Wake flow characteristics in low ambient turbulence conditions

”Copenhagen Offshore Wind 2005”

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Abstract

Inflow measurements performed with a five hole pitot tube mounted on one of the blades of a 80 m diameter wind turbine, situated at the Tjæreborg wind farm site in Denmark, were conducted from October to November in 2003. The aim of the experiment was to get detailed insight in the structure and dynamics of the wake flow caused by a wind turbine rotor. This was achieved, as both local inflow angle (local angle of attack) and relative velocity can be derived from the five hole pitot tube data. The considered turbine was exposed to different *single wake* situations, with the closest position of an upstream turbine being equal to 3.3 D.

In general, the measurements have confirmed that an important mechanism for increased loads in wake operation is the meandering of the wake deficit from the upstream turbine as proposed in a new model for simulation of wake operation, presented first time in the spring 2003. For the further validation and refinement of this model a key question is how much added turbulence is caused by the up-stream rotor (in particular from the discrete tip vortices), and how much will this contribute to the loading of the rotor relative to the loading from the meandering of the wake deficit. This is the main issue of the paper, and the analysis has been focussed on analysis of a number of data files, measured during very low ambient turbulence conditions, which seems to occur in some situations where the wind comes from the sea which is in a distance of about 1 kilometre from the site. When the ambient turbulence is low, as is typical for offshore operation, the meandering of the wake is also modest, and therefore it is possible to separate the part of the blade azimuth being inside the wake from part being outside in such files. This enables derivation of statistics for angle of attack variations for the blade inside the wake and a direct comparison with the corresponding data for the blade being outside the wake.

The analysis of the data, and the comparison with simulations, has shown that additional turbulence should be added in the model for the azimuth interval, where the blade is passing through the wake. For the analyzed cases with a high thrust coefficient it seems that the turbulence, created by the upstream rotor, corresponds to at least 15 % turbulence intensity in the inflow. However, rainflow counting results, based on the measured and simulated flapwise blade root moment, indicate that the length scale of the added wake turbulence should be less than the length scale of the ambient turbulence.

1. Introduction

The results presented in the present paper is part of a research work at Risoe initiated in 2002 with the aim of developing a computational aeroelastic model complex, which can be used for detailed analysis of fatigue loads as well as extreme loads in wind farms. A specific goal has been to develop a tool enabling an improved prediction of the extreme rotor loads as for example yaw loads.

The most common methodology for prediction of fatigue loads in wake operation is the approach, where the influence of the wake is taken into account by introducing an increased, effective turbulence in the aeroelastic simulations. This increased turbulence will be dependent on a number of parameters such as distance to the upstream turbine, turbine loading, component Wöhler exponent and ambient turbulence. A description of this methodology, and the research work on which the method is based upon, has been presented in the final reporting of the pioneering work of the Joule project “Dynamic

Loads in Wind farms" [1] and in a recent comprehensive report by Frandsen [2]. It is also at present the recommended method to take into account wake operation in the IEC standard [3] for wind turbines.
The new model complex was first presented in Thomsen et. al [4] and in Madsen et. al [5]. The underlying hypothesis is that the wake deficit from the upstream turbine, in combination with meandering of this deficit, is a major contributor to the increased loading. The detailed formulation of the meandering mechanism, applied in the new proposed wake method, has been described by Larsen et. al [5].
However, the meandering of the wake, and its influence on the *fatigue*- and *extreme loading* on a down stream turbine, seems not to have been paid much attention in the past and is for this reason also only briefly considered in a recent review study on wakes by Vermeer, Sørensen and Crespo [7]. When meandering is mentioned it is often in cases where computed wake characteristics are compared with full-scale measurements in free wind. Tylor [8] compared model results with wake measurements on the Nibe 630 kW turbines. He describes that the variations in on-site wind direction shift the wake across the downstream rotor disc, and this will increase the average power output from the downstream turbine measured over some time, a mechanism not taken into account in the modelling. Ainslie [9] discusses the subject in more details and mentions that wake meandering effects can have considerable influence on measured wake deficits, in particular in non-stable atmospheric conditions. It seems that Ainslie [9] is the first to model the effect from wake meandering on wake deficits by correlating the wake meandering to the variability in the wind direction. In this way he computes the averaging of wake deficits for two full scale experiments, and the influence from the meandering is considerable in reducing the depth of the deficits [9]. Further comparisons of model results, including the correction for meandering with a number of different full scale experiments, are presented by Ainslie [10], and a good correlation between experimental data and model results is found for the centreline velocity deficit decay as function of downstream distance.
The influence of meandering is also described by Frandsen et. al [11] in the way, that the maximum velocity deficit measured in full scale in free wind will be less than the one predicted by wake models not taken into account meandering. Further, that additional velocity fluctuations from the meandering of the wake deficit will appear in measurements at fixed positions in the wake and thus contribute to the total turbulent kinetic energy.
In the new proposed wake method the meandering is assumed to be due to the bigger scales of the lateral- and transversal free stream turbulence components - in summary the meandering is computed on basis of the average lateral- and transversal turbulence components over the rotor disc. It then follows that the meandering should be modest in low turbulence conditions as will be considered in the present paper. A modest meandering of the wake means that the downstream turbine will operate under approximately identical degree of wake conditions over some time which enables a more detailed study of the turbulence characteristics inside the wake, than if the wake continuously is moving due to wake meandering. The size and character of the turbulence inside the wake, and its influence on fatigue loads, is the main subject of the paper.
The experimental basis for the study is inflow measurements performed in 2003 on one of the blades of a 2 MW turbine situated in the small Tjæreborg wind farm in the south-western part of Jutland about 1 km from the north sea. The local inflow is measured with a five hole pitot tube mounted on the blade, and the local relative velocity and angle of attack can be derived from these measurements. A period with a very low turbulence, in combination with wake operation caused by a turbine positioned around 3.3 rotor diameters upstream, has been studied in detail.
The new model for aeroelastic simulation of wake operation will be briefly described. So far the turbulence generated by the upstream rotor has not been taken into account in the model but, even without this additional turbulence wake contribution, the model has been shown to predict extreme rotor loads in good agreement with measurements, Thomsen and Madsen [13]. On basis of the results from the experimental analysis of the wake turbulence, the inclusion of this turbulence contribution in the model will be considered, and simulation results will be analyzed and discussed.

