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Survey of Modelling Methods for Wind Turbine Wakes and Wind Farms

A. Crespo,* ETS de Ingenieros Industriales, UPM, José Gutiérrez Abascal 2, E-28006 Madrid, Spain
J. Hernández, ETS de Ingenieros Industriales, UNED, Ciudad Universitaria, E-28040 Madrid, Spain
S. Frandsen, Risø National Laboratory, DK-4000 Roskilde, Denmark

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This article provides an overview and analysis of different wake-modelling methods which may be used as prediction and design tools for both wind turbines and wind farms. We also survey the available data concerning the measurement of wind magnitudes in both single wakes and wind farms, and of loading effects on wind turbines under single- and multiple-wake conditions. The relative merits of existing wake and wind farm models and their ability to reproduce experimental results are discussed. Conclusions are provided concerning the usefulness of the different modelling approaches examined, and difficult issues which have not yet been satisfactorily treated and which require further research are discussed. Copyright ©1999 John Wiley & Sons, Ltd.

1. Introduction

Wind turbine wakes are an interesting topic of study, because the momentum deficit and the increased level of turbulence created by turbines in a wind farm may cause a reduction in power output and unsteady loads on other machines. On the other hand, owing to the cost of land and civil works, wind turbines tend to be built as closely as possible to each other, and to this effect, Builtjes and Smit[1] and Milborrow and Surman[2] have provided guidelines for wind turbine spacing in a wind farm. The final report of IEA, Annex IX on Wake Effects,[3] indicates that the experimental and analytical studies reported in the Annex point to significant energy losses in arrays spaced at less than seven turbine diameters. Similarly, turbulence may increase in arrays, sufficiently to cause measurable damage due to fatigue and dynamic loads.

Machines based on lift-like forces, associated with the generation of circulation, develop less intense wakes than drag-type units, which may be one reason, apart from other aerodynamic considerations, for preferring lift-type to drag-type machines.[4] Nevertheless, although most modern machines are of the lift type, the wake effects that they produce are still important enough to be studied.

In an early approach to the problem of modelling wind farms, it was assumed that when an area contained a large number of machines, the turbines acted as distributed roughness elements, and that they modified the ambient atmospheric flow (see reviews by Bossanyi *et al.*[5] and Milborrow[6]). More recent work using this approach has been carried out by Frandsen[7] and Emeis and Frandsen.[8] This topic of turbines acting as distributed roughness elements will be treated in more detail in Section 2.

*Correspondence to: A. Crespo, ETS de Ingenieros Industriales, UPM, José Gutiérrez Abascal 2, E-28006 Madrid, Spain.

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However, the most common approach to the problem, set in motion by the classical paper of Lissaman,[9] considers each turbine wake of the farm individually and examines its interaction with and superposition on neighbouring ones. It thus calculates the detailed flow field and not the average distribution. Section 3 is dedicated to individual wake behaviour and Section 4 to wake superposition and the multiple-wake case that occurs in wind farms.

Frandsen[7] compared the results of both approaches in a particular example, and although further research along these lines was desirable, this, to the best of our knowledge, has not been carried out.

Section 3 starts with a description of wake behaviour and continues with a discussion of the kinematic models, also known as explicit models, which have been used extensively because of their simplicity and low computational cost. They use self-similar velocity deficit profiles obtained from experimental and theoretical work on co-flowing jets. The wake growth rate is calculated as being caused by the ambient turbulence, the turbulence created by the shear in the wake and that created by the turbine itself. The magnitude of the maximum velocity deficit at each section is obtained from global momentum conservation, and the ground is taken into account by introducing an image machine. These methods provide acceptable results if the adjustable coefficients are appropriate.

Field models, also known as implicit models, calculate the flow magnitudes at every point of the flow field. Field models require a substantially larger computer capacity than kinematic models, although their requirements are well within the capabilities of modern computers, not only in the case of single wakes but also for multiple wakes occurring in a wind farm, if appropriate simplifying assumptions are made (see below). The field models give an acceptable representation of the flow field and a good insight into the processes governing wake development.

Both kinematic and field models use as starting or boundary conditions those at the end of the expansion region and the beginning of the near-wake region. If a uniform velocity deficit is assumed at the initial cross-section, this deficit can be estimated from the overall thrust on the machine; other possibilities are contemplated in Section 3.

Kinematic and field models do not directly take into account the bodily movement of the wake with the large atmospheric eddies, known as meandering. This is also examined in Section 3.

An important issue in wind farm modelling is the interaction of several wakes and the way in which the velocity deficits and turbulence created by each machine accumulate at locations where several wakes meet. Different types of assumption are made regarding superposition rules, the most straightforward approach consisting of adding the velocity deficits and turbulence kinetic energy. This and other alternative methods will be reviewed. The main problem is that any approach based on single-wake calculations will fail, because the ambient basic flow in which the wake diffuses is to some extent also affected by the wakes of the upstream machines and will also be evolving. A more correct approach would be to solve the flow equations for the whole wind park. At first sight and from a practical point of view this would not seem feasible for wind farms with a large number of wind machines; however, if some simplifying assumptions are made, namely a parabolic approximation, the field model for a single wake can be extended to the multiple-wake case and be practically solved with reasonable computer times, giving an acceptable degree of agreement with experimental measurements. This issue will be examined in more detail in Section 4.

The problem of how to take into account terrain effects in wind farms placed in moderately irregular topography, not contemplated in Section 3 for single wakes, is also treated in Section 4.

Although this article concentrates more on modelling aspects, the empirical or quasi-analytical expressions that may be used to estimate the downstream evolution of relevant wake parameters, such as velocity deficit and turbulence intensity, are briefly reviewed in Section 5.

Section 6 deals with the influence of wake effects on wind turbine loading. We review available load measurements in wind turbines under different types of wake conditions. Some existing models to estimate wake-loading effects are also described.

In Section 7 we present what we think is the state of the art regarding wind turbine wakes and wind farm modelling, accompanied by the corresponding conclusions and recommendations.

2. Turbines Acting as Distributed Roughness Elements

The models of Templin,[10] Newman,[11] Crafoord[12] and Moore,[13] reviewed by Bossanyi *et al.*[5] apply to infinite clusters. They assume a logarithmic wind profile for the unperturbed wind, which includes ground roughness as a parameter. The presence of the turbines increases the value of the roughness, which is then calculated. From the modified wind profile the wind velocity incident on each machine can be obtained and then the power produced can be calculated. Whereas the previous models assumed a single logarithmic profile, Emeis and Frandsen[8] assumed that below hub height there is a logarithmic profile with the real ground roughness, and above hub height another profile with a roughness related to the drag of the machine; the profiles match each other at hub height. Frandsen[7] also applied a logarithmic profile above hub height and assumes the validity of a simplified form of the geostrophic drag law, obtained from the Rossby number similarity theory.

Bossanyi *et al.*[5] explained how the previous models can be extended to the case of finite clusters. Schmid[14] used results obtained by Taylor[15] for a step change in roughness to calculate the friction velocity at each row of turbines. Crafoord,[12] Moore[13] and Musgrove[16] considered a mixing layer of air above the ground and perform either a momentum or energy balance in this layer. It was assumed that sufficient mixing occurs so that, by the time the next row of turbines is encountered, the velocity deficit is averaged out across the whole mixing layer. The difference between the momentum (or energy) fluxes of two consecutive rows is due to the drag (or power extraction) of the turbine, the amount lost to the ground and the amount entrained from greater heights through mixing processes. The difference between the last two quantities was termed the replenishment rate by Bossanyi *et al.*,[5] who discussed several hypotheses concerning the way to estimate the relevant parameters, in particular the mixing layer thickness and the replenishment rate, and compared the corresponding results.

Although these models are not much used, they could be of interest to predict overall effects of large wind farms on wind characteristics.

3. Individual Wakes

This section is dedicated to reviewing the models for individual wakes. It is of interest to present first a general description, based on physical grounds, of the behaviour of the wake characteristics to be simulated with the models. In the second and third subsections the more simple kinematic models and the field models respectively are described. The procedures and methods used by the different models are presented and the results discussed. In the third subsection the results obtained with both kinematic and field models are examined simultaneously and compared with experiments, in order to discuss the merits of both types of models. Finally, the meandering effect, which is not usually taken into account explicitly in the models, is examined in the last subsection.

