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Title: **Advanced wake model for closely spaced turbines**
Session: **Technical Track: Resource Assessment and Forecasting**

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Abstract

Array losses in modern wind farms typically range from 5 % to more than 15 % of the gross energy production depending on the wind farm layout. These significant losses need to be carefully modeled when designing a wind farm and predicting the expected energy production. Different models can easily result in yield differences of several percent.

Complex models exist that simulate many wind turbines in a wind farm simultaneously with the flow over the terrain, but they are computationally demanding to a degree that renders them impractical for commercial applications.

Commonly used commercial models are only applicable to the free-stream expansion of the wake. For such conditions the existing models work very well, however, if turbine spacing is below a certain limit the model equations become invalid and the results uncertain. Typical model limits are between 2 and 4 turbine diameters (D).

In some parts of the US and Spain the winds are either uni- or bi-directional leading to wind farm layouts which fall into tightly spaced rows perpendicular to the prevailing wind direction, called “wind walls”. Typical wind farms of this type often feature in-row turbine spacing significantly less than 2 D and in some instances only just greater than 1 D. Such wind walls are the subject of this paper.

An approach that improves wake model accuracy for closely packed lines of turbines is presented. This approach is validated with experimental data and based on theoretical considerations, combining empirical solutions with sophisticated modeling. The pragmatic nature of the approach maximizes the practical potential of the method and its usefulness to the industry.

Introduction

Wind turbines extract energy from the moving air. The air downwind of a turbine is affected by this extraction, the removal of energy results in a decrease in wind speed in comparison with the flow incident on the turbine. This region of velocity deficit defines the wake of the turbine.

In modern wind farms, turbines are often placed in the wake of other turbines due to a desire to maximise the installed capacity within the siting constraints defined by, for example, land use and civil and electrical costs. The resultant decrease in energy or increase in array losses typically ranges from 5 % to over 15 % depending on the wind farm layout. Knowledge of turbine wakes and their interaction in a wind farm serves not only to predict the wind speed and the corresponding loss in energy yield 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. These have recently been discussed by Crespo et al. [Crespo1999] and their performance compared with respect to offshore applications [Barthelmie2003]. 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 characterized by self-similar wind speed profiles and simple assumptions for the expansion of the wake. Dominant in industrial applications are mixed models that combine an efficient numerical solution of the basic flow equations with empirical assumptions simplifying the problem to an extent that it can be solved in an acceptable time frame. 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. These models are included in wind farm design software and have been proven to demonstrate good agreement with experimental data in most situations [Barthelmie2003, WFValidation2003]. Figure 1 presents an example of the Garrad Hassan Eddy Viscosity Model validation [WFValidation2003].

With the energy yield of over 30GW of wind farm capacity analyzed by Garrad Hassan over the past 21 years, a few of the wind farms analyzed have stood out because difficulties with the modeling of their annual energy yield became apparent. Their “closely spaced” nature sets these wind farms apart from the majority of wind farms built worldwide.

Advanced wind farm design software tools that are commonly applied to model wind farm wake losses fail to reproduce the yield of closely spaced wind farms. The actual observed wake losses are much higher than those modeled. From practical experience, Garrad Hassan was aware of this problem and made significant downward adjustments of yields forecast. While 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 described here.

