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Advanced wake model for very closely spaced turbines

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Abstract

Accurate determination of array losses for very close turbine spacing is increasingly required as there is pressure to build more compact wind farms to optimise land use. Below a certain spacing, the equations typically used in commercial wake models become invalid because these models primarily describe the free-stream expansion of the wake. Free-stream expansion of the wake does not occur when the turbines are close together, and hence conventional wake model limits are between 2 and 4 rotor diameters (D) for the in-row turbine spacing.

This paper presents an improved model for the wakes downstream of such very closely packed lines of turbines. The model is based on a well-proven eddy viscosity wake model but additionally takes account of the specific type of overlap and merging of adjacent wakes which is expected to occur with tight spacing. This merging is postulated to lead to reductions in horizontal velocity gradient, reductions in added turbulence intensity in the wake and changes in the velocity profile across the wake.

The new model is validated with data from operating wind farms having a range of in-row turbine spacings down to 1.1 D. It is based on theoretical considerations, combining empirical solutions with sophisticated modelling. The pragmatic nature of the approach maximises the practical potential of the method and its usefulness to the industry.

Introduction

In modern wind farms, the decrease in energy yield or increase in array losses arising from wake effects ranges typically from 5 % to over 15 % depending on the wind farm layout. Knowledge of turbine wakes and their interaction is essential not only to predict the reductions in wind speed and corresponding yields but also helps to assess the additional loading on the turbines generated by the increased turbulence in the wakes.

The study of wakes has led to models of varying degree of sophistication, as outlined in the next section. Dominant in industrial applications are models based on fundamental physical equations but including empirical assumptions to simplify the problem to an extent that it can be solved in an acceptable timeframe. These models are included in wind farm design software and have been proven to demonstrate good agreement with experimental and operational data in most situations [1-3]

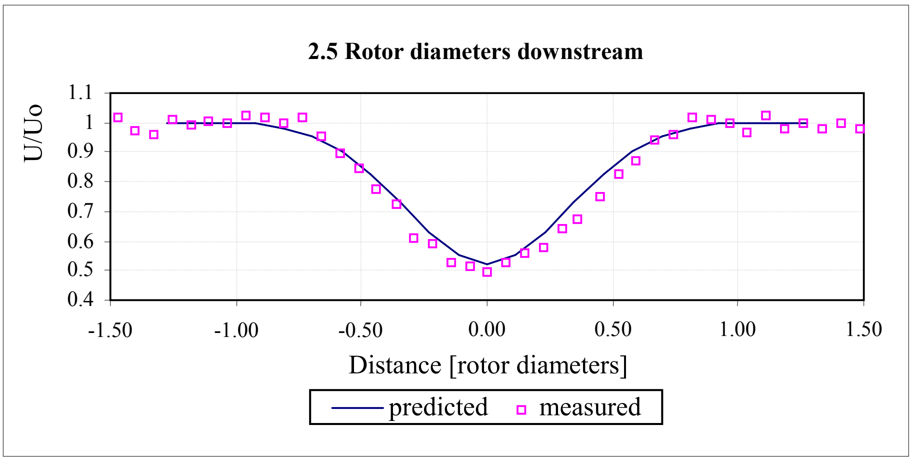
Amongst over 30 GW of wind farm capacity analysed by Garrad Hassan over the past 21 years, a small number of the wind farms have stood out because of difficulties with modelling their annual energy yield. Unlike the majority of wind farms built worldwide, these wind farms comprised multiple rows of very closely spaced turbines. Such wind farms are typically in locations with either uni- or bi-directional wind regimes. Mostly these regimes arise from thermally induced winds combined with complex terrain effects. Typically the wind in these wind farms is from one direction during one time of the day and from 180 degrees opposite for the rest of the day. Wind from other directions occurs hardly at all. Under such circumstances, wind farms are often designed with very closely spaced rows across the main wind direction. Inter-turbine distances from 1.1 to 2.5 times the rotor diameter (D) are typical. Along-wind inter-row distances are typically 6 to 9 D.

The advanced wind farm design software tools that are commonly applied to model wind farm wake losses did not reproduce the yield of such closely spaced wind farms: the observed wake losses were much higher than those modelled. From practical experience, Garrad Hassan was aware of this problem and made significant downward adjustments of yields forecast. Whilst these pragmatic, experience-based adjustments satisfied the immediate need for accurate predictions, a better understanding and an improvement of analysis tools was required and this requirement stimulated the improvement of the model.