Description of the Wake Behaviour

As the air approaches the wind turbine, its velocity decreases and the pressure increases. As it crosses the rotor, there is a sudden decrease in pressure. In the region immediately downstream of the rotor there are non-uniform deficits of pressure and axial velocity, which are associated with the axial thrust, as well as an azimuthal component of velocity, which, in turn, is related to the torque on the machine. Vortex sheets, associated with the variation in circulation along the blades, are shed from their trailing edge and roll up in a short downstream distance, forming tip vortices that describe helical trajectories. When the inclination angle of the helix is small enough, the tip vortex can be interpreted as a cylindrical shear layer which separates the slow moving fluid in the wake from that on the outside. The velocity deficit can be considered as induced by the vortices. The difference in pressure between the fluid behind the rotor and that on the outside is supported by the centrifugal force due to the curvature of the streamlines. As we

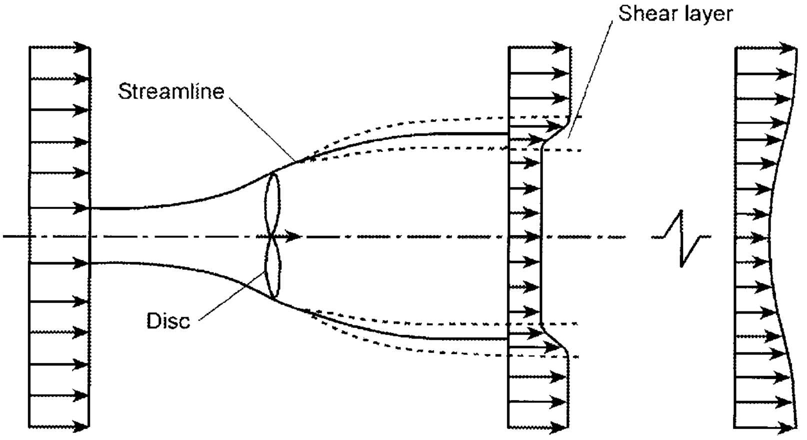

Figure 1. Schematic representation of a wind turbine wake

move downstream, the cylindrical shear layer expands, the pressure increases and the velocity inside the wake decreases until ambient pressure is reached (Figure 1). According to the simple actuator disk theory, which assumes that flow is ideal and that the shear layer is infinitely thin, the velocity deficit at the disk itself is half that in the expanded wake. Because of turbulent diffusion, the thickness of the shear layer increases with downstream distance, but if the length of this expansion region is sufficiently small, it may not be a bad approximation to consider that the thickness of the shear layer is small compared with its diameter. The length of this expansion region is about one turbine diameter.

As we proceed further downstream, turbulent diffusion of momentum becomes the dominant mechanism. Turbulence production is more important in the shear layer, where the velocity gradients are larger. A well-defined ring-shaped domain where there is a high turbulence intensity is observed in this cylindrical shear layer, both experimentally[17–23] and numerically.[24–26] There are also significant velocity gradients both inside the wake, since the velocity deficits created by the turbine are not uniform, and in the atmospheric flow, where the wind velocity changes with distance to the ground. Most of the turbulence that makes the wake diffuse is, at this stage, probably created by the shear in the wake, mainly in the shear layer. However, the shear in the external atmospheric flow also plays an important role, at least in the redistribution of the generated turbulence. As will be shown later, the turbulence of the ambient flow is responsible for a non-uniform distribution of turbulence in the shear layer, where a maximum is observed in the upper part[25,27] (Figure 2). Turbulent diffusion makes the shear layer thickness increase with downstream distance, and at a certain distance downstream (about two to five diameters) the shear layer reaches the wake axis. This marks the end of the near-wake region.

After the near-wake region there is a transition region leading to the far-wake region, where the wake is completely developed and, in the hypothetical absence of ambient shear flow, it may be assumed that the perturbation profiles of both velocity deficit and turbulence intensity are axisymmetric and have self-similar distributions in the cross-sections of the wake. The only overall properties of the turbine that appear as parameters in these profiles are the thrust on the turbine and the total turbulence kinetic energy produced by the rotor itself. This property of self-similarity of the velocity profiles is the basis of the kinematic models describing wind turbine wakes. However, the presence of the ground and the shear of the ambient flow invalidate the assumption of axial symmetry and, to some extent, the hypothesis of self-similarity. It has been observed both numerically and experimentally that the maximum turbulence intensity in the far wake is located above the turbine axis,[21,28] and the point of maximum velocity deficit is usually below the turbine axis.[29–32] The maximum of turbulence intensity is about one turbine radius above the axis, and this is probably related to what happens in the near wake.

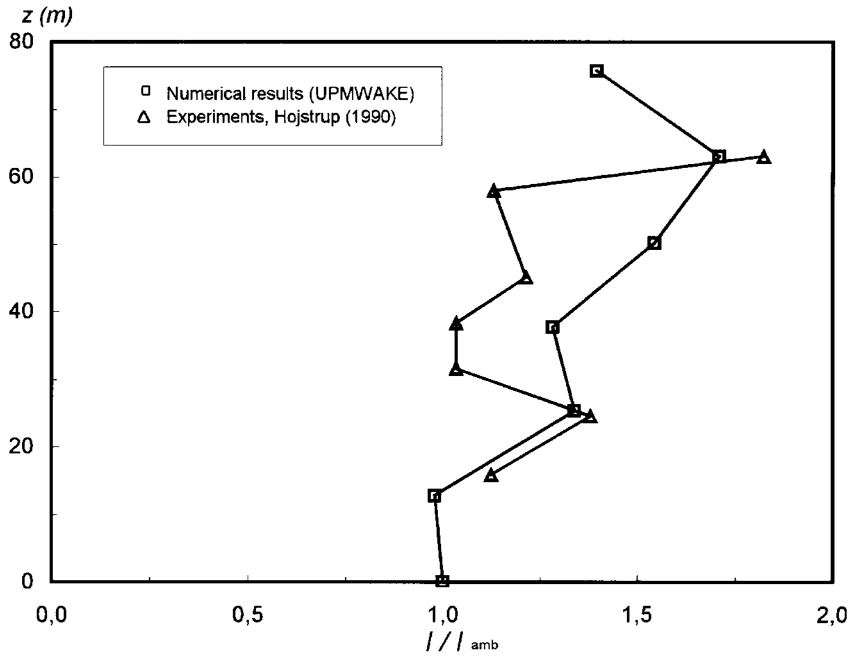

Figure 2. Vertical distribution of turbulence intensity normalized with its ambient value. Comparison of numerical[27] and experimental[21] results. 1D downstream, $D = 40$ m, $H = 45$ m. Notice peaks located at $H + D/2$ and $H - D/2$

Kinematic Models for Single Wakes

As already mentioned, kinematic models are based on self-similar velocity deficit profiles obtained from experimental and theoretical work on co-flowing jets. The wake description does not consider the expansion region and gives different types of profiles for the near-wake, transition and far-wake regions. For the far wake these profiles are self-similar and in the near wake there is usually a central core of constant velocity and diminishing radius; when this radius becomes zero, the near wake ends. Lissaman[9] and Voutsinas *et al.*[33] used the velocity profiles proposed by Abramovich.[34] Vermeulen[35] used a Gaussian type of profile quite similar to that of Abramovich.[34] Katic *et al.*[36] simplified the problem further and assumed a top-hat profile everywhere. More recently, Kiranoudis and Maroulis,[37] based on a kinematic model similar to the previous ones, developed a 'short-cut model of wind park efficiency', giving simple analytical expressions of the efficiency as functions of the farm and turbine characteristics.

In these models the initial velocity deficit is usually obtained from the thrust coefficient of the machine. Voutsinas *et al.*[38] related it to the power given by the machine, the advantage of which is that the power curve is usually more available than the thrust curve.

In all the studies published to date, the reference value of the velocity deficit at each section has been obtained from global momentum conservation, except in the case of Voutsinas *et al.*,[38] who claimed that they obtained it from mass conservation, based on the fact that agreement with the results of Taylor[39] was better. However, it is not clear what they mean by this and, in particular, how they take into account the mass entrainment through the lateral surface of their control volume. As a matter of fact, when applying the classical equation of momentum conservation (see e.g. Reference 35), it is implicitly assumed that mass is also conserved.

Lissaman[9] regarded the wake growth as being caused by the sum of the ambient turbulence and the turbulence created by the shear in the wake. Vermeulen[35] added another term, the turbulence created by the turbine itself, although, in a later work based on the experimental results of Taylor,[39] Voutsinas *et al.*[33]

considered that this effect was negligible. Katic *et al.*[36] assumed that the wake radius increases linearly with downstream distance; the proportionality constant must be adjusted by comparison with experiments.