2. Summary of wind turbine wake characteristics

The wind loading of turbines placed in a wind farm deviates significantly from the wind loading of a similar stand-alone wind turbine subjected to an identical wind climate. This is a result of formation of wakes behind upstream turbines, in which the mean wind field, as well as the turbulence characteristics, deviate from the "free" stream conditions.
A wind turbine wake is the regime behind a wind turbine rotor characterised by (inhomogenously) reduced mean wind speed and modified turbulence characteristics. Typically, the wake turbulence

tends to be *more isotropic* and displays *increased turbulence standard deviation* and *reduced turbulence length scale*.
Conventional turbulence is in general caused by both thermal and mechanical sources. The thermal contribution relates primary to instable atmospheric conditions, whereas the mechanical contribution is related to ground shear.
The additional wake turbulence is driven by a number of additional purely mechanical sources, however, with mutual different characters. Basically, the wake turbulence contributions are caused by tip vortices, trailed vorticity, shed vorticity and hub vortices. Immediately behind the rotor, the turbulent part of the flow is characterized by the ambient turbulence superimposed by inhomogenous blade flow structures caused by tip vortices, trailed vorticity and shed vorticity as well as by hub vortices. The combined effect of these additional flow disturbances close to the rotor plane is an inhomogeneous instationary flow contribution with energy content only on a limited number of distinct frequencies. As the flow graduately moves downstream the rotor plane, instability effects and viscous effects takes over and cause a degradation of the established distinct vortices to more conventional turbulence.
The transformation of the shed vorticity and trailed vorticity to conventional turbulence is expected to take place within the wake near field (i.e. within of the order one rotor diameter downstream). The more energetic and distinct tip vortices may be more persistent, but will also eventually break down to conventional turbulence. In a recent wind tunnel study on wake flow characteristics the distinct tip vortices were traced down to 3 rotor diameters [14].
Along with the degradation of the distinct vortices to conventional turbulence, the mean flow field behind the rotor tends towards a flow field without flow structures around the individual rotor blades. At this stage a mean *wake shear layer* is formed, which will contribute to the turbulence generation together with the ground shear layer and contribute to a redistribution of the generated turbulence, often with a maximum intensity in the upper part of the wake regime. However, contrary to the ground shear layer, the wake shear layer contribution to turbulence generation will weaken with increasing downstream distance to the wake generating turbine due to the continuously weakening of the wake shear caused by turbulent diffusion of momentum, and eventually, at sufficient long down stream distances, the turbulence will return to the characteristics of the ambient turbulence. From the above description, it is obvious that the wake turbulence field is both inhomogenous and instationary.

3. The new computational aeroelastic tool for wake operation

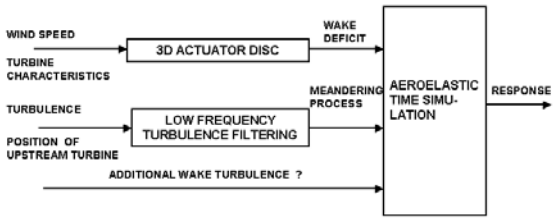

Figure 1 The two main elements in the computational aeroelastic tool is the computed wake deficits and the meandering of this deficit.