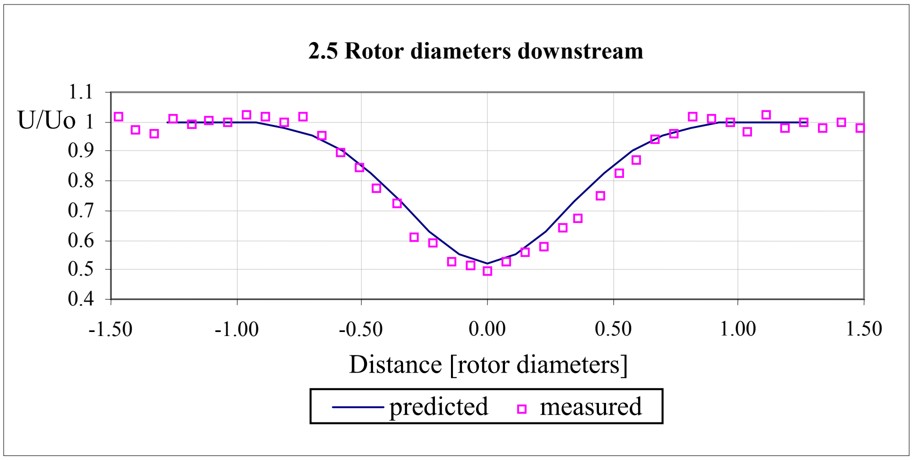
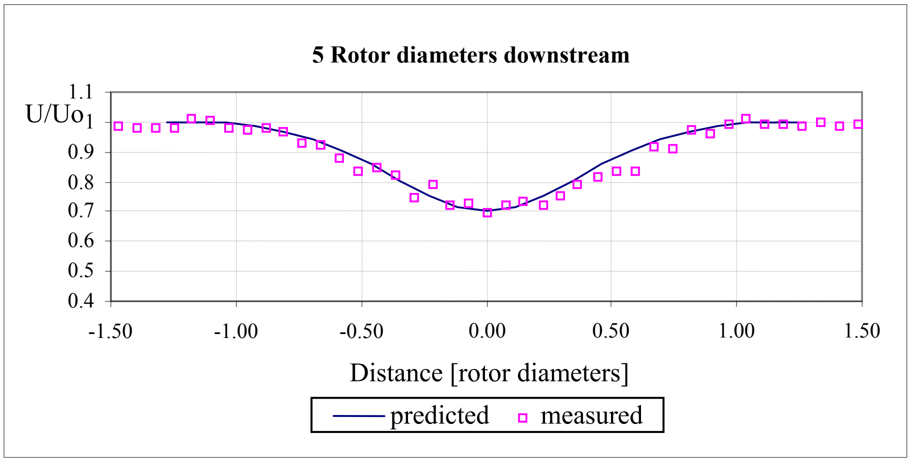


Figure 1 Comparison of the GH Eddy Viscosity Wake Model with wind tunnel measurements, continued.



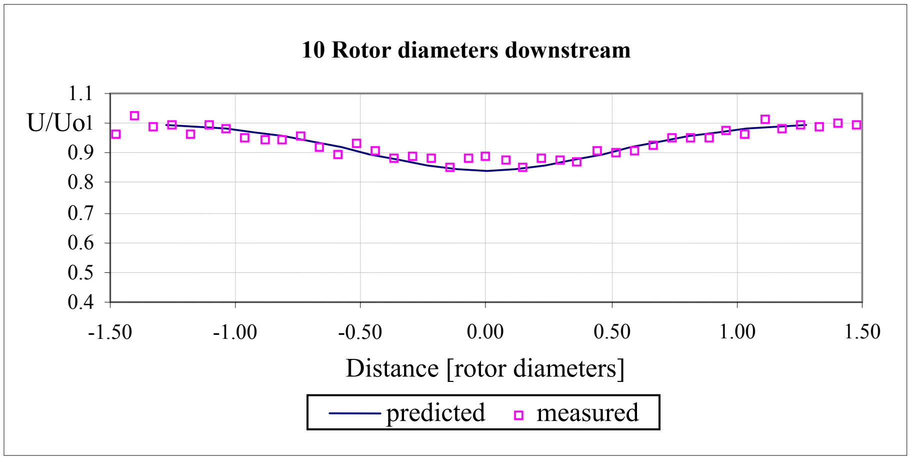


Figure 1 Comparison of the GH Eddy Viscosity Wake Model with wind tunnel measurements, concluded.

The experimental setup

The wind farms in question are all built in areas with either uni- or bi-directional wind regimes. Mostly this is due to thermally induced winds and 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 other part of the day while intermediate directions hardly exist at all. Under such circumstances wind farm designers choose to build their wind farms in very closely spaced rows across the main wind direction. Inter-turbine distances from 1.1 up to 2.5 times the rotor diameter (D) are observed as typical. Along-wind inter-row distances are typically 6 to 9 D.