The ground effect is simulated by imaging techniques. Lissaman[9] included a symmetrical turbine and added the velocity deficits of both the real and image turbines, so that drag conservation is satisfied. He pointed out that the ground surface can be treated exactly like the vertical-dividing plane between two adjacent identical rotors abreast. However, when there is ground, the total drag is not actually conserved because of friction; the three-dimensional models show that there is a slight decrease in total deficit as the downstream distance increases. According to the image procedure, the velocity deficit will be double that due to a single wake at the ground, whereas in reality any perturbation would be damped to zero. Crespo *et al.*,[29] Crespo and Hernández[40] and Kambezidis *et al.*[41] use an antisymmetric wake so that velocity deficits are subtracted and give zero perturbation at the ground; if it is considered that in reality the ambient velocity is not uniform and that it falls to zero at the ground, the perturbed velocity calculated will also be zero at the ground. However, although this alternative procedure eliminates the previously mentioned inconsistency that occurs near the ground, it is not clear that it will give a more valid result in the rest of the flow field, where the ground effect is not so dominant. Another procedure followed by Voutsinas *et al.*[38] consists of superimposing the squares of velocity deficits and taking into account the spatial variability of the incident velocity to estimate the location of the image turbine, although this method does not seem to be capable of overcoming the difficulty. Indeed, the ground effect seems to be an intrinsic difficulty of all the kinematic models that assume axial symmetry, and there is no satisfactory way in which they can deal with it. The ground effect can only be treated properly with 3D models.

Recently, Larsen *et al.*[42] proposed a simple analytical model, based on the classical wake theory as presented by Schlichting.[43] The flow is supposed to be axisymmetric, and a single self-similar velocity profile is assumed for the whole wake. The velocity deficit decays with downstream distance as $x^{-2/3}$, the turbulence intensity decays as $x^{-1/3}$, as in References 25 and 27, and the wake width increases as $x^{1/3}$. Compared with the previous kinematic models, this model only considers the far-wake region and the turbulence created by the shear. They compared the turbulence intensity and length scale calculated from their model with predictions based on empirical relations, and obtained relative differences lower than 5% in all cases where the downstream distance x is larger than two diameters.

In spite of all the previous difficulties, in many cases the kinematic models provide results that are in good agreement with the experimental measurements if appropriate values are chosen for the parameters appearing in them.[17,44,45]

Field Models for Single Wakes

Sforza *et al.*[46,47] described the wake using only the linearized momentum equation in the main flow direction, with constant advective velocity, a constant eddy diffusivity and a parabolic approximation. For two-dimensional configurations they obtained analytical solutions with acceptable wake shapes. In the three-dimensional case they integrated the equation numerically using an alternating direction implicit (ADI) method. They made small-scale experiments and compared measured and calculated values for the velocity deficit and wake growth as functions of downstream distance, obtaining agreement within 10% error, except for cases of high thrust loading, for which the error could reach 20%. This agreement was reasonably close considering the simplicity of the model. Besides, the tendencies were well predicted in all cases.

A numerical model based on solving the flow equations for wakes in neutrally stratified atmospheric boundary layers was proposed by Taylor,[48] who considered an eddy viscosity gradient closure scheme. The wake effect was assumed to be small enough for the equations to be linearized around a basic flow, and a boundary layer approximation was used. The model was two-dimensional and presented results integrated across turbine rows. Coriolis forces were retained and the pressure gradients were given by the geostrophic wind. However, this assumption cannot be justified, because the length scale of the wake is not sufficiently large for the Coriolis forces to play a dominant role; indeed, they can be neglected and the pressure field will be that resulting from the momentum conservation in the wake. If a parabolic approximation is made, pressure variations across the wake can be neglected in the momentum equation for the main flow direction, but not for the momentum components in the transverse direction, particularly when there is neither axial nor two-dimensional symmetry. Taylor[48] compared his results with those of kinematic models and other models based on the assumption that the turbines act as distributed roughness, and with experimental results of Builtjes.[49] Although there was reasonable agreement, Taylor[48] admitted that the linear superposition of the effects of several rows of turbines may lead to low or even negative power outputs for the backmost rows.

Liu *et al.*[50] proposed another, three-dimensional, model which includes atmospheric stability effects. However, these authors neglected the diffusion due to turbulence originated in the wind turbine and the diffusion caused by the shear in the wake, and considered the turbulent viscosity and the diffusion coefficients to be those of the unperturbed flow. Along with Taylor,[48] they retained Coriolis forces and assumed that the pressure gradients were given by the geostrophic wind.

Ainslie[51–53] developed a parabolic eddy viscosity model (EVMOD) which assumes axisymmetric wake flow. Pressure variations are uncoupled in the analysis, and only the continuity and the axial momentum equations have to be solved. Consequently, the model is incapable of dealing with ground effects or with variations in ambient flow conditions with height. The turbulent shear stresses are described using an eddy viscosity closure scheme in which the eddy viscosity is represented by a simple analytical form based on Prandtl's free shear layer model, but which also includes a contribution from ambient turbulence. This eddy viscosity is an average value over a cross-section, and variations in turbulent properties across the wake cannot be estimated from the model. At small downstream distances the eddy viscosity is modified by an empirical filter function to account for the lack of equilibrium between the mean velocity field and the developing turbulence field. Several constants appear in the problem. They are adjusted by comparison with particular experiments, although their validity in more general situations is not clear. The model is fairly simple and gives reasonable results when compared with wind tunnel experiments. For large-scale experiments the results are corrected by taking into account meandering effects (which will be described at the end of this section). Albers *et al.*[54] found that there was greater agreement between Ainslie's model and experimental results if the incident logarithmic profile was superimposed on the calculated axisymmetric wake. Luken and Vermeulen[55] and Luken *et al.*[32] used the experimental results from the TNO wind tunnel to validate Vermeulen's[35] kinematic model (MILLY) and Ainslie's[51] model (EVMOD) (see Figure 3). Although they found an acceptable degree of agreement, some aspects such as the downshift of the wake centreline, which appears in Figure 4, were not well predicted. To reproduce such effects, models which retain three-dimensional effects are needed. These will be described next.

Crespo *et al.*[29] developed the UPMWAKE model in which the wind turbine is supposed to be immersed in a non-uniform basic flow corresponding to the surface layer of the atmospheric boundary layer; further developments of the model are given by Crespo and Hernández.[56] The properties of the non-uniform incident flow over the wind turbine are modelled by taking into account atmospheric stability, given by the Monin–Obukhov length, and the surface roughness. It is supposed that this basic flow, described by analytical expressions obtained from theoretical considerations and experimental results given by Panofsky and Dutton,[57] is perturbed by the wind turbine. The equations describing the flow are the conservation equations of mass, momentum, energy, turbulence kinetic energy and dissipation rate of turbulence kinetic energy. The modelling of the turbulent transport terms is based on the k–ε method for the closure of the turbulent flow equations. This set of equations has been solved numerically using the SIMPLE algorithm proposed by Patankar and Spalding.[58] Finite difference methods were used in the discretization of the equations. A parabolic approximation was made and the equations were solved numerically by using an ADI method. The developed wake model is three-dimensional, and pressure variations in the cross-section have to be retained in order to calculate transverse velocities.

A simplified version of UPMWAKE, which assumes that all the convection is due to the unperturbed ambient flow, was presented by Crespo *et al.*[29] This seemed a very attractive idea, because it was possible to retain the three-dimensional character of the problem and reduce the system of partial differential

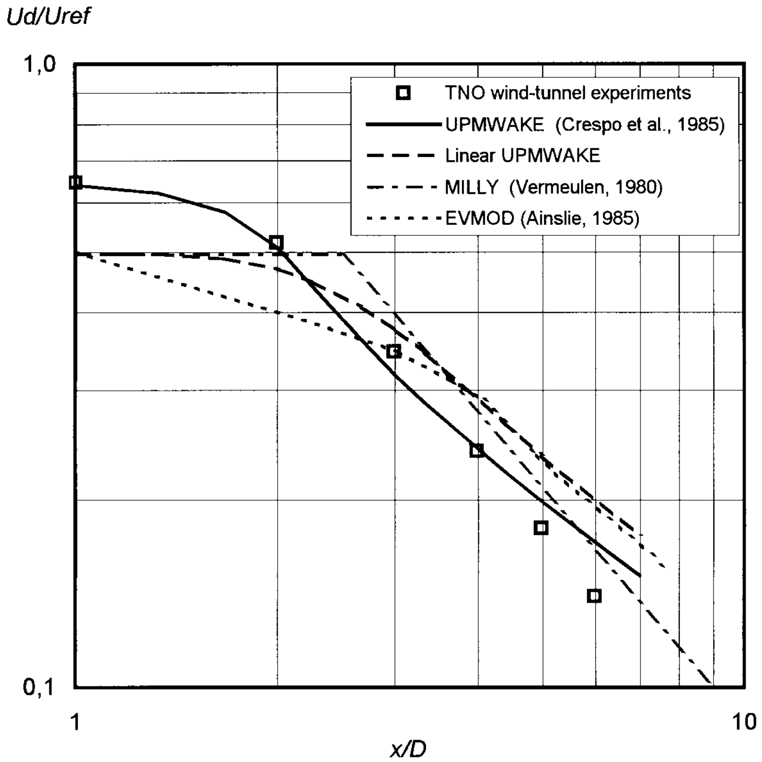

Figure 3. Decay of maximum dimensionless velocity deficit along wake, made dimensionless with wind velocity at hub height, as a function of downstream distance divided by turbine diameter. Comparison of wind tunnel measurements and results of different wake models