In this paper, the development of the modified wake model is described. Comparisons are then made with the wakes in closely spaced wind farms where production data were available, and examples are presented of simulated wind farms with varying turbine spacing.

Wake modelling

Modelling methods for wind turbine wakes and wind farms have been discussed recently by Crespo et al. [4]. In the ENDOW project, their performance has



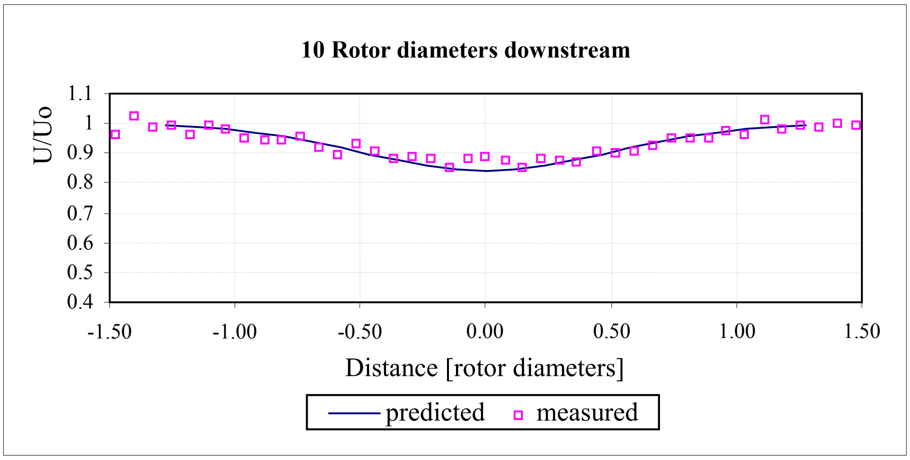


Figure 1 Comparison of the GH Eddy Viscosity Wake Model with wind tunnel measurements for a single wake

been compared with respect to offshore application [1]. While complex field models at one end of the spectrum try to model the wake of wind turbines on the basis of the fundamental equations of motion, at the other end of the spectrum kinematic models use empirical approximations to describe the wake.

Complex field models calculate the complete three-dimensional flow at regular intervals in the flow field, combining the wakes from the turbines with the flow over the terrain. Whilst these models give a good understanding of the wake development, they are computationally demanding and are not a practical solution for wind farm engineering. Empirical models are less computationally demanding. They are characterised by self-similar wind speed profiles and simple assumptions for the expansion of the wake. The mixed models commonly used in industrial applications combine an efficient numerical solution of the basic flow equations with empirical assumptions to reduce the calculation time. Typical simplifications are rotational symmetry, a wake development that is independent of the structure of the boundary layer, and a wake expansion that depends on the ambient turbulence intensity.

Figure 1 presents a sample from the Garrad Hassan Eddy Viscosity Model validations [2]. Validation studies have included single and multiple wake comparisons with wind tunnel measurements and numerous detailed analyses of operational wind farms [3].

Published data and investigations concerning wakes with a distance of approximately 2 D or less behind a wind turbine rotor are extremely rare [1, 5-8]. Even fewer data are published from the wake of two or more adjacent turbines with an inter-turbine spacing of less than 2 D [9-11]. To improve general understanding and prediction accuracy for these particular cases, Garrad Hassan has undertaken an internal re-analysis of several closely spaced wind farms.

Structure of the wake

The wake has a high level of turbulence which can be attributed to three main sources: the ambient turbulence, turbulence generated by the shear due to the momentum gradients in the wake itself and turbulence generated by the rotor. The relative