Operational data from several close spaced wind farms have been analyzed. Periods have been excluded during which the wind direction changed considerably and only considered for scenarios in which 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.

Published data and investigations concerning wakes with a distance of approximately 2 D or less behind a wind turbine rotor are extremely rare [Taylor1990, Albers1993, Helmis1995, Barthelmie2003, Seifert2003]. Even fewer data are published from the wake of two or more adjacent turbines with an inter-turbine spacing of less than 2 D [Nierenberg1990, Smith1990]. To improve the general understanding and prediction accuracy for these cases, Garrad Hassan has undertaken an internal re-analysis of several cases of closely spaced wind farms with available production data. Due to the commercially sensitive nature of the information the wind farm operational results presented have been disguised. The data presented is 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.

In Figure 2 a hypothetical but typical wind farm layout with 7 rows of 10 turbines each is defined. 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.

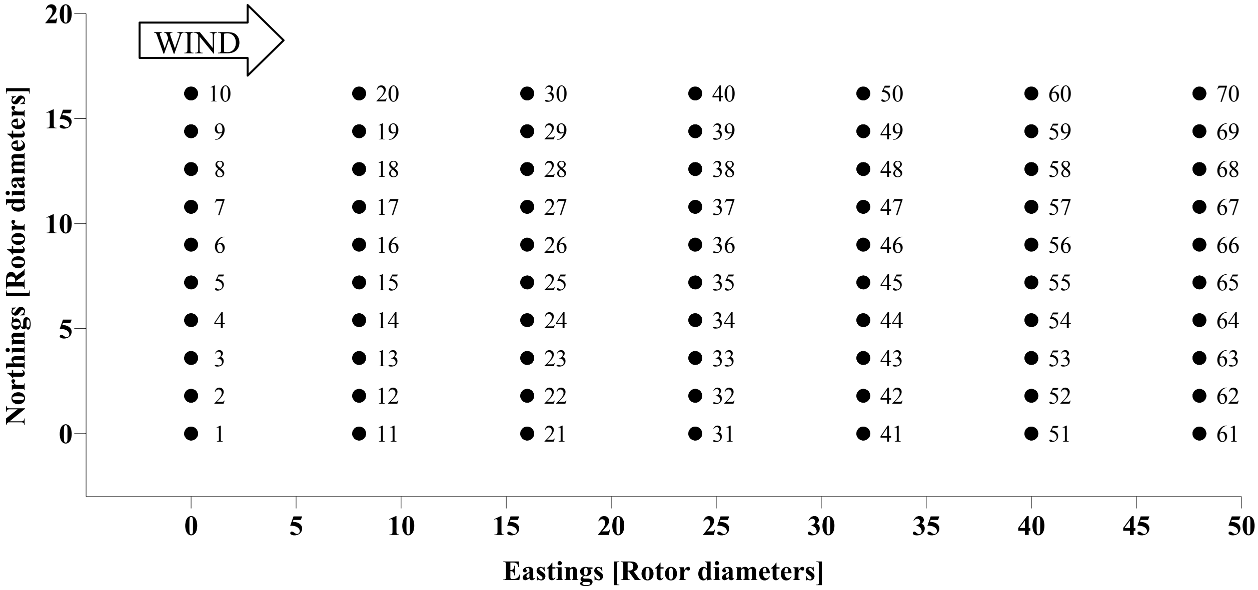


Figure 2 Example of a typical close spaced wind farm with spacing of approximately 1.8 D within the rows oriented from south to north and 8 D from row to row from west to east.