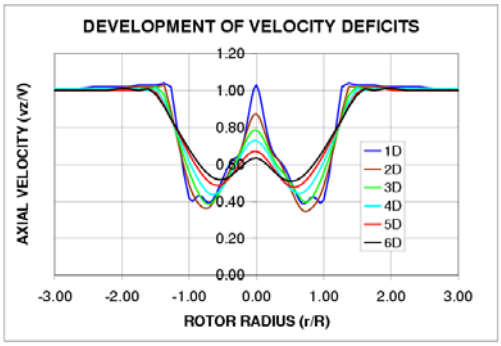

Figure 2 Computed wake deficit profiles in steady flow with a 3D actuator model using a $k-\varepsilon$ turbulence model.

Contrary to more traditional wind farm computational approaches, the new dynamic wake model constitutes a consistent, unifying methodology for computation of power production reduction as well as of increased wind turbine loading during wind farm conditions. Therefore the method, in addition to power and load estimation, has an obvious potential for application in optimisation of wind farm topology and wind farm operation, respectively, as well as in optimisation of dedicated wind turbines for wind farm applications. Last, but not least, the new model also offers the necessary link between loading and production required for development of advanced control strategies for the individual turbine in a farm in order to reduce the blade- and turbine fatigue loading during wake operation.
Basically, the new wake model contains two main elements: 1) computation of stationary wake deficits as function of mean wind speed and 2) computation of the meandering, Figure 1.

The *wake deficit* profiles are computed with a 3D actuator disc model coupled to the aeroelastic model HAWC, [15]. In brief, the idea is to calculate the induction and the flow field around the rotor, associated with the aerodynamic model of a wind turbine rotor in the aeroelastic model, by means of a 3D actuator disc model. The flow through the actuator disc is computed with the CFD code FIDAP, and turbulent flow simulated with the $k-\varepsilon$ turbulence model is specified. An example of computed wake deficits as function of downstream position, and associated with a particular mean wind speed, is shown in Figure 2. Immediately behind the rotor, the deficit correlates directly to the load distribution on the rotor. Typically the highest loading is in a region around 2/3 radius, and close to the hub the loading is much less. Further downstream the deficits develop, influenced by the turbulence mixing, and close to the rotor also due to the pressure field from the rotor.

The other main component in the new wake model is computation of the transport or meandering of the wake deficit in the 3D turbulence wind field in which the turbine operates. Basically, it is assumed that there is a continues release of wake deficits from the upstream turbine, and that the deficits are transported as a passive tracer in the turbulent wind field and moved by turbulence scales larger than the rotor diameter. This means that a suitable filtering is applied on the 3D turbulence wind field before calculation of the trace of the deficit releases. The 3D turbulence modelling is based on the Mann model combining Rapid Distortion Theory, an assumed linear mean wind shear, the Von Kármán spectral tensor and a model for eddy lifetime, [16]. Details of the formulation of the meandering process are described by Larsen et. al. [6].

In the first version of the model complex, the additional turbulence caused by the upstream rotor has been neglected. Thus, the main mechanism, in the description of the unsteady wake flow, in the integrated wake model for aeroelastic computations, is to superimpose the instantaneous wake deficit from the upstream turbine on the undisturbed atmospheric turbulent flow, used as input for aeroelastic simulation of the downstream turbine considered as stand-alone turbine. In this way the downstream turbine will see as input the (undisturbed) atmospheric turbulence superimposed a wake deficit, which, due to the meandering effect, will sweep around in the incoming flow in a plane perpendicular to the mean wind direction, however, most pronounced in lateral direction. For example for a 10-minute period, where the average wind direction gives half wake operating conditions for the downstream turbine, there will be time periods where the deficit has moved so much in the lateral direction, that the deficit does not interfere with the downstream turbine, and likewise other periods where the downstream turbine will be in full wake. The meandering mechanism will therefore result in an apparent intermittent contribution to the turbulence, measured at a fixed position at the location of the downstream turbine, although its origin is basically not traditionally turbulence production.

4. Measurement set-up in the Tjæreborg wind farm

The technique of measuring inflow to a rotating wind turbine blade was developed in a project at Risoe in the period 1987 to 1990 [17], aimed at studying detailed aerodynamics of a rotating blade. In fact it is the same pitot tube and pressure transducers that have been used in the present experiment. A small housing with aerodynamic shape was build in glasfiber, and inside the four pressure transducers were mounted. Also the pitot tube was attached to this housing which finally was mounted on the blade surface in a radius of 24 m with the pitot tube bent to the pressure side of the blade in an angle of 31 deg., Figure 3. A preferable radius of mounting the pitot tube, in order to measure the most representative inflow to the rotor, would have been around 30 m, but this was not possible due to the pressure range in the transducers. The pitot tube measurements have been recorded with a sampling frequency equal to 25 Hz, and prior to recording, the signals have been passed through a low pass filter with cut-off frequency equal to 25 Hz in order to avoid aliasing. With measurement of four differential pressures on the pitot tube the *local inflow angle* in a plane perpendicular to the blade span as well as the *local relative flow velocity* can be derived. The measured local inflow angle is influenced by the bound circulation on the blade as discussed in [17], and a correction to account for this was applied. Further details of the experimental setup can be found in [18].