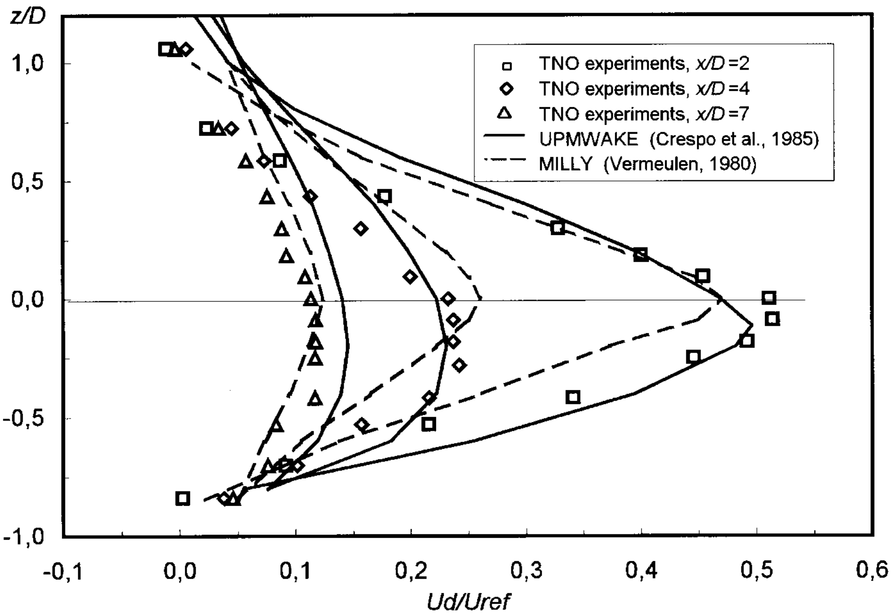

Figure 4. Vertical distribution of maximum dimensionless velocity deficit along wake as a function of vertical distance divided by turbine diameter for several downstream sections. Comparison of wind tunnel measurements and results of wake models

equations from seven to three. However, this approximation can only be justified very far downstream where the wake perturbation is small, and although in some cases the results obtained were in quite good agreement with the full model and with experiments, in others, particularly in the near wake, they were wrong. Most of the UPMWAKE calculations that have been published correspond to the seven-equation code.

Crespo and Hernández[40,56] and Crespo *et al.*[28,30] compared UPMWAKE results with the results of wind tunnel experiments obtained by Luken *et al.*[55] (see Figures 3 and 4) and those of field experiments using full-scale machines.[59] The wake model has also been validated numerically by using the general-purpose CFD PHOENICS code,[24] and the corresponding results agree well with those of UPMWAKE. The code can predict effects such as the downward tilt of the wake centreline, as can be seen in Figure 4, the upward displacement of the point of maximum added turbulence kinetic energy, or the different vertical and horizontal growths of the wake width, which have been confirmed experimentally by other authors.[3] Based on their experimental results, Helmis *et al.*[60] attribute the downshift of the maximum velocity deficit to the tower shadow rather than to the asymmetry due to the terrain. Some discrepancies between the UPMWAKE results and those of the experiments of Taylor *et al.*[59] were found in the initial wake region, where the predicted velocity deficits were smaller than the measured ones.

More recently, and based on the results of the code, Crespo and Hernández[25,27] have developed correlations to calculate the turbulence intensity in both the near and far wakes, and compared them with a great number of experiments (many of them compiled by Quarton[61]), both wind tunnel[17,35,62–67] and field[20,68,69] experiments. The comparison was acceptable and demonstrated that UPMWAKE may be a useful tool for estimating turbulence characteristics. For the far wake, Frandsen *et al.*[70] proposed correlations that give similar predictions for the decay in turbulence intensity with growing downstream distance. Crespo and Hernández[25,27] also proposed a simple method for obtaining the turbulence spectra in the wake from the values of k and ε obtained from UPMWAKE, and compared their results with the experiments of Højstrup,[21] obtaining good agreement in some cases. The results of this procedure for calculating the spectra are compared with measurements made in Vindeby wind farm by Frandsen *et al.*[70] and Crespo *et al.*;[71] some of the results obtained for the turbulent length scale that are needed to estimate the spectrum seem to be smaller than those measured. Possible reasons for this discrepancy are, on the one hand, that UPMWAKE does not take into account the small-scale (large-frequency) turbulence originated by the boundary layers of the blades of the wind turbines, and, on the other hand, that the wind turbine is capable of responding to low-frequency fluctuations of wind speed and extracts energy from the wind in the low-frequency (large-scale) range,[21] although this tendency may be reversed for wind speeds higher than that corresponding to the maximum power coefficient, as measured by Papadopoulos *et al.*[72] Larsen *et al.*[42] proposed another procedure, in which the individual contributions of the different scales to the spectrum are calculated and added; the details of the method are not included in the paper and will be published elsewhere.

One aspect of modelling which has been insufficiently treated is wake diffusion in non-neutral atmospheres. Crespo *et al.*[29] showed that, as was to be expected, diffusion is inhibited in stable atmospheres and enhanced in unstable ones, although no experimental results were available for comparison. More recently, some interesting experimental results have been presented by Magnusson[73] and Magnusson and Smedman,[74] who found that for unstable stratification, with Richardson number (Ri) values smaller than $-0{\cdot}05$, the velocity deficit is independent of stability, while it increases linearly with Ri in the interval $-0{\cdot}05 < Ri < 0{\cdot}05$. They also found that, unlike in the experimental results of Luken *et al.*,[32] there is an upshift of the point of maximum velocity deficit. The calculations of Crespo *et al.*[29] showed that in most cases there is a downshift, except for stable atmospheres, large surface roughness and a high level of turbulence kinetic energy created by the turbine. It would be of interest to compare the results of numerical models that can simulate atmospheric stability with these experiments.

Smith and Taylor[23] and, in more detail, Taylor[26] presented a non-symmetric two-equation model that is in many ways similar to the three-equation model of Crespo *et al.*[29]. They neglected transverse velocities and just solve the momentum equation in the axial direction. To model the turbulent viscosity, they use a

k–L method where the turbulent length scale L is related to the width of the wake, obtained by fitting a Gaussian profile to the calculated profile. The value of the dissipation rate of the turbulent kinetic energy, ε, was obtained from an algebraic combination of k and L, and consequently a partial differential equation for ε was not needed. The same type of problem previously mentioned for the three-equation version of UPMWAKE also appears in this case. The results obtained in a comparison with their wind-tunnel experimental results are very good, although a comparison with full-scale Nibe measurements showed that the model overestimates the values of the velocity deficit. They attributed this discrepancy to meandering and obtained better agreement when they corrected for this effect using the method proposed by Ainslie,[53] which will be discussed later. A starting Gaussian velocity deficit profile is imposed, which would correspond to the end of the near wake (Figure 1). The results of the calculations show a clearly defined annular peak of turbulence intensity, as shown in Figure 2, although this peak should really be located in the near wake, upstream of the starting region (in general, as will be pointed out again later, application of the initial conditions of the wake is an uncertain aspect of all wake models). Although there is considerable scatter of the experimental results around the line of calculated values, the peak values of turbulence intensity are well defined and, in a cross-wind profile, are predicted within an error of 3%. In a vertical plane the turbulence intensity distribution is similar to that appearing in Figure 2, and the upper and lower peaks are predicted within errors lower than 0·1% and 5% respectively.

Based on the model developed by Ainslie,[53] the company Garrad and Hassan has developed the code EVFARM, described by Tindal *et al.*[75] and Adams and Quarton.[76] The code incorporates two alternative semiempirical models to calculate wake turbulence. One of them, described by Hassan,[77] gives uniform turbulence in the wake, whereas the other, described by Luken *et al.*,[32] takes into account radial variations in turbulence intensity. Adams and Quarton[76] use both EVFARM and UPMWAKE codes in combination with machine load predictive tools to provide a method for fatigue load prediction. As part of this study, a comprehensive validation of both codes is made using the wind tunnel measurements of Hassan;[77] good agreement is found for the velocity deficit, which is underestimated by 2% and 3% by UPMWAKE and EVFARM respectively; the turbulence intensity is overestimated by 11% by EVFARM and underestimated by 17% by UPMWAKE. They also noted that there was better agreement with experiments if a downstream displacement of the origin is considered to account for development of the expansion region. The physical reason for this displacement is not clear, because even though the expansion region is located downstream of the rotor, the shear layer starts immediately behind the rotor. In the initial region of the wake some important discrepancies were also observed between the results of UPMWAKE and the Nibe measurements published by Taylor *et al.*[59] By eliminating the boundary layer approximation used in UPMWAKE, Crespo *et al.*[28] and Crespo and Hernández[78] proposed an elliptic model to deal simultaneously with the axial pressure gradients and diffusion effects by retaining both the axial and transverse diffusion terms. Their model therefore describes both the evolution of the expansion region and the diffusion processes. No fundamental differences between the results of the elliptic and parabolic models were found, and displacement of the origin was apparently not necessary. Other elliptic models have also been proposed by Cleijne *et al.*[79] and Ansorge *et al.*[80] Any improvement in the agreement with experiments when comparing elliptic and parabolic codes is only slight and does not seem to justify the additional computational effort needed.