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

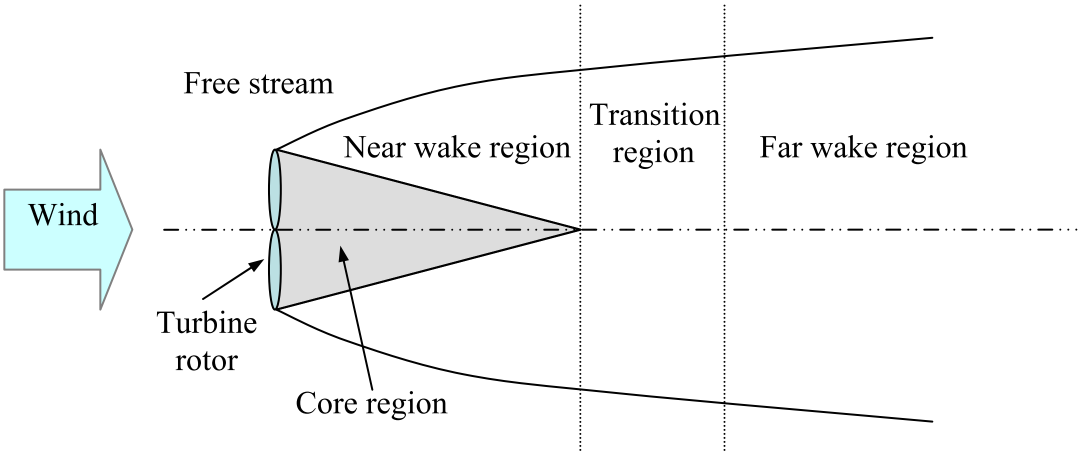


Figure 3 Wake structure with core, near, transition and far wake regions.

Figure 3 illustrates the different regions of a wake following the definitions introduced by Lissaman [Lissaman1977]. 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 [Quarton1990]. 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 1D and 3D. 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 [Lissaman1977, Lissaman1982] pioneered the transfer of profiles describing turbulent jet flows [Abramovich1963] 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.

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. The centerline 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 [Ainslie1988] 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 centerline wake deficit at 2D 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 [Hassan1993] which allowed systematic validation of Ainslie's approach.

The strength of the Eddy Viscosity Model proposed by Ainslie is its parameterization 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 without further proof 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 [Smith1990].

If the cross wind 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 reduced 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 velocity deficit is allowed to add up cumulatively
- the added turbulence is reduced in the wake
- the Gaussian profile is replaced by a blunter profile

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 center 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 center line deficit that could not be matched at the center line with the deficit of the Gaussian solution. As a pragmatic choice the center 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 of the new model with data

The data presented below are normalized measured and modeled 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.

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 to undertake a selection of 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 normalized with the power of a turbine exposed to the undisturbed wind speed measured at a representative location. Figure 4 shows a typical example of the power output for a row of turbines. 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, normalized power fluctuates due to wake effects and also due to natural changes of the wind resource within the wind farm.

Figure 5 shows the power output of the second row. The spatial variation of the undisturbed wind resource over the second row was considered when modeling 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.

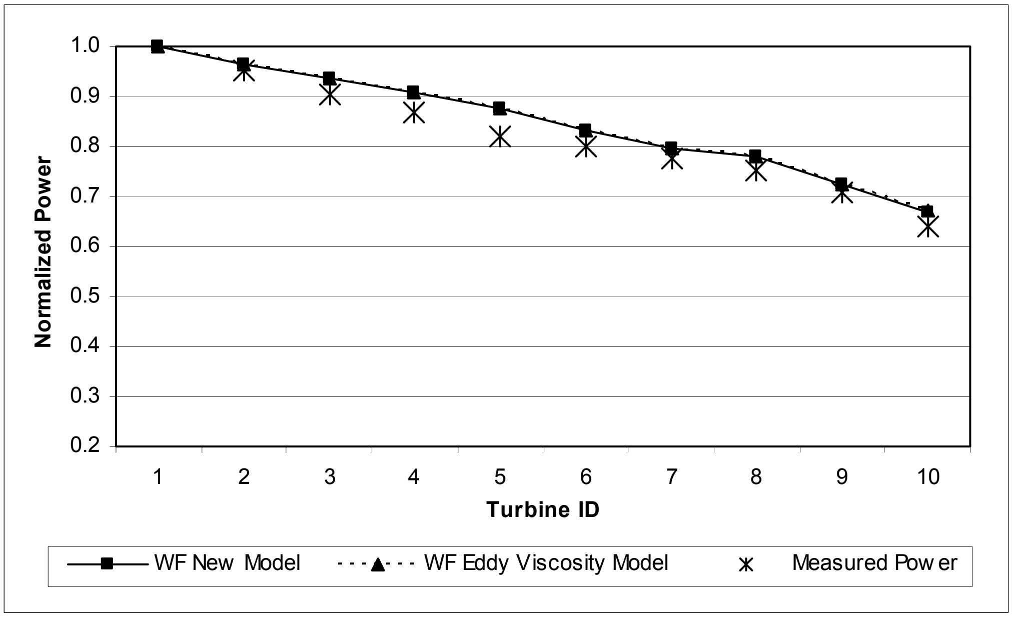


Figure 4 The first row of the example wind farm showing the normalized power outputs of each turbine without any wake effects.