The instrumented turbine is situated in the Danish Tjaereborg wind farm sited on a flat and in-homogenous terrain close to the sea. The distance from the NM80 turbine to the North Sea is approximately 1 kilometre in a westerly direction. The site is characterized by almost offshore roughness conditions in a westerly sector, and class 1 conditions in the remaining sectors, with the terrain slope being less than 2 deg. in all directions within several kilometres. In the direction southwest to the instrumented turbine, four NM80 turbines are aligned in a row, and a number of different wake situations can thus be measured for the instrumented turbine. The present analysis focuses on wake situations caused by the closest of these turbines, which is positioned 3.3 rotor diameters upstream in a direction of 205 degree, Figure 4. Unfortunately, the meteorology mast

situated close to the NM80 turbine was not in operation during the measurement period, so that no free stream measurements are available. Signals from two nacelle anemometers and two wind direction sensors are available, but they are of course influenced substantially by the rotor.
Besides the inflow measurements on the rotating blade a number of different strain gauge measurements on the turbine components are available, and for the present analysis, the measured flapwise blade root moment has been used.

Figure 3 The five hole pitot tube mounted on the leading edge of the blade. (The plate mounted on the blade is used for measurement of the angle of the pitot tube relative to the tip pitch).

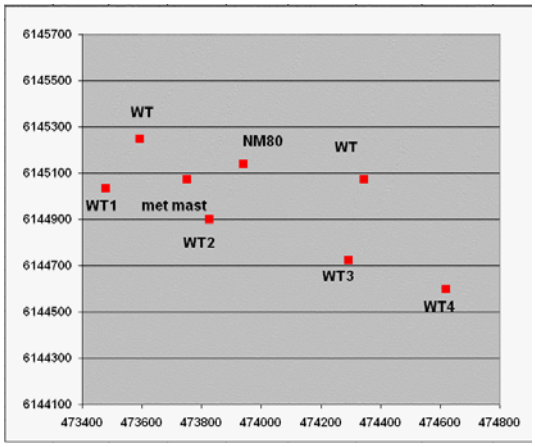

Figure 4 The turbine NM80 used for the measurements is situated in the small Tjæreborg wind farm close to the North see. Operation in the wake from WT2 is considered in the present paper.

5. Results and discussion

Correlating the free inflow conditions in the aeroelastic model to the measurements in free inflow

Three data files, measured within one hour on the night of November 11th 2003, have been used in the present analysis, because these data files combine very low ambient turbulence conditions with both free inflow conditions (file 1104-2137) and partial wake operation (file 1104-2227 with about 1/3 wake; and file 1104-3337 with about 2/3 wake) during this one hour of measurements. At the same time, a significant wind shear has been measured, in agreement with stable atmospheric conditions at night.
As no meteorological reference measurements are available, the first step in the analysis has been to tune the input parameters, in an aeroelastic modelling of the free inflow case, as to fit the measured results of the deterministic variation of the local inflow angle α_l, the local relative velocity w_l and the std. dev. of these two quantities binned on azimuth position.
The parameters varied in the aeroelastic simulation were: the roughness length z_0 in the logarithmic wind shear model (finally set to 10 m), the turbulence intensity (finally set to 3%), the yaw error angle (set to 13 deg.) and the mean wind speed (set to 5 m/s). The turbulence intensity was determined solely by correlating the measured and simulated standard deviations of the local inflow angle, Figure 2, and an almost azimuth independent distribution is seen for both simulated and measured results. The azimuth variation in relative velocity is caused mainly by the yaw error, whereas the variation in inflow angle is due to the mean wind shear. Finally, the mean wind speed was determined by correlating simulated and measured rotor power. The obtained correlation between measurement and simulation is certainly not perfect, as for example the shapes of the azimuth variation of w_l differ somewhat, Figure 4. This deviation might be due to a possible change in mean flow direction up through the boundary layer, which has not been modelled. However, the present analysis focuses on the *relative changes* in the quantities α_l, w_l and flapwise response M_{flap}, when comparing free inflow conditions with wake conditions, and slightly different conditions in the free inflow are therefore not expected to have a significant influence on the result.