Another reason for the discrepancies observed between models and experiments in the near wake may be the uncertainty involved in the initial velocity deficit, assumed to be either uniform or of a prescribed shape (Gaussian in Reference 26) and obtained from the thrust coefficient. More recently, Magnusson,[81] using blade element theory and experimental results, investigated the influence of the non-uniform incident wind and the yaw on the near-wake characteristics. Zervos *et al.*[82] relate initial wake development to the aerodynamics of the rotor, using a vortex particle method governed by the vorticity transport equations and the Biot–Savart law. Although these authors do not need initial data to start calculating the wake, the validity of the solution is limited to the short initial expansion region where diffusion effects can be neglected. In general, non-uniform values of axial azimuthal velocity components at the end of the expansion region can be obtained using a classical blade element model, a strip model[83] or even vortex particle and lifting line methods, such as those proposed by Zervos *et al.*[82] or Cleijne *et al.*[79] The blade element and strip methods include the effect of drag on each blade section, and this can be used to estimate the dissipated power and the turbulence kinetic energy produced, whereas vortex particle methods, which do not include aerodynamic losses, do not have this possibility. Cleijne *et al.*[79] attempted to combine field and vortex particle models in such a way that boundary conditions for the field model are obtained from the vortex particle method; although there is better agreement with the experimental results in some cases, the complications and additional computing costs involved do not appear to be justified.

An alternative approach that requires less computing capacity is the multiparametric wake model of Voutsinas *et al.*,[84,85] which was further developed by Cleijne *et al.*[79] and Voutsinas *et al.*[86] This model divides the wake into the rotor region, the near-wake region and the far-wake region, and applies a vortex particle method in the rotor region, a field model in the near-wake region and, in the far-wake region, explicit self-similar expressions similar to those used in the kinematic models. Different assumptions are made to match the different regions. The method was partially successful in simulating the experimental results of the Nibe turbines given in Reference 39. Later, Magnusson *et al.*[87,88] applied the model to reproduce the experimental results of Alsvik wind farm. The agreement between experimental and model results for the velocity deficit is qualitatively reasonable, with relative errors of less than 25% and a scatter of experimental results of similar order. However, the comparison of turbulence characteristics (turbulence kinetic energy and Reynolds stress) is poorer, with relative errors that can even reach 200%, although tendencies are well predicted.

All the previous models solve the Reynolds-averaged turbulence flow equations and use a closure scheme, based on zero-, one- or two-equation models, to calculate the turbulence transport terms. An eddy viscosity is used in all cases which implicitly assumes an isotropic turbulence field. Transport equations for the Reynolds stresses have only been used occasionally to calculate this type of wake. Ansorge *et al.*[80] used a Reynolds stress turbulence model based on the commercial code PHOENICS and obtained reasonable results, although the computational effort may still be considered too great from an engineering point of view. Neither is it clear whether there was improved agreement with experiments.

In general, the field models give an acceptable representation of the flow field and a better insight into the processes governing wake development than the kinematic models.

Meandering of the Wake

In general, field models show better agreement with wind tunnel experiments than with field experiments, one reason being the meandering of the wake. When there is meandering, turbines can be significantly misaligned most of the time. Whale *et al.*[89] found significant differences between the experimental results obtained in a wind tunnel and those of large-scale tests, although they point to other factors being partially responsible besides wake meandering, such as the scale effect and the influence of terrain.

The individual wakes calculated by both kinematic and field models do not directly take into account eddies that are large in comparison with the size of the wake and which can move it bodily, a phenomenon known in studies of atmospheric dispersion as meandering. Nor is this effect usually included in wind tunnel tests. The maximum velocity deficit will be smaller than that predicted by the theoretical models or wind tunnel tests, and, in addition, velocity fluctuations may appear that can be interpreted as an additional contribution to the turbulence kinetic energy. Baker and Walker,[68] Ainslie[52] and Taylor[26] took meandering into account by assuming that the large eddies increase in size linearly with downstream distance x and in proportion to the standard deviation of the wind direction, σ_θ. However, Högström *et al.*[20] argue that this is not the correct approach, because σ_θ is caused by eddies of all sizes, including those that are smaller than the wake diameter, and take for their analysis a value of $0{\cdot}053x$ for the size of large eddies, based on the results of some oil-fog experiments.

4. Wind Farm Models

This section is dedicated to study wake effects in wind farms, where there are usually many machines located in irregular terrain. The first subsection is dedicated to study the interaction of several wakes, and the next one to the topographic effects. In this last subsection, methods to take into account simultaneously wake and topographic effects are also reviewed. A brief review is also made of offshore wind farms, which are nowadays of great interest, although this subject is so broad that it will have to be treated in a separate review.

Interaction of Several Wakes

A wind farm consists of many wind turbines whose wakes can interact and whose turbines may be affected by the wakes of several machines located upstream. Wind farm codes usually rely on the results of single-wake calculations and make superposition assumptions to take into account the combined effect of different wakes. The linear superposition of the perturbations created by wakes of different machines in a wind farm model was first used by Lissaman[9] in a classical paper, although this assumption fails for large perturbations as it overestimates velocity deficits and could lead to the absurd result of negative velocities when many wakes superimpose. Instead, Katic *et al.*[36] assumed linear superposition of the squares of the velocity deficits. In this case the cumulative effect, when there are many wakes, will be smaller than that calculated for linear superposition, and, in general, this assumption provides better agreement with experimental results than the linear superposition. The corresponding code, named PARK, was applied by Beyer *et al.*[90] for the optimization of wind farm configurations using genetic algorithms. Voutsinas *et al.*[38,86] formulated an explicit energy equation, also used by Kiranoudis and Maroulis,[37] by assuming the total energy loss at each point of the flow field due to the presence of different machines to be equal to the sum of the individual energy losses due to each machine. In this way they obtained the velocity field and then calculated the incident velocity on each machine by taking the average over the turbine disk. To evaluate the individual energy losses of each wake, they considered the difference between the wake velocity and the inflow velocity on the machine that creates the wake, whereas Katic *et al.*[36] considered the difference between ambient and wake velocity. For small velocity deficits both methods should give similar results. Based on the idea that wake turbulence should increase diffusion when the wakes superpose, Beyer *et al.*[91] proposed a modification of the parameters describing single-wake development. However, although they obtained acceptable agreement with experimental results in the Hamswehrum wind farm, no systematic procedure is provided of how to apply the method to other configurations.

Smith and Taylor[23] found, for a particular experimental configuration of two machines in a row, that the wake velocity of the downstream machine recovers more rapidly than the one upstream, so that, at the same relative position, the velocity deficit is smaller in the downstream machine wake. This result contradicts the qualitative behaviour predicted by the two previous superposition assumptions and may be explained by the turbulence levels and shear stress profiles generated by the upstream machine, which enhance momentum diffusion, leading to a faster recovery in the downstream machine. Stefanatos *et al.*[92] also showed experimentally that the linear superposition of wakes provides a poor approximation of the flow. By making a number of crude assumptions concerning the momentum transfer within the downstream wake that is imbedded in the upstream wake, Smith and Taylor[23] were able to formulate a semiempirical superposition law that works quite well. However, it is cumbersome and can only be applied for the interaction of the wakes of two turbines in a row. For small velocity deficits the method reduces to the linear superposition assumption, but it is not clear what the limit is for the quadratic superposition assumption to be recovered. Voutsinas *et al.*[38,86] claimed that their explicit energy equation gives similar results to this method but do not give any physical explanation.