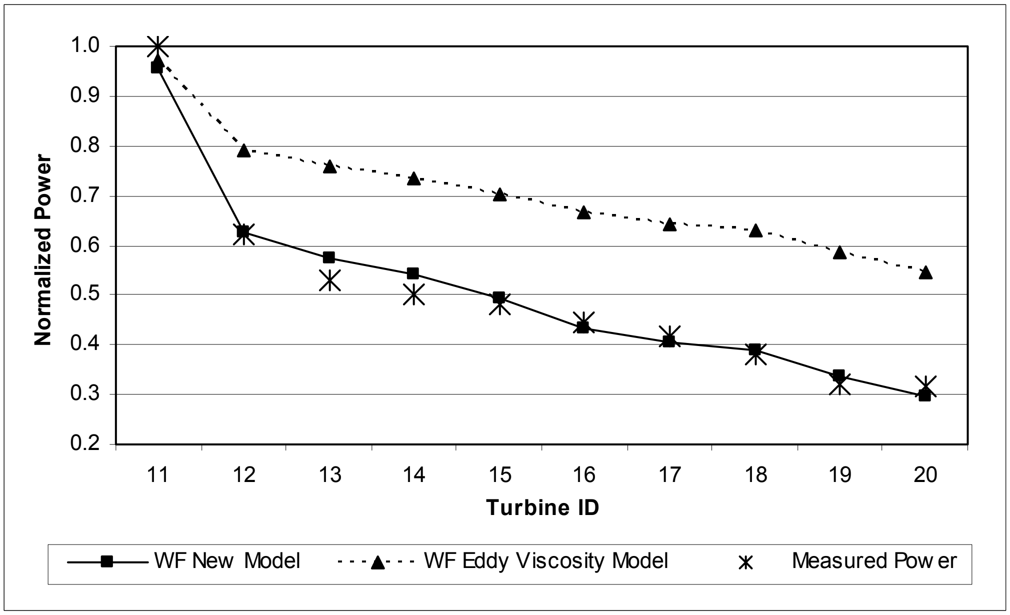


Figure 5 Row 2 of the example wind farm with close spacing.