Influence of wake conditions

A slow change in wind direction (measured as the yaw position of the turbine), caused both free- and partial wake situations to occur. Based on the results of a binning of the measured inflow angle on azimuth position, file 1104_2227 is considered to represent a 1/3 wake situation, as the std. dev. of α_l and w_l increase substantially in the azimuth range from approximately 100 deg. to 225 deg., Figure 2 and Figure 4. In analogy, file 1104_2237 is considered to represent a 2/3 wake situation, with increase in α_l and w_l variability in the azimuth range from approximately 50 deg. to 275 deg.. Note, that azimuth angle equal to 180 degree corresponds to the blade pointing downwards, which means that the wake from the upstream turbine has been deflected downwards. The same two wake situations have been simulated with the wake simulation model, and the results are shown in the right part of Figures 5 to 9. In general, there is a good qualitative correlation, but there are also many differences. The std. dev. of α_l increases in the simulation for the blade being inside the wake region, but not as pronounced as in the measurements. However, the simulated std. dev. of w_l is almost unaffected by the wake, which is not surprising as the influence from the small meandering of the deficit mainly will change the std. dev. of α_l. On the other hand the measured std. dev. of w_l increases from 0.2 m/s to at least 1 m/s inside the wake, Figure 10, reflecting the increase in the lateral and transversal turbulence components inside the wake. Comparing the time traces of α_l and w_l, Figure 1 and Figure 3, it is clear that the small scale variations seen in the measurements for the blade inside the wake are missing in the simulations. These are, however, not considered essential as seen from a loading point of view. The simulated and measured flapwise moments are compared in Figure 5, and again there is a reasonable good correlation between the shapes of the std. dev. curves, although the absolute values are not identical. However, this is to some degree due to different shapes of the deficit (the decrease in flapwise moment is steeper on the left hand side compared to the simulations), and maybe also that the measured wake situation, contrary to the simulation, is not completely centred around 180 degree.

Increasing the wake turbulence in the simulations

It is clear from the above comparison, and also a priory expected, that some turbulence is missing in the simulations, when the blade is passing through the wake. This is most clearly seen in the std. dev. of w_l in Figure 4. As an initial rough attempt to add this supplementing turbulence contribution in the simulations, we simply scaled the turbulence with a constant factor for the blade being inside the wake region. This was tested for the 2/3 wake situation, where the turbulence was scaled with factors 3 and 5, respectively, for the blade being within the azimuth interval extending from 75 deg. to 275 deg.. With a specified ambient turbulence in the simulations equal to 3%, this factor raises the turbulence level inside the wake to 9% and 15 %, respectively. The result is a better correlation of measured and simulated std. dev. of all three quantities α_l, w_l and M_{flap}, Figure 6 and Figure 7. However, the shape of the std. dev., as function of azimuth position, of particularly w_l indicates that the factor should not be constant over the wake region but vary, for example as function of the gradient of the deficit. This would result in a maximum amplification of the turbulence on the outer part of the deficit, and the peaks observed there are probably due to the tip vortices or to turbulence generated by the tip vortices.

Associated with the question about how much the turbulence should be increased inside the wake, a second question concerning the scale of the turbulence in the wake arises. We have already an indication from the time traces, Figure 1 and Figure 3, showing much less scales in the measurements than seen in the simulation. The power spectra of α_l and w_l, Figure 8 and Figure 9, also supports this indication. The spectra of w_l show this tendency, as an increase of the turbulence inside the wake improves the correlation with measurements. However, the spectra of the flapwise moment show a rather good correlation up to a frequency equal to 0.7 Hz, which is around 4 P, indicating that much of the small scale turbulence influence on the spectra and standard deviation of α_l and w_l is not really seen in the flapwise moment. Finally, the results of rainflow counting of the flapwise moment in Figure 11 show that the influence of increasing the turbulence inside the wake, using the same length scale as used for the ambient turbulence (80 m for the present simulations), decreases the correlation with measurements for the large load ranges, again indicating that a considerable lower length scale should be used for the added turbulence inside the wake.

Result figures

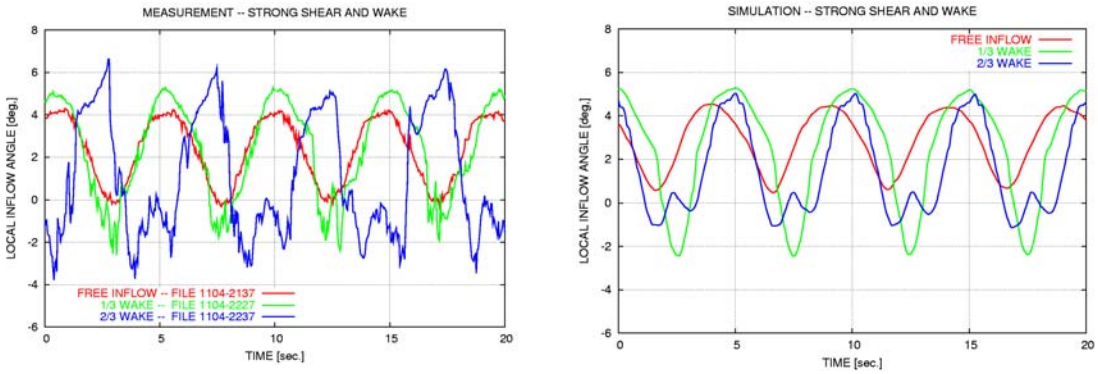

Figure 1 **An example of time series of measured and simulated local inflow angle during low turbulence wind conditions with strong wind shear and two wake conditions, respectively.**