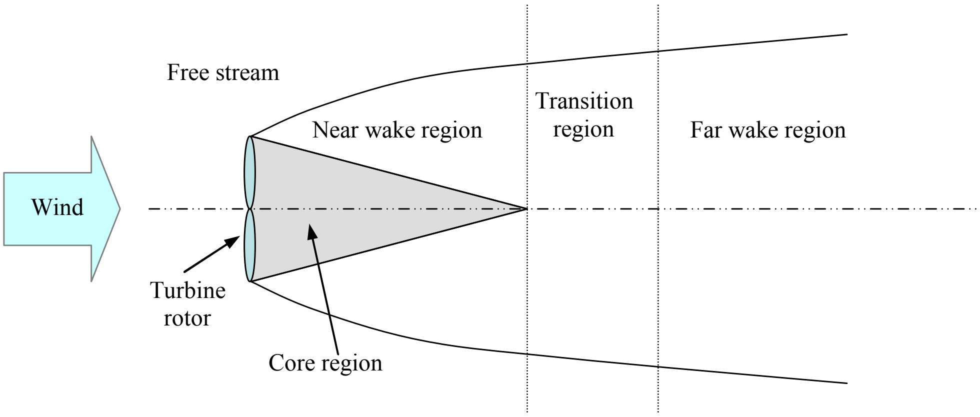


Figure 2 Wake structure with core, near, transition and far wake regions

dominance of these sources and the characteristics of the wake change with distance downwind.

Figure 2 illustrates the different regions of a wake using the definitions introduced by Lissaman [12]. In the core region constant velocity is assumed. The large velocity gradient at the edge of this area together with the tip vortices generate the additional turbulence in the wake [13]. This additional turbulence, in conjunction with the ambient turbulence, erodes the core area. The end of the core region also defines the end of the near wake region. The length of the near wake region typically varies between 1 D and 3 D. The transition region is small and it can be concluded that downstream turbines in the close spaced array situation being considered here are located in the far wake.

In the far wake turbulence is no longer generated by the rotor. The ambient turbulence is the dominant driver for momentum transfer. As the wakes propagate downstream, mixing of the wake with the ambient flow disperses the momentum deficit and restores the velocity in the wake to match that of the free stream. In a close spaced wind farm, the wakes overlap with one another at an early stage in the wake propagation which reduces the shear generated turbulence and therefore momentum transfer. This impedes the wake recovery and hence increases wake losses. This matter is discussed in more detail below.

Wake profile

Lissaman [12,14,15] pioneered the transfer of profiles describing turbulent jet flows [16] to their application in describing wind turbine wakes. Using the phenomenological description of the wake regions above Lissaman postulated three profiles for the wake and the transition between them.

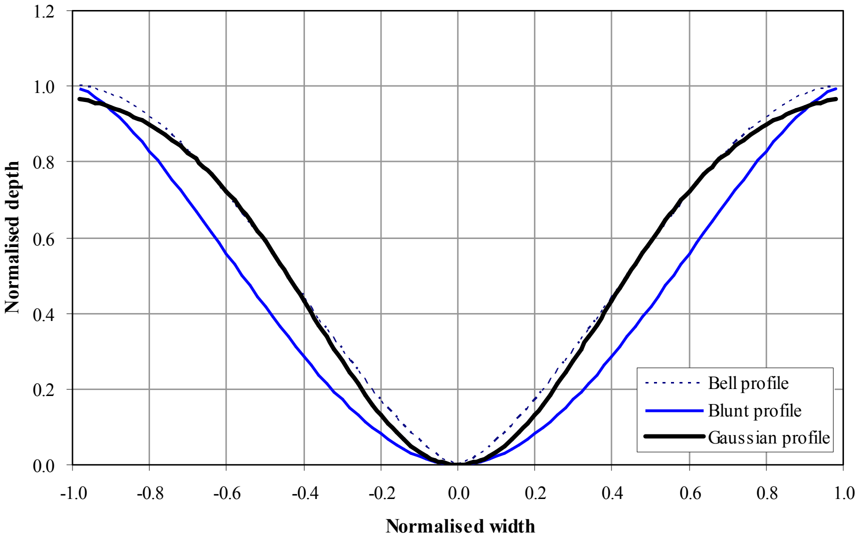


Figure 3 Lissaman bell, Lissaman blunt and Gaussian wake profiles

For the core region he selected a box shaped profile, for the near wake and the end of the core he used a blunt bell shaped profile and for the far wake region the profile has a bell shape similar to a Gaussian profile, as shown in Figure 3. The centreline deficit was determined by the momentum integral which represents the axial momentum deficit extracted by the turbine. The wake width was described by a simple set of empirical rules, which present the Achilles' heel of the model because at the time very little experimental data were available.