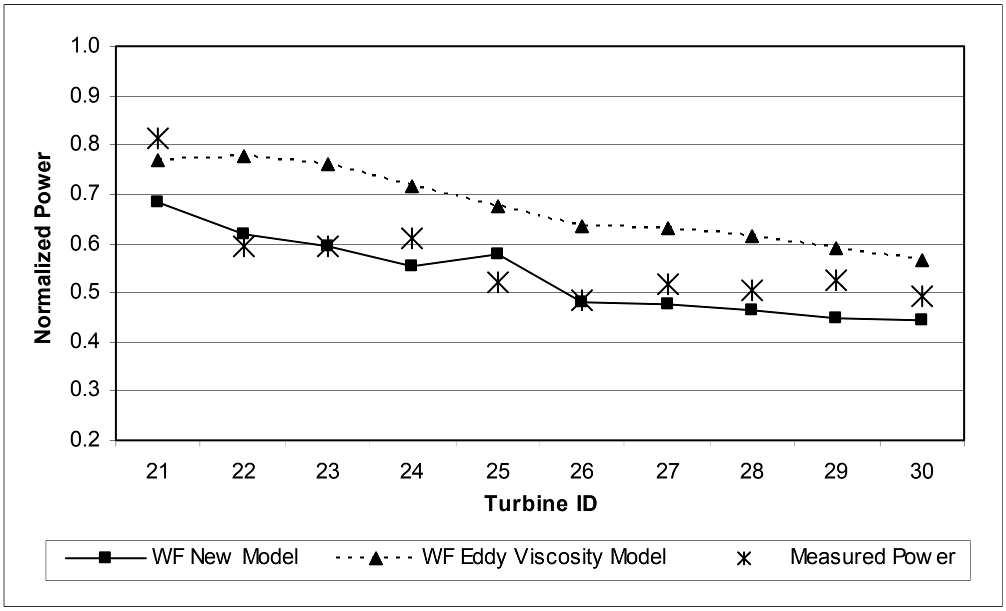


Figure 6 Row 3 of the example wind farm with close spacing.

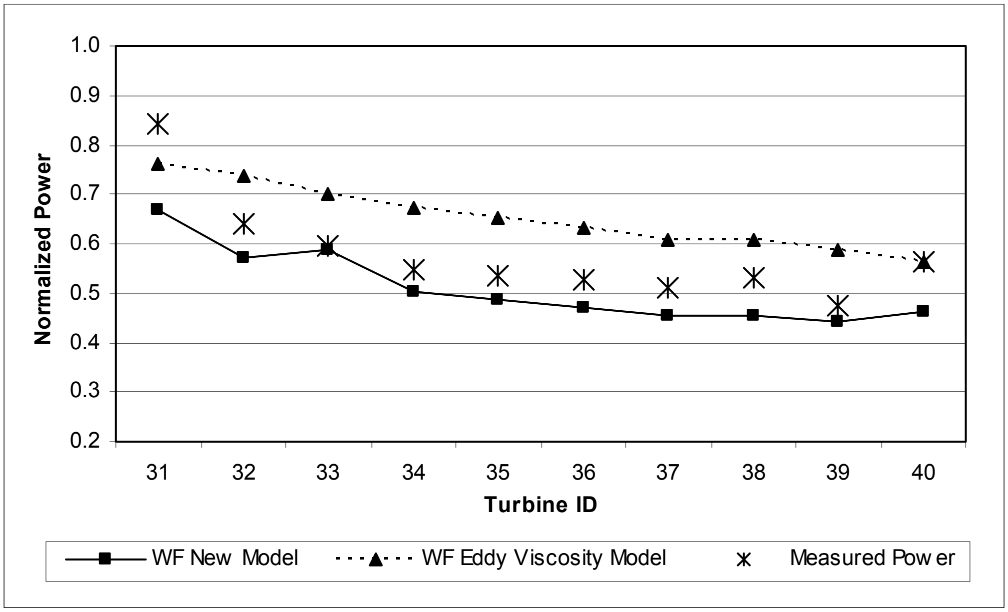


Figure 7 Row 4 of the example wind farm with close spacing.