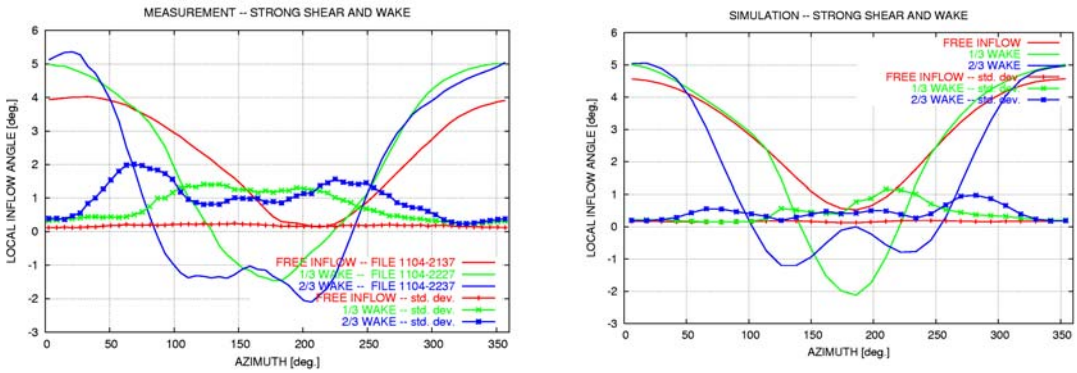

Figure 2 **Measured and simulated local inflow angle binned on azimuth positions.**

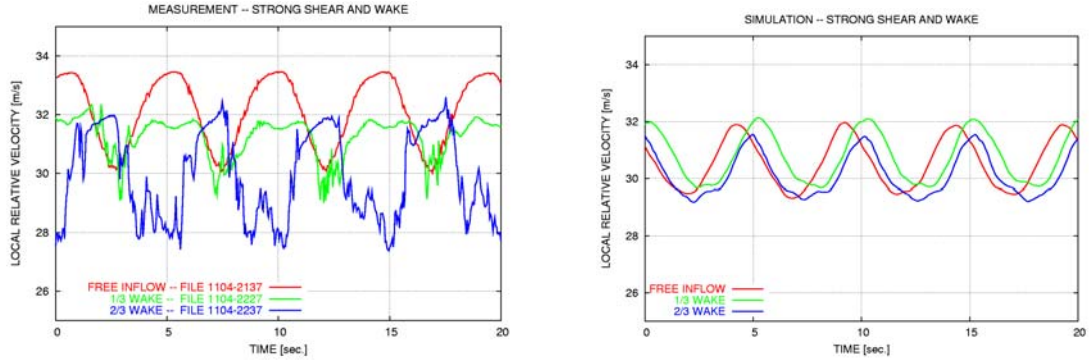

Figure 3 **An example of time series of measured and simulated local, relative velocity during low turbulence wind conditions with strong wind shear and two wake conditions, respectively.**

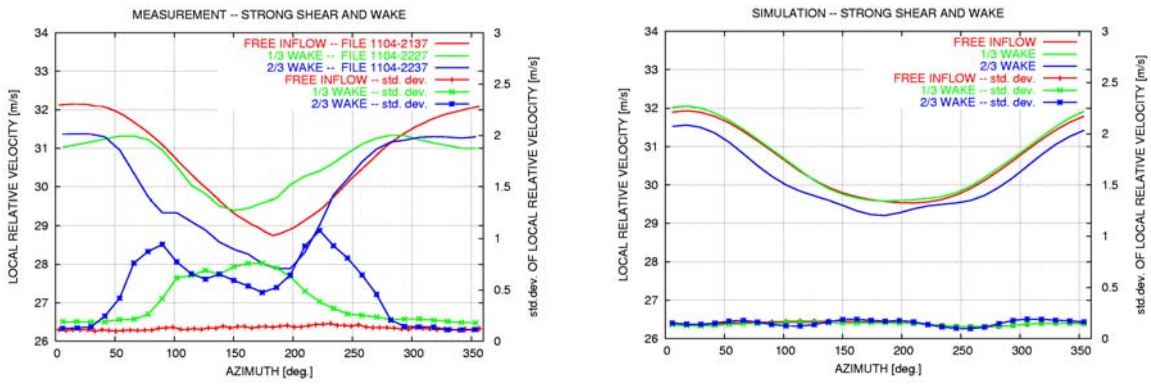

Figure 4 **Measured and simulated local relative velocity binned on azimuth positions.**