Ainslie [17] first proposed the prototype of the model that today is used in almost all industrial software packages for wind farm design. The model starts with an empirical description of the centreline wake deficit at 2 D behind the rotor disk. At this point the momentum integral and the assumption of a Gaussian profile result in a computed wake width. The downstream development of the wake is then based on a numerical solution of the fundamental equations using an eddy viscosity turbulence closure. A comprehensive study was undertaken by Hassan [18] which allowed systematic validation of Ainslie's approach.

The strength of the Eddy Viscosity model proposed by Ainslie is its parameterisation with the ambient turbulence and that the further wake development is calculated based on first principles. This makes its range of safe applications in the wind industry superior to older models that are calibrated and applicable only to a particular scenario.

Phenomenological discussion

If the distance between two adjacent turbines is sufficiently large the overlapping wakes of these turbines can develop independently from each other. As the turbines become more closely spaced the wake deficits start to overlap at some distance behind the wind turbines.

Where the wakes overlap for large inter-turbine distances between two or more adjacent turbines, adding the overlapping velocity deficit would lead to high wake losses at some distance downstream. As a consequence larger velocity gradients would occur which lead to a faster wake decay. However, experimental evidence shows that such joint wake effects are best represented by just the larger of the two deficits [10].

If the in-row turbine spacing is reduced then the turbine wakes do not develop independently. Two or more adjacent wakes do not just overlap, they merge into one. While the momentum transfer in the vertical direction still takes place, the merging of the wakes results in a changed situation for the horizontal direction:

- The increased velocity gradient vanishes because the neighboring wake causes a deficit of similar magnitude. This means the decay of the velocity deficit is reduced and the superposition of the wakes leads to a much larger deficit than before.
- The missing horizontal velocity gradient also leads to a reduction in added turbulence intensity in the wake.
- While independent wakes develop over a distance into a Gaussian velocity profile this is not true for the merged wakes of adjacent turbines. A blunter profile shape is expected.
- The expansion of the wakes will be reduced due to the reduced possibility of wind speed recovery in the horizontal direction.

New model design

Strictly speaking, losing the independence between the developments of independent wakes and breaking the rotational symmetry requires a numerical calculation of the fundamental equations over a domain that encloses all wakes of a row at the same time. This however would lead to unacceptable computational requirements. For this reason it has been decided to modify pragmatically the independent solution for the single wake to take the adjacent wakes into account. A new model has been implemented to this effect with the following changes:

- For close spaced turbines the momentum deficit is allowed to add up cumulatively
- The added turbulence is reduced in the wake
- The Gaussian profile is replaced by the Lissaman blunt profile (Figure 3)

The last of the three changes leads to a dilemma: ideally the Gaussian profile would be maintained for the vertical direction and only the horizontal component changed. The centre wake deficit however is calculated on the basis of a Gaussian profile from the axial momentum drawn by the turbine. The equivalent calculation for a blunt profile of the same width would result in a lower centreline deficit that could not be matched at the centreline with the deficit of the Gaussian solution. As a pragmatic choice the centre wake deficit has been kept as calculated by the original model while replacing the Gaussian profile by a blunter profile. This results in an overall higher momentum deficit, which may serve to compensate somewhat for the reduced wake expansion postulated earlier.

Comparison with operational data

Operational data from several close spaced wind farms have been analysed. Periods have been excluded during which the wind direction changed considerably. Data have only been considered when all relevant turbines of a wind farm were operational. The wind direction was considered to be perpendicular to the row. The bin widths for the direction and wind speed were 5 to 10 degrees and 1 m/s respectively.