When there are many turbines in a line, it has been observed experimentally[93] that while the first turbine produces full power, there is a significant decrease in power in the second turbine, with practically no further loss in successive machines. Based on these observations and on the results of the calculations of

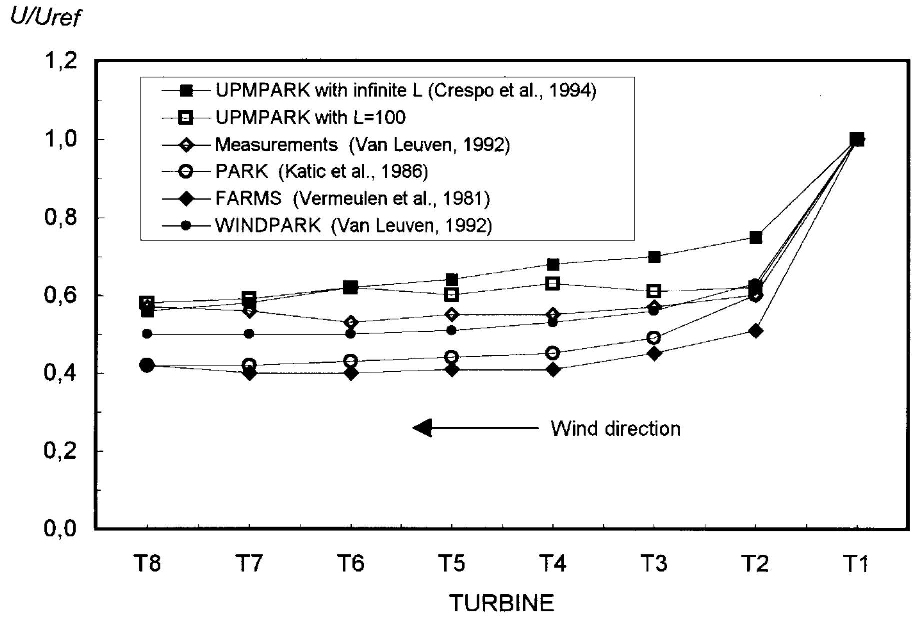

Figure 5. Velocity distribution in wake region of seven turbines forming a row. Comparison of measurements and results of several wind farm codes. Measurements and configuration correspond to the Zeebrugge wind farm.[93,94] *U_{ref} is the unperturbed upstream velocity at hub height. The UPMPARK calculations have been performed for two stability situations: neutral atmosphere (Monin–Obukhov length, $L = \infty$) and stable atmosphere ($L = 100$ m, hub height 31 m)*

Crespo *et al.*,[28] van Leuven[93] assumed in his farm model (WINDPARK) that a given turbine is only affected by the wake of the closest upstream turbine, obtaining good agreement in comparison with measurements made at the Zeebrugge wind farm[93,94] (see Figure 5). In this figure are also shown the results of calculations with UPMPARK,[95] PARK[36] and FARMS, based on the kinematic model MILLY.[96,97]

Regarding the increase in turbulence intensity which occurs when there are many turbines in a line, Builtjes and Vermeulen[98] carried out an experimental investigation in a wind tunnel with wind turbine simulators and found that turbulence intensity reached an equilibrium value after three to four rows of turbines. They also observed that turbulence intensity had a maximum in the second row of turbines, where it was higher than the equilibrium value. Luken[99] proposed a simple correlation to calculate the equilibrium value of turbulence intensity as a function of turbine spacing.

Crespo *et al.*[28] applied their elliptic model for studying the interaction of the wakes from two turbines in two configurations: abreast and in a line. There was good agreement with experimental results, and when other superposition assumptions were compared, it was found that the linear superposition worked well for the two machines abreast, in which velocity deficits in the interference region are small. However, for the two turbines placed in a row the linear superposition overestimated the velocity deficit, as was to be expected. The previously mentioned model of van Leuven[93] which considers that only the wake of the closest turbine upstream acts on a given turbine also agrees well with the elliptic model.

When the results of the elliptic model of Crespo *et al.*[28] are considered, it can be observed that the truly elliptic effects, such as axial pressure variations, only occur very close to the turbine, so that the parabolic approximation may be a suitable approach for studying wake interactions over most of the region where this interaction occurs. Moreover, to extend the fully elliptic code to a wind farm consisting of many machines, besides consuming a lot of calculation time, would require very powerful computers and would therefore be of little practical interest for modelling wind farms. Because of this, Crespo *et al.*[95,100] have developed a code, UPMPARK, extending the parabolic UPMWAKE code for a single wake to the case of a park with many machines. No assumptions are required regarding the type of superposition or the type of wake to be used, as all the wakes and their interactions are effectively calculated by the code. A brief description of UPMPARK follows.

The conservation equations solved are the same as those for the single-wake code UPMWAKE, as specified in Reference 56, and turbulence is closed using a k–ε model. The wakes of the machines diffuse in an ambient flow that represents the surface layer of the atmospheric boundary layer, in which instability effects are retained by means of the Monin–Obukhov length. For uniform terrain this ambient basic flow is the same over the whole wind farm, although the code could also handle moderate terrain irregularities, using a superposition assumption for the effects of terrain and wakes[101] that will also be reviewed below. At infinity, in regions not perturbed by the wind turbines, and in the upstream section, boundary conditions are imposed that correspond to an unperturbed ambient flow. As we progress downwind in the numerical marching procedure associated with the parabolic model, each turbine found at any cross-section of the farm acts as a source (or sink) of the three velocity components, k and ε. The number of grid points should be large enough to contain the whole cross-section of the park and to consider that the lateral boundaries are at infinity. As the code is parabolic, there is no limit to the downstream distance, except for the fact that if the wakes diffuse very much, the number of grid points may not be large enough to apply the boundary conditions at infinity. The case of wind turbines in a row is particularly suited for this code, which has been validated by comparison with measurements made on wind farms in Zeebrugge, Sexbierum and Vindeby and on the Nibe wind farm.

Adams and Quarton[76] extended the UPMWAKE model to wind farms using a procedure quite similar to that of UPMPARK, and compared the results obtained with this extended version of UPMWAKE and EVFARM (also extended to wind farms) with the wind tunnel experiments of Hassan[77] for double-wake cases, and found a degree of agreement smaller than for the single-wake case. EVFARM predicted the velocity deficit within 1% error for the near wake and within 10% for the far wake, whereas UPMPARK underpredicts the velocity deficit by 33% for the near wake and by 5% for the far wake.

Topographic Effects

Usually, wind farm models make the assumption that the terrain is flat and that the unperturbed wind velocity is uniform, an assumption which is not reasonable in many cases of interest, since, as is well known, terrain irregularities can be used to enhance or concentrate wind power. Studies on the influence of ambient flow on the wake development are scarce. John and Schobeiri[102] made an experimental study of the influence of streamline curvature and longitudinal positive pressure gradient on the development of the wake of a cylinder in a two-dimensional curved channel, observing that the wake decay is slower with the positive pressure gradient than with a zero pressure gradient. The effect of curvature on mean velocity deficit distribution is small, whereas it strongly affects the Reynolds stress distribution, particularly in the inner half of the channel.

For terrains that are moderately complex, the simple procedure of adding the velocity perturbations of the wake and terrain should give an approximate flow field; this procedure was applied to the Ampurdán wind farm.[31,40] Measured and calculated values of power output of the wind farm as a function of wind direction were compared. A scatter of measurements of the order of 20% was found and their average was predicted with an error of less than 10%. A similar procedure was used by Adams and Quarton[76] and by van Leuven[93] to take into account the interaction of an obstacle and turbine wakes in the Zeebrugge wind farm. However, in all the above cases there were simultaneous interactions of terrain and several wakes, which raises some uncertainty about the validity of the results, since, as is well known, the linear superposition of several wind turbine wakes overestimates the velocity deficit, as indicated in the previous section. Crespo *et al.*[101] studied the Monteahumada wind farm, in which the velocity irregularities of the terrain and the velocity deficit created by a single wake interact and are both of a similar order of magnitude; this configuration is thus appropriate to examine the validity of the assumption of linear superposition of wake and terrain effects. Although the data were few and not easy to interpret, the study shows that for a moderately irregular terrain the linear superposition of wake and terrain effects gives good results (with relative errors of the order of 10% and less than 20%), whereas for the interaction of two wakes with perturbations of a similar order of magnitude this assumption is less valid.

Voutsinas *et al.*[38] described a procedure to take into account non-uniformity in wind velocity and the curvature of the streamlines in wind farms with small terrain irregularities, which is similar to the linear superposition; some sample calculations were made, but no experiments were presented to validate the method. Stefanatos *et al.*[103] developed another model which assumed that the vorticity fed by the wind turbine into its wake follows the streamlines of the unperturbed wind flow field, and compared the results with the experimental ones, obtaining a good degree of agreement in the upper part of the wake (within 5%). However, in the lower part of the wake the calculated velocity deficits exhibit a downward displacement of one-tenth to one turbine diameter. Taylor and Smith[104] made measurements in a wind tunnel which showed that the changes in the wake characteristics due to topography may be important. Hemon *et al.*[105] made a theoretical study of how terrain may modify turbine aerodynamics and near-wake characteristics. Second-order corrections to the linear superposition of terrain and wake effects were made by van Oort *et al.*[106] using PHOENICS. They found that terrain irregularity creates additional turbulent diffusion near the ground, which diminishes the wake effect; on the other hand, above the apex of a hill the streamlines concentrate, thereby increasing wake effects. Crespo *et al.*,[100] Günther *et al.*[107] and Ansorge *et al.*[80] also used the commercial code PHOENICS to model the interaction of wakes with obstacles and terrain irregularities. Stefanatos *et al.*[103,108] and Helmis *et al.*[60] give some guidelines, obtained from their experimental results in both wind tunnel and large-scale tests, to study the interaction between wake and terrain.