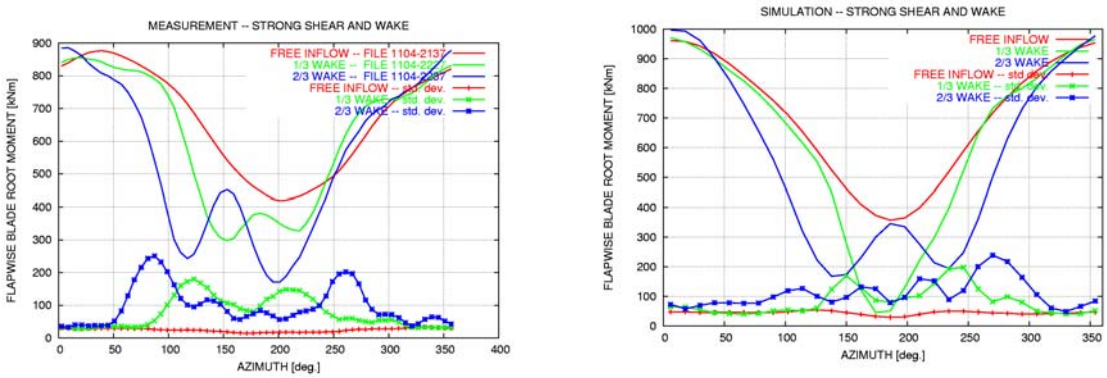

Figure 5 **Measured and simulated flapwise blade root moment binned on azimuth positions.**

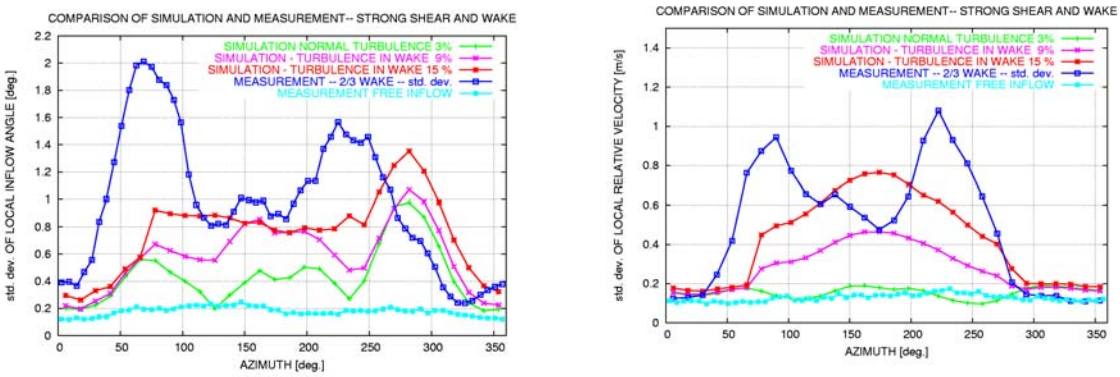

Figure 6 **Influence of increasing wake turbulence in simulations and compared with measurements.**

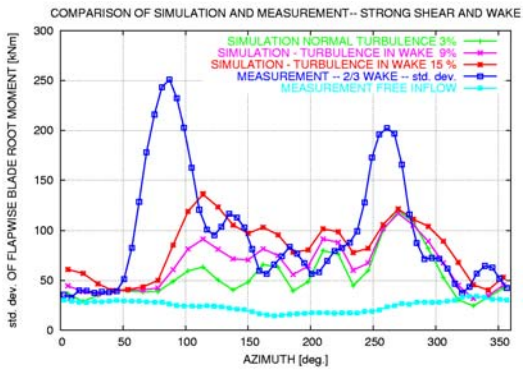

Figure 7 **Influence of increasing wake turbulence in simulations and compared with measurements.**

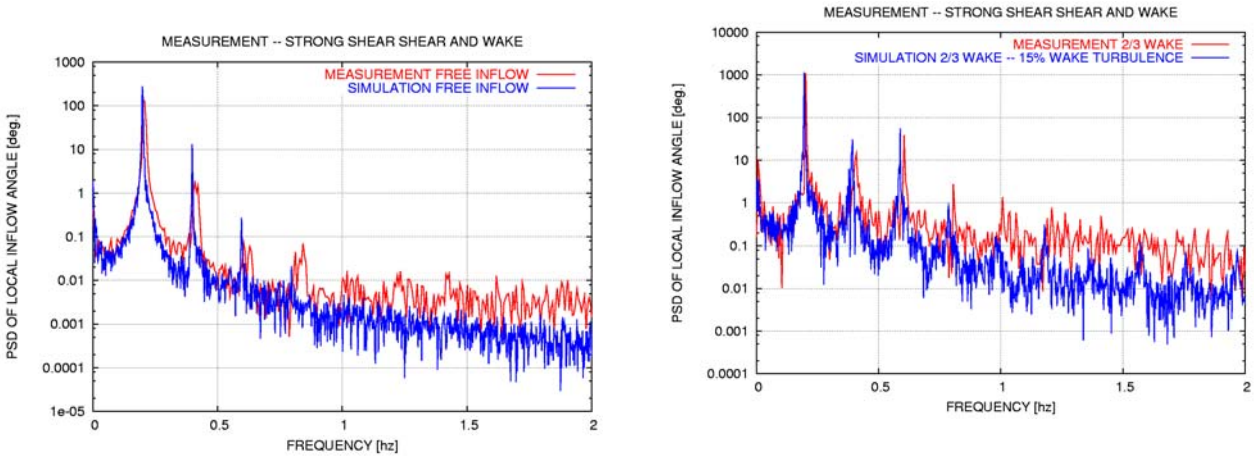

Figure 8 **Measured and simulated power spectrum of local inflow angle in free wind and in wake, respectively.**