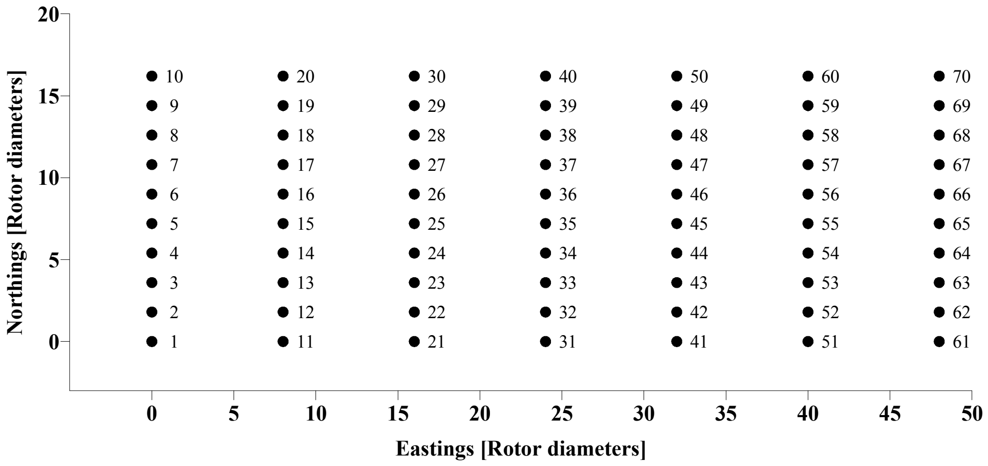


Figure 4 Example of a typical close spaced wind farm with spacing of approximately 1.8 D within the rows oriented from south to north and 8 D from row to row from west to east.

In **Figure 4** a hypothetical but typical wind farm layout is defined with 7 rows of 10 turbines each. The inter-turbine cross wind distance is around 1.8 D and the distance between rows around 8 D. For this paper the wind is assumed to blow from the west and the turbine numbering in each row runs from south to north.

Due to the commercially sensitive nature of the information the wind farm operational results presented have been disguised. The data presented are limited to giving a summary of the experimental results because they are of academic interest as well as of general interest to the wind energy community. The data presented in **Figures 5 to 8** are measured and modelled power outputs for a number of wind farms under investigation projected to our hypothetical example wind farm. Each figure is an example of results encountered in rows 1 to 7 of a typical closely spaced wind farm. More detailed results have been presented in a previous paper [19]

The data have been selected for a 5 to 10 degree direction sector approximately perpendicular to the turbine rows. For all operational cases, a nearby free stream mast has been used to indicate the wind speed when selecting concurrent operational records. The mean wind speeds considered are between 10 m/s and 12 m/s. The ambient turbulence intensity assumed for the scenarios ranges between 10 % and 16 %. The power in all the figures has been normalised with the power of a turbine exposed to the undisturbed wind speed measured at a representative location.

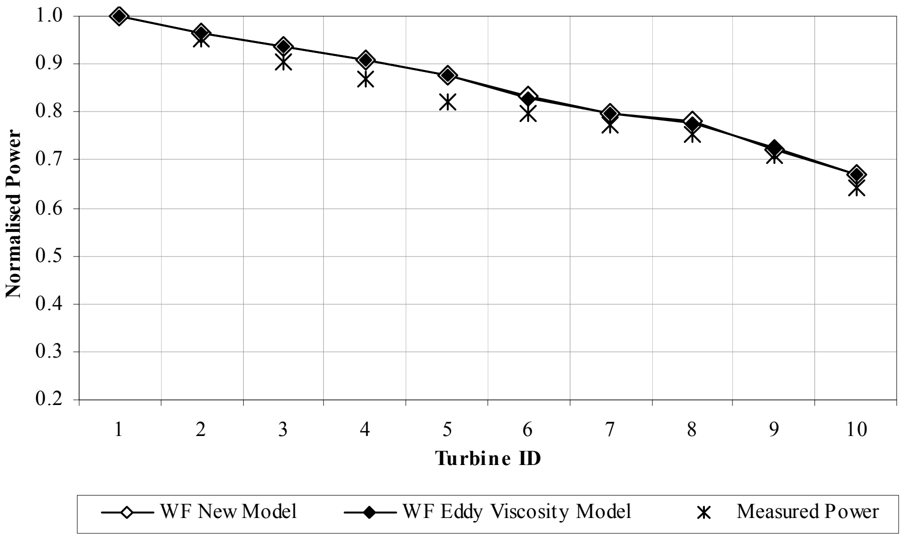


Figure 5 Row 1 of the example wind farm showing the normalised power outputs of each turbine without any wake effects

