site EWTW. Thereto the
upstream turbine in the EWTW has been operating alternately under the Normal Operation (NO) for 12 hours, followed by 12 hours under the Noise Reduced Operation (NRO). These measurements were carried out in the period from August 1 until September 14 2006.

The NRO is a standard operational mode for the turbines in the EWTW by which these measurements could be easily accomplished without the need for a control adaptation. The NRO means an increase in pitch angle and a decrease in rotational speed which altogether decreases the axial induction factor far below the optimal value as calculated from the Fluxfarm program in section 5. As such the NRO operation should be considered as an ‘exaggerated’ Heat and Flux Operation.

Furthermore it should be realised that the Normal Operation was applied during daytime and the NRO was applied during nighttime. As such the two different modes were active at two different distinct daily periods. This is important to keep in mind, since it will have its effect on the dominating atmospheric conditions, such as the atmospheric stability.

The results are presented in the figures 9 and 10. They show the measured power binned versus wind speed. In figure 9 the results for the upstream turbine is given, where figure 10 shows the summed power of the first two turbines in the row. Figure 10 also indicates the standard deviation and it shows a comparison with calculations from the WAKEFARM program, described in section 3. It should be noted that this comparison requires a translation from wake wind speeds to power data. This translation has been obtained from the rotor averaged wake speed using the ‘standard’ power curve. It is then implicitly assumed that this rotor averaged wake speed is representative for the free stream wind speed in the power curve measurement. Figure 9 shows that the Noise Reduced Operation leads to a clear reduction in power of the upstream turbine. However, in figure 10 this loss has almost disappeared! This then indicates that the losses from the NO on the upstream turbine are compensated by the reduced wake effects which asserts the Heat-and-Flux hypothesis. As mentioned before, the Noise Reduce Operation mode is a sub-optimal Heat-and-Flux setting. The fact that even at these sub-optimal settings a neutral power production seems possible gives rise to the believe that a production gain is possible at more optimized settings. This expectation is strengthened by the good comparison between calculations and measurements in figure 10. The good agreement gives confidence in the optimisations presented in section 5 since these optimisations are based on the same calculational model.

It should be emphasized however that these conclusions are still very premature. First it can be mentioned that the spread in results is relatively large (and in the same order of magnitude as the difference in production between NRO and NO) It should also be mentioned, that the atmospheric stability is left out of the analysis, although the two modes were active at two different distinct daily periods.

At the time of writing the paper, the optimised settings from section 5 have been implemented in the EWTW turbines and an extensive measurement program is carried out. However, the number of data is still too limited to draw firm conclusions.

7. Conclusions
The WAKEFARM model is used at ECN to compute the wake flow behind a wind turbine. In its original formulation the WAKEFARM model is inapplicable in the near-wake region, due to it’s parabolic nature. Instead, the near-wake effects are taken into account by prescribing a modified velocity profile at a certain distance behind the rotor. This velocity profile was tuned on experimental data. The empirism in this model puts some doubt on the general validity of it. Therefore the model has been improved by implementing a physical sound near wake model in the WAKEFARM program where at the same time the parabolic nature (and the resulting saving in computational effort) remained. Thereto force terms (i.e. pressure gradients) have been calculated from a free wake model and stored into a database which is delivered along
The actual force terms are then found by interpolation in the database and prescribed as source terms to the governing equations.

Comparison with measurements showed that the modified WAKEFARM model performs at least as good as the original model. The fact that no tuning is needed anymore gives the model a much wider general validity.

The ‘Heat and Flux’ concept proposed in [3] aims to optimize the yield of a wind farm by operating the upwind turbines below their optimum in order to reduce the wake effects. Calculations on ECN’s Wind Turbine Test Site EWTW show the possibility for a substantial gain at lower wind speeds and for wind directions along the ‘central wake line’. The overall gain (averaged over all wind speeds and wind directions) will be limited to < 0.5%. This is still worthwhile since the gain can be reached at almost no additional costs. Preliminary measurements on the EWTW confirm a potential for a Heat and Flux gain indeed. However, this validation was only based on the performance of the first two turbines in the row at conditions which are expected to be non-optimal. As such a much more thorough investigation at different configurations and layouts is needed to draw definite conclusions. Such investigation is currently carried out at ECN.

8. References
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