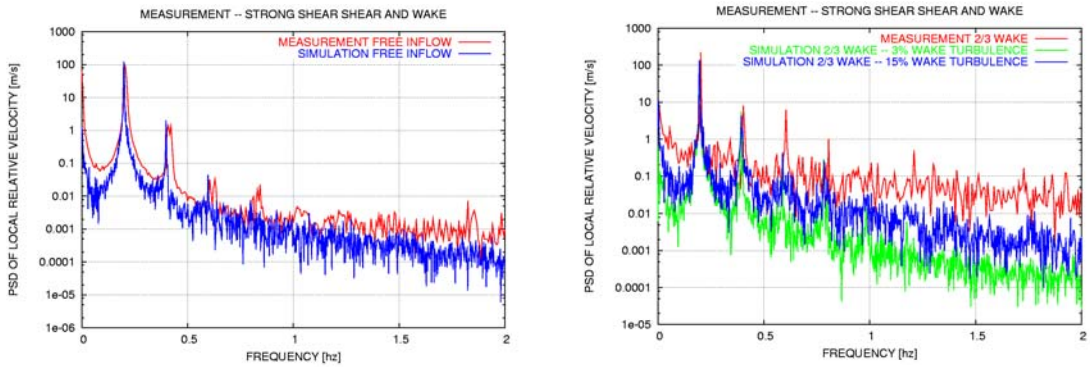

Figure 9 **Measured and simulated power spectrum of local relative velocity in free wind and in wake, respectively.**

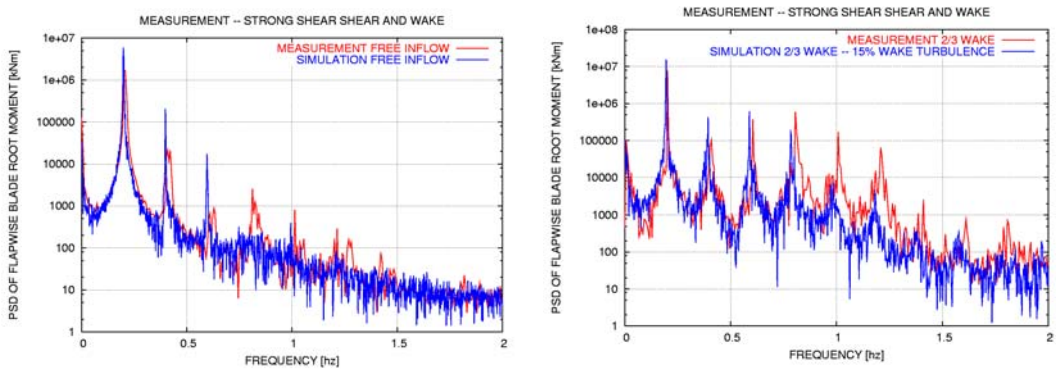

Figure 10 **Measured and simulated power spectrum of flapwise blade root moment in free wind and in wake, respectively.**

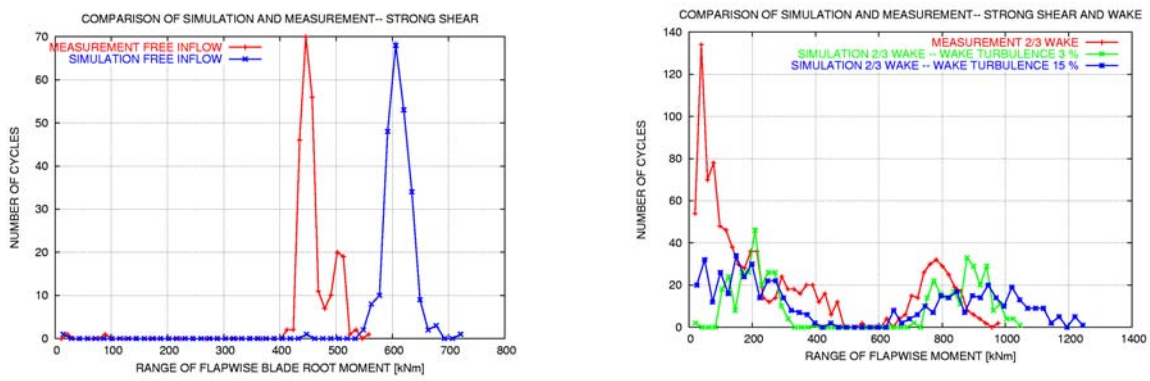

Figure 11 **Distribution of ranges from fatigue analysis of flapwise blade root moment.**

6. References

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