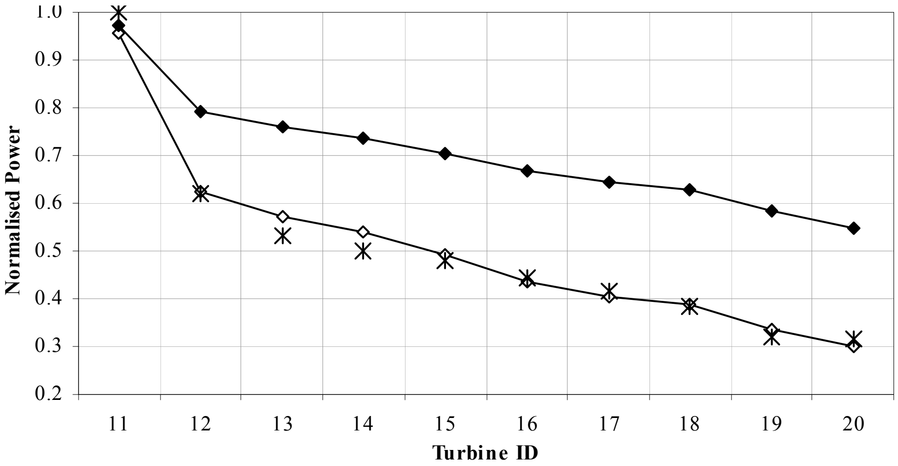


Figure 6 Row 2 of the example wind farm with close spacing.

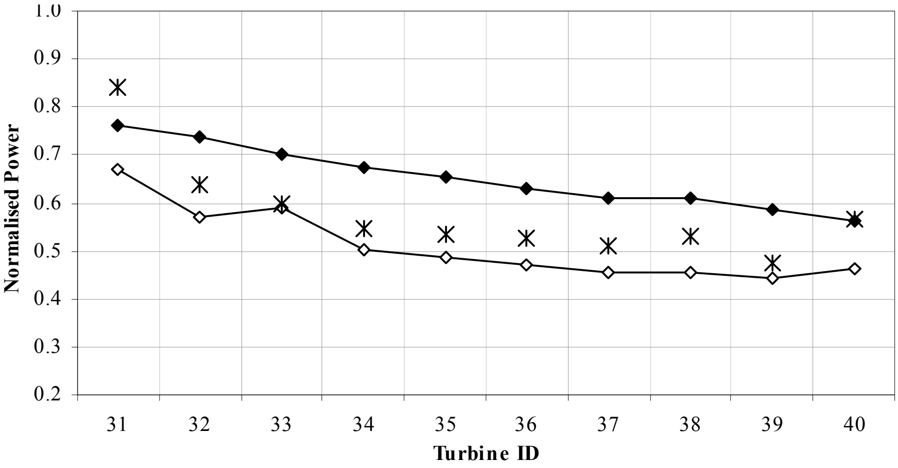


Figure 7 Row 4 of the example wind farm with close spacing

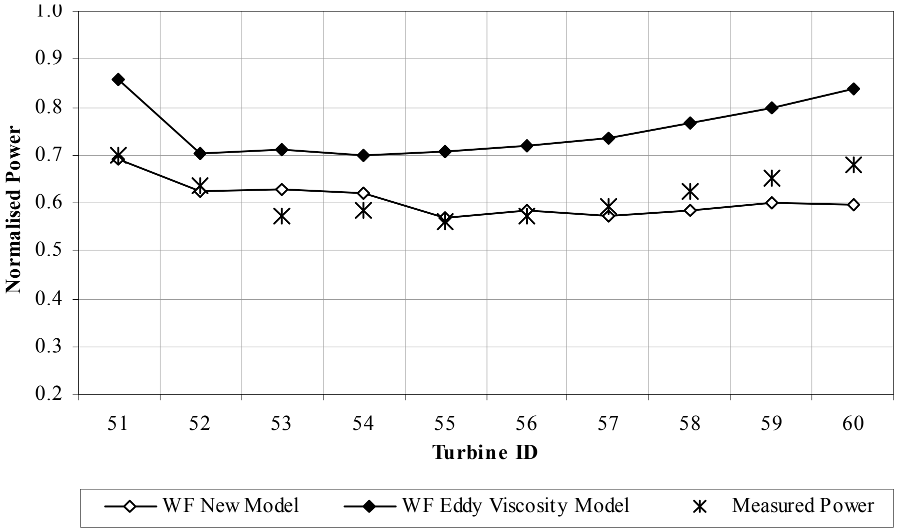


Figure 8 Row 6 of the example wind farm with close spacing

Figure 5 shows a typical example of the power output for a row of turbines not affected by wakes. Visible in this figure is the apparent variation in the incident wind speed along the row. This variability in the wind resource is characteristic of wind farms in complex terrain. Thus, in all the rows presented below, normalised power fluctuates due to wake effects and also due to natural changes of the wind resource within the wind farm.