A related problem arises in offshore wind farms where, when the wind blows from land to sea, there is an internal boundary layer, whose development is superposed on that of the wakes, as mentioned by Crespo and Gómez-Elvira.[109] As the surface roughness of the sea is usually much smaller than the corresponding roughness on land (see e.g. Reference 110), it is to be expected that wind velocity will be greater and turbulence intensities lower than for equivalent inland stations. Consequently, turbulent diffusion of the wake will also be lower and wake effects will probably be more persistent downstream. Wake effects in offshore wind farms obtained from both experiments and numerical models are reported by Frandsen *et al.*[70] and Crespo *et al.*,[71] and their effect on fatigue loading by Frandsen.[111]

5. Quasi-analytical and Semiempirical Expressions to Describe Wake Evolution

In many cases it is of interest for the designer to have, as an alternative to numerical models, analytical expressions which can estimate the order of magnitude and the tendencies of the most important parameters characterizing wake evolution. However, this issue will not be examined in detail in this article, which is more concerned with aspects of modelling. Regressions or correlations of this type were obtained by different authors to describe single-wake behaviour: see References 20, 32, 40 and 112–114 for the velocity deficit and the width of the wake, and References 20, 25, 27, 42, 61, 113 and 115 for turbulence intensity. Taylor[26] performed a parametrization of the calculated wake magnitudes as functions of several dimensionless input parameters; however, the results were represented in graphic form and no regressions were made. The case of wind clusters is covered in a review by Luken,[99] who proposed a correlation for the equilibrium value of the turbulence intensity reached in a row of turbines, using the experimental results of Builtjes and Vermeulen.[98] This point is discussed in more detail by Frandsen *et al.*[70] who presented correlations giving values of the average velocity, turbulence intensity, turbulence scale and width of the wake at different positions of each machine in a row as functions of their operating characteristics. These correlations are obtained by making the best fit with numerical results from UPMPARK, and are validated by comparison with measurements made in Vindeby wind farm.

Most of the above studies express wake diffusion as a function of downstream distance made dimensionless with turbine diameter, x/D, dimensionless turbine height H/D, thrust coefficient C_T and ambient turbulence intensity. Instead of using x/D, Magnusson[112] and Magnusson and Smedman[113,114] expressed wake diffusion as a function of the transport time $t = x/u$ (where u is the local incident velocity), made dimensionless with t_0, the transport time where the near wake ends. In turn, t_0 is made dimensionless with the rotational frequency f. Implicitly, then, the authors were considering another parameter, the tip speed ratio $\pi f D/u$.

The effect of atmospheric stability (expressed in terms of the Richardson number) on velocity deficit decay was taken into account in the correlation given by Magnusson and Smedman.[74]

All these correlations have been compared with some experimental results and show at least an acceptable degree of agreement, although more work is needed to carry out a full comparison both among these correlations and with experimental results.

6. Loading under Wake/Wind Farm Conditions

As already mentioned, there is large body of data available in the literature which has been obtained from measurements made of the flow characteristics of wind turbine wakes, and considerable efforts have been made to develop numerical models, whose results are in many cases in good agreement with the experimental results. However, although such wake measurements and modelling have focused on energy production and loads, relatively few direct measurements of structural loads under wake conditions have been made, despite the shortcomings of the international standard on loads and safety[116] and the lack of guidelines on how to take loads into account.

Dynamic and Fatigue Loading

The most serious expected structural effect on a wind turbine which is in the wake of a neighbouring machine is fatigue. The combined effect of increased turbulence, wind speed deficit and changes in turbulence structure causes dynamic loading which may excite the wind turbine structure. The apparent effect on, for example, flapwise bending moments depends primarily on the distance to the neighbouring machine. As mentioned in Section 3, two wake regions can be considered: the near wake, which extends over three rotor diameters, and the far wake. The three-diameter length is chosen as the distance below which the effect on a machine which is partly in the wake of another (half-wake load case) is clearly visible on, for example, blade loads.

Near Wake

Some of the first measurements of fatigue loading in wakes were made in the early 1990s by Vølund[117] and Stiesdal.[118] The measurements made by Vølund[117] on a 250 kW machine, which was in the wake of a turbine of similar size placed two rotor diameters upstream, showed an increase in the standard deviation of flapwise bending moment of approximately 100% relative to the unobstructed case. Measurements also showed that loads were largest when the machine was exposed to half-wake conditions. The concept of equivalent load, which is the amplitude of a sinusoidal load with a fixed frequency that would generate the same fatigue damage as the actual (random) load, was introduced by Stiesdal[118] to provide a more precise fatigue measurement than the standard deviation. Here the separation between the 450 kW machine on which measurements were made and the wake-generating machine was $2{\cdot}5D$. The equivalent flapwise load increase was about 100% at $12\,\mathrm{m\,s^{-1}}$ and lower for high wind speeds. When loading under wake conditions was weighted with non-wake operation, the average effect was much smaller (10%–20% in terms of equivalent load).

Far Wake

Frandsen and Christensen[119] made measurements in the large wind turbine array Nørrekaer Enge II in Denmark, consisting of 42 machines of 300 kW, separated by $6D$–$8D$. Two turbines in opposite corners

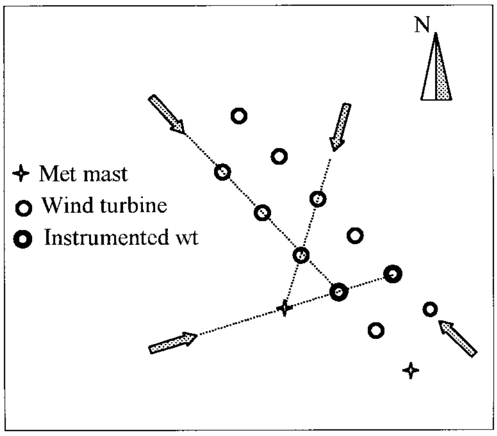

Figure 6. Schematic sketch of Vindeby wind farm

were instrumented to measure stresses in towers and blades. To the north of the wind farm there is open water and the surrounding terrain is farmland. For northerly winds one of the instrumented machines is exposed to the low turbulence of the sea and the other one to the turbulence environment of the interior of the wind farm. For southerly winds one instrumented machine is exposed to the wind farm turbulence while the other is open to the free (ambient) flow off the farmland. In both cases there was a clear increase in the equivalent load when the instrumented machine was in the direct wake of a neighbouring machine, but the integrated effect of wake and non-wake operation was significantly smaller. It was found that the integrated effect in terms of fatigue loading for the higher ambient turbulence (southerly wind) was insignificant. For low ambient turbulence (northerly wind) the added loading in terms of equivalent load due to wake effects of the wind farm was approximately 10%.

Frandsen and Thomsen[120] carried out similar measurements in the Danish offshore Vindeby wind farm. The wind farm, which is represented schematically in Figure 6, consists of 11 machines of 450 kW which are arranged in two rows, each machine and each row separated by approximately $8D$. Two instrumented masts provided measurements of ambient and wake flow parameters. The geometry of the wind farm and the instrumentation allowed for both single- and multiple-wake measurements. Data, including equivalent loads, were recorded for 2 years. An example of the measured data is shown in Figure 7, where equivalent widths of the flapwise bending moment of a blade are plotted against wind direction. Each data point represents 0·5 h of operation. For a wind direction of around 255° the machine rows are aligned with the wind. As can be seen, despite the fairly large spacing between wind turbines, the fatigue load increase in the wake is significant, about 80%. The data shown for other wind directions demonstrate that there is no appreciable difference between single- and multiple-wake loads. In

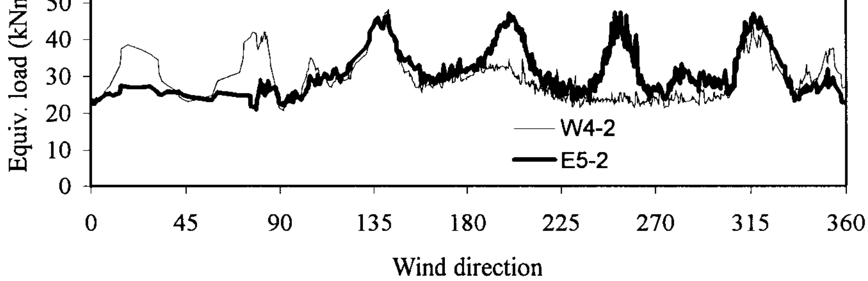

Figure 7. Equivalent load widths of flapwise bending moment of instrumented units 4 W and 5E in Vineby wind farm

Reference 120 a model for adding up the wake effects was devised to reproduce the integrated effect of the individual wakes. As in the case of Nørrekaer Enge II, the integrated effect was much lower. It was also estimated that the integrated fatigue loading would be approximately 20% lower in offshore conditions than in onshore sites.