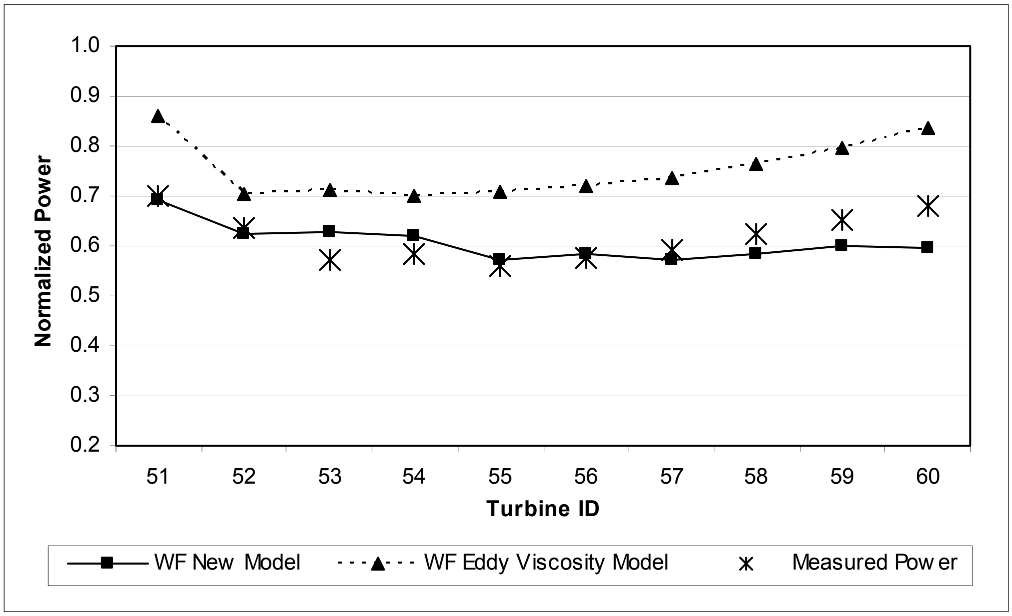


Figure 8 Row 6 of a hypothetical wind farm with close spacing.

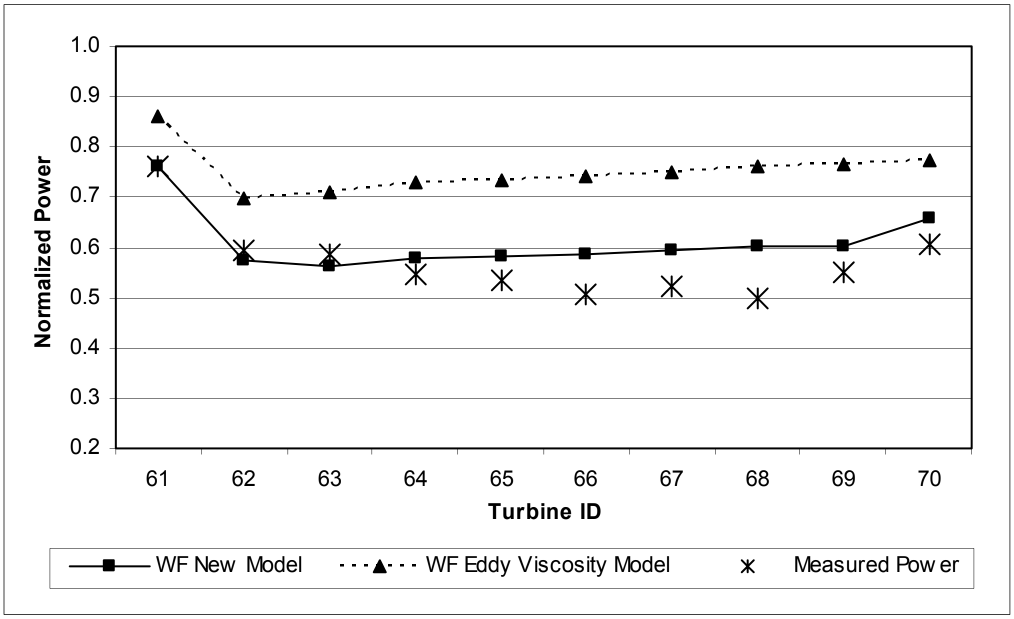


Figure 9 Row 7 of a hypothetical wind farm with close spacing.

Figures 4 to 9 show the differences between a traditional modeling approach and typical losses in production experienced in the wind farms investigated. The traditional approach seriously overestimates the performance of these turbines by 10 to 20 %. The actual wake losses in the wind farms of the close spacing type 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 achieved a close match between predictions and performance data, presented as the "New Model" data in the Figures 4 to 9 above.

Noteworthy is also the performance of the turbines at the end of each row. In some cases it is observed that they are not only not affected by the cross-wind close-spacing effect but even show an increased performance if compared to a traditional wake calculation. A possible explanation for this would be that the wind is being drawn into the center of the array causing a locally different wind direction and effectively putting the end of row turbines into a free wind stream position.

Conclusions

The wake losses between rows of very closely spaced turbines are much higher than predicted by conventional modeling. A modified, pragmatic approach to model the higher wake deficits has been presented and compared with experimental results. The results serve to improve our understanding and the modeling of cross-wind close-spacing effects which are highly relevant to the wind energy industry. The results will be made available to the wind energy community through implementation in the next release of GH WindFarmer Garrad Hassan's wind farm design software.

Acknowledgements

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