Figure 6 shows the power output of the second row. The spatial variation of the undisturbed wind resource over the second row was considered when modelling the wake losses. It can be seen that the traditional Eddy Viscosity wake model predicts 20 % more energy than actually produced while the new model gives accurate predictions. **Figures 7 and 8** show that the improvement in the modelling is continued in rows of turbines that lie deeper in the wind farms.

The traditional wake modelling approach overestimates the performance of these turbines by 10 to 20 %. The actual wake losses in the closely spaced wind farms investigated are much higher than in wind farm designs that feature a wider inter-turbine spacing. The traditional approach has been modified as described above and achieves a close match between predictions and performance data as presented.

Combination with Eddy Viscosity model

The new Close Spacing wake model has been incorporated as a new option into the Garrad Hassan wind farm design software. The wake modifications are only fully applied when the upwind turbines are less than 2 D apart. Above 3 D spacing, the standard Eddy Viscosity model is applied and for intermediate spacings, a combination of the models is used.

Figure 9 demonstrates the wake predictions for turbine spacings of 1.5 D to 4 D. The plots show wind speeds at 8 D downstream in the wake of a row of five turbines, comparing the new wake model with the standard Eddy Viscosity model.

For the demonstration, an undisturbed wind regime was designed with the wind always from the 30 degree sector perpendicular to the row alignment. The handling by the model of the directions within a single sector is typical of the direction spread found at a closely spaced wind farm. A Rayleigh distribution of wind speeds was used, with a mean of 8 m/s. The turbine power and thrust curves were taken from a typical 2 MW machine of 80 m rotor diameter.

For turbine spacings of 1.5 D, the new model predicts a 13 % decrease in annual mean wind speed in the wakes 8 D downstream compared with the free stream wind speed. The standard Eddy Viscosity model predicts a 9 % decrease. This translates into energy array losses of 24 % and 15 % respectively for this particular scenario, representing an 11% underprediction of annual yield by the conventional model. It would be expected however, that the magnitudes of the losses will be very sensitive to the wind speed distribution and turbine characteristics.

At greater turbine spacings the differences between the two models reduces as the close spacing modification contributes a decreasing proportion.

The choice of 2 D to 3 D as the inter-turbine spacing range for the transition between the two wake models is thought to be the most appropriate on the basis of known wake behaviour. Further validations are planned as more operational data becomes available.

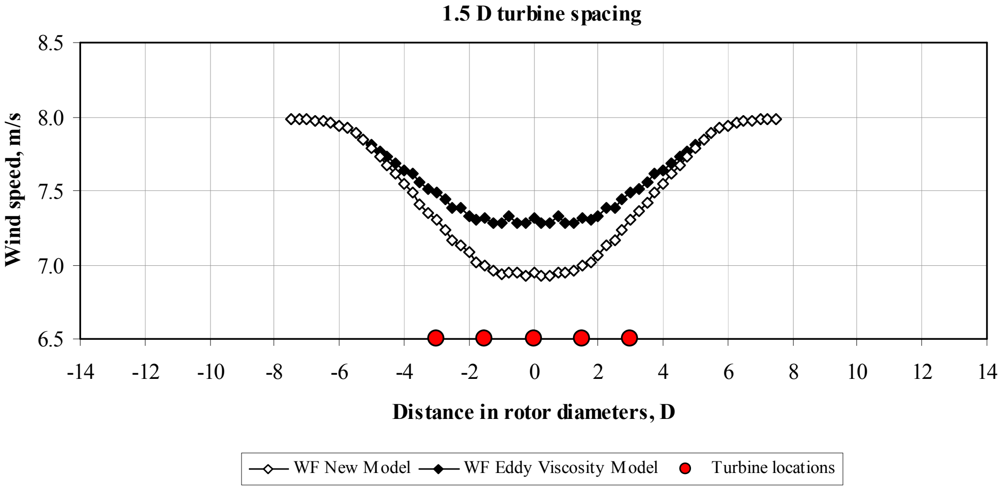


Figure 9 Comparison of new wake model with standard Eddy Viscosity model for different turbine spacings, continued.