The Sexbierum wind farm in the Netherlands consists of 18 units of 300 kW, placed in three rows, each with six machines.[121] The machines are spaced $5D$ or $10D$ apart and the rows are separated by $8D$. Six meteorological towers provided information on flow characteristics. As in the Vindeby wind farm, it was found that equivalent loads under single- and multiple-wake conditions were very similar.

Measurements have been made on one wind turbine in the experimental Alsvik wind farm in Sweden,[122] which has four machines sited so that the instrumented unit is exposed to $5D$, $7D$, or $9{\cdot}5D$ single-wake loads, depending on wind direction. The terrain is smooth and the ambient turbulence low. The wind farm layout is unique in offering many experimental possibilities. It was found that when the instrumented machine is within $7D$ to $9{\cdot}5D$ downstream of another machine, there are no significant half-wake loads. However, the effect on a machine which is only partly in the wake of another one is different in the $5D$ situation. It was also found that under full-wake conditions the equivalent load is increased by 10% at $9{\cdot}5D$ and up to 45% at $5D$.

The Kappel wind farm in Denmark consists of 24 units of 400 kW, sited in a row on a westerly shoreline, with $3{\cdot}7D$ separations. Thomsen *et al.*[123] discussed whether fatigue load increased (in the integrated sense) under wake conditions, arguing that the load increase would be smaller for high-wind cases, as wake effects are lower in such conditions. Nevertheless, the experimental evidence pointed to a significant increase in the equivalent load, which represents a fatigue loading.

Modelling

As mentioned above, there have only been limited efforts made towards directly estimating wake loading. In References 75 and 120 the task was solved by altering the (free flow) design turbulence. Thus the change in design turbulence accounted for intermittent wake conditions with high turbulence, smaller turbulence scale and half-wake cases. Tindal *et al.*[75] presented an elaborate scheme of how to summarize the numerous load cases. The reader is referred to the report for more details.

In Reference 120 a simplified model of taking the increase in fatigue loading into account was discussed and, to some extent, verified by the data presented. Similar models have previously been applied[124] and different expressions have been proposed for the 'virtual' or 'efficient' turbulence intensity that will result in the same fatigue damage occurring as in the flow-wise complicated environment of a wind farm array. This turbulence intensity depends on the geometry of the array, the thrust coefficient of the wind turbines, the separation of wind turbines and the ambient turbulence. Despite the mentioned complexity of the flow in wakes/wind farms, the model proposed by Frandsen and Thomsen[120] has been demonstrated to work for turbine separations larger than $3D$–$4D$ and, with some modifications, also for smaller separations.

Extreme Loading

Extreme loads are to be expected occasionally during the lifetime of a wind turbine. Extreme loading may occur either under common wind conditions with the wind turbine in operation or under extreme wind conditions (e.g. 50 years return-period wind gust). Loads on an operating machine increase with increasing wind speed up to a certain velocity, above which they may still continue to increase, depending on the turbine design.[120] At wind speeds higher than about $15\,\mathrm{m\,s^{-1}}$, wake effects rapidly diminish, since the thrust coefficient decreases, making the wind farm more 'transparent'. Under extreme wind conditions the wind turbines will be parked, with little or no wake effects from neighbouring machines. However, extreme loading may also occur during non-extreme wind conditions, since (1) the typical blade tip speed of large machines is about $60\,\mathrm{m\,s^{-1}}$ and the loads may be correspondingly high, (2) large yaw errors generate large dynamic response which may also cause large extremes, and (3) transient loads caused, for example, by emergency stops may signify the largest loads for one or more machine components in the machine's lifetime. This case has not been satisfactorily dealt with in the literature.

7. State of the Art and Conclusions

There are many different models which simulate the behaviour of wind turbine wakes and wind farms. Most of them are based on a deterministic simulation which takes into account each individual wind turbine. Models considering the turbines as distributed roughness elements are not much used now, although they may be of interest in the future to predict overall changes in wind characteristics originated by the large wind farms which are likely to be established.

Many of the models proposed show an acceptable degree of agreement with the experiments with which they are compared. However, the assumptions and coefficients that are chosen are such that the agreement with some particular experiments may be good, although the overall validity has not been checked in more general situations. The models which depend on the least simplifying assumptions are better suited in dealing with different configurations and in reproducing wake development in more detail. For example, an axisymmetric model will never be able to reproduce the peak in turbulence intensity in the upper part of the shear layer in the near wake. In general, the more complicated models are more likely to accurately reproduce flow field characteristics, although in many cases the physical reasons for the hypotheses used, particularly in those aspects related to turbulence modelling, are not always clear.

The classical wind farm model relies on an individual wake model, usually a kinematic model, and some sort of superposition assumption. In general, the superposition assumptions cannot be justified from a physical point of view and may even lead to absurd or contradictory results; the corrections and alternatives necessary to handle such physically unrealistic situations are either unjustifiable or difficult to implement.

Although it is a generally held opinion that field models are too complicated and that they are impossible to extend to a wind farm consisting of many turbines, we do not think that this is still necessarily the case. For example, the UPMPARK model, which retains all the characteristics of one of the most complete non-symmetric k–ε wake models, UPMWAKE, can be successfully run on a workstation in reasonably short times for large wind farms such as Sexbierum or Taendpibe, and even on a PC for wind farms with a smaller number of machines. The most important simplifying assumption used by UPMPARK is the parabolization of the mathematical problem in the main wind direction.

While greater emphasis used to be directed to calculations of velocity deficits and park efficiency in terms of energy production, calculations are nowadays more orientated to other issues, such as estimating magnitudes related to the structural and fatigue behaviour or fluctuations in the electrical energy produced by machines affected by upstream wakes. To estimate these magnitudes, it is necessary to know the turbulence characteristics of the flow (turbulence intensity, correlations and spectrum) and wind shear data, which clearly cannot be provided by simple kinematic models.

There is experimental evidence that wake effects may significantly increase the equivalent load experienced by a turbine under wake conditions, although further research is still necessary for a more precise estimation of their influence in different operational conditions. However, measurements also show that the integrated loading effect of wake and non-wake operation may be, in some circumstances, significantly smaller than that measured under continuous wake conditions. It has also been found that under multiple-wake conditions the equivalent loads due to different wakes are not additive. Only limited efforts have been made towards developing predictive models to estimate the loading increase due to wake effects.

An issue of some importance is the non-isotropic nature of the turbulence of ambient atmospheric flow, in contrast with the more isotropic turbulence in the wakes. This problem cannot be dealt with by the k–ε or eddy viscosity wake models. The use of Reynolds stress models involves greatly increased mathematical difficulties and we do not think it can be treated by the engineering codes in general use. Alternative strategies should be explored.

One of the most important difficulties that has not been treated satisfactorily is the choice of appropriate input parameters to define ambient unperturbed flow, particularly in complicated terrains. Usually, a comparison with wind tunnel experiments is reasonably straightforward, but when field experiments are compared, there are many difficulties, and effects such as meandering have never been satisfactorily modelled. The results obtained from experimental and modelling studies for terrains of varying roughness and the appearance of internal boundary layers, such as those observed in wind farms located near the coast to offshore, should be incorporated into the description of ambient flow. For a terrain that is moderately irregular, UPMPARK assumes a superposition of the perturbations due to the wakes and those of the terrain, which are estimated either from measurements or from codes such as WASP. However, for complicated topography this approach may not work. A code which simultaneously takes into account terrain and wind turbine wakes would be too difficult to apply and still contain many uncertainties regarding the appropriate boundary conditions. Some work has been done, but more is needed, towards estimating the local effects of interference of single wakes and terrain irregularities. The problem is that it is difficult to envisage solutions and we will always be solving particular problems that, at most, could only point to general tendencies. A possible alternative for cases in which turbine spacing is small compared with the characteristic length of variation in terrain irregularities could be to treat the problem as one of flow over an irregular terrain of changing roughness, as indicated in Section 2.

Although considerable progress has been made since 1992, some of the conclusions and recommendations presented here are of a similar nature to those formulated in the final report of IEA, Annex IX on Wake Effects.[3,125]

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