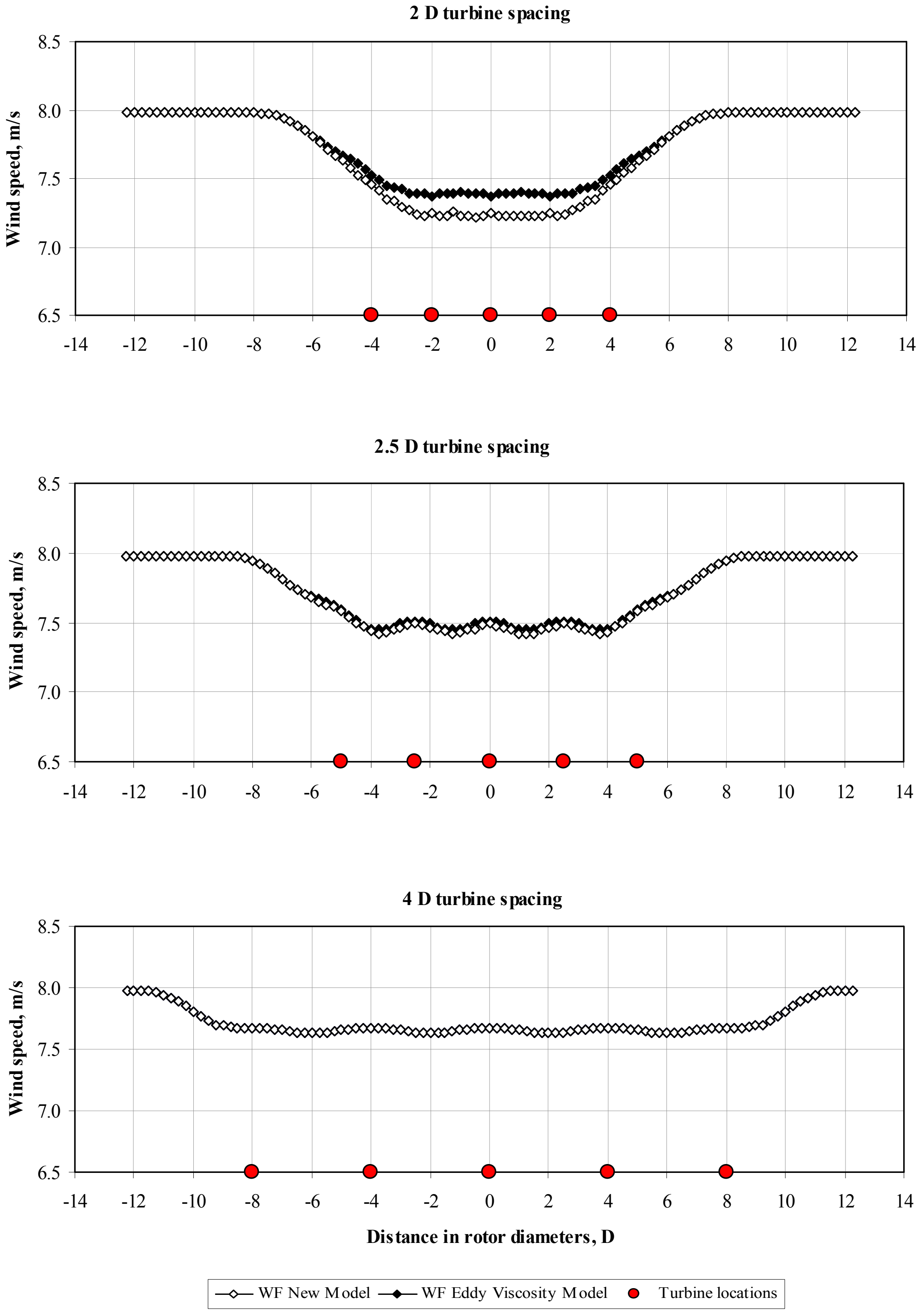


Figure 9 Comparison of new wake model with standard Eddy Viscosity model for different turbine spacings, concluded

Conclusions

The wake losses downstream from rows of very closely spaced turbines are much higher than predicted by conventional modelling. A modified, pragmatic approach to model the higher wake deficits has been presented and compared with operational data. The modifications of the standard Eddy Viscosity model to incorporate the new close spacing model have been demonstrated using a range of turbine spacings. The results serve to improve our understanding and modelling of cross-wind close-spacing effects which are highly relevant to the wind energy industry. The new model is available to the wind energy community through implementation within GH WindFarmer, Garrad Hassan's wind farm design software.

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