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# Wake effects above rated wind speed. An overlooked contributor to high loads in wind farms.

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## Abstract

In this paper a new validation of the Dynamic Wake Meandering method for calculating wake effects on power and load levels on a turbine is presented based on load and power measurements on a turbine located in the Lillgrund wind farm. What is unique is the large set of measurements available, where the wake effects from multiple neighboring turbines in high wind speed conditions could be included. It appears that the DWM method gives accurate results in single wake situations as well as for multiwake situations below rated wind speed. However, the so far used method for superposition of multiple wakes above rated wind speed has led to non-conservative load predictions for high wind speeds. Therefore a new approach is presented and compared to both measurements and present practice in the IEC61400-1 standard.

## 1. Introduction

The Dynamic Wake Meander (DWM) model [1,2] has previously been validated both directly against full-scale flow field data [7,8,12] and indirectly by comparing simulated wind turbine loads resulting from wake affected inflow fields with full-scale load measurements [2,3,6,10,11].

Concerning validation in terms of derived structural wind turbine loads, the most comprehensive comparisons were performed in the Egmond aan Zee study [3], where a very satisfactory agreement between model predictions and measurements was concluded for the ambient mean wind speed regime between 3m/s and 14m/s. This study was based on full-scale measurements from a Vestas V90 turbine located in the Dutch Egmond aan Zee wind farm (WF) [3] for the specific wind direction, where the turbine in focus was located as the 6th turbine in a row with uniform turbine interspacing equal to 7 rotor diameters (D).

In general only very limited load validation material from multiwake wind farm exist, and for wind situations above rated wind speed practically nothing has so far been published. So far the main interest in wake effects has been on the power consequences, which is mainly important for wind speed below rated.

This paper describes a load validation study based on simulated and measured fatigue loads from the Swedish Lillgrund off-shore wind farm, which has a layout characterized by exceptionally small wind turbine (WT) inter-spacings. Full-scale measurements from this wind farm have previously been presented with focus on power production [5,11] as well as on wind turbine fatigue loading [4] effects in the below rated mean

wind regime. In the load study predicted flapwise fatigue loads for a full polar were shown to agree very satisfactorily both for single turbine wake situations and for deep array wake operation up to about rated (ambient) mean wind speed. However, for higher than rated (ambient) mean wind speeds, significant deviations between predictions and full-scale measurements were observed for deep array wake cases; i.e. for wake situations characterized by multiple upstream turbines.

In the present paper a simple update to the DWM model is proposed for multiple wake operation in the high ambient wind speed regime, and the performance of the updated model under such conditions is investigated in terms of both flapwise fatigue loads and tower fatigue loads with particular emphasis on deep array cases. Simulations and full-scale measurement are compared, and as the DWM model is about to be included in the new edition of the IEC61400-1 ed. 4 standard, these results are expected to be of major importance for future wind farm projects. For completeness, the measured results are further compared to load predictions as based on the existing recommended practice in the IEC61400-1 ed. 4 standard [9].

## 2. DWM model update

The DWM model basically simulates the non-stationary wind farm flow field, which is required for wind farm load predictions, as a linear superposition of an ambient turbulent atmospheric boundary layer (ABL) flow and a non-stationary wake flow contribution. The wake contribution is obtained by treating WT wakes as passive tracers transported downstream by the mean ABL flow field superimposed by a stochastic meandering process driven by the large scale cross wind turbulence components [1]. The method for deriving the deficit and the magnitude of the added wake turbulence can be found in [2]. The result is an intermittent type of flow field with the intermittence resulting from the wake meandering. This wake flow model has been integrated with the DTU aeroelastic code HAWC2 in order to facilitate load and production predictions of wind turbines located in wind farms.

Compared to the DWM version applied in the former Lillgrund study [4], the DWM sub-model, used to determine the aggregated wake deficit from upstream turbines at a given WF location, has been revised in the present study. Two different wake superposition approaches are applied for the wind regimes corresponding to respectively below and above rated wind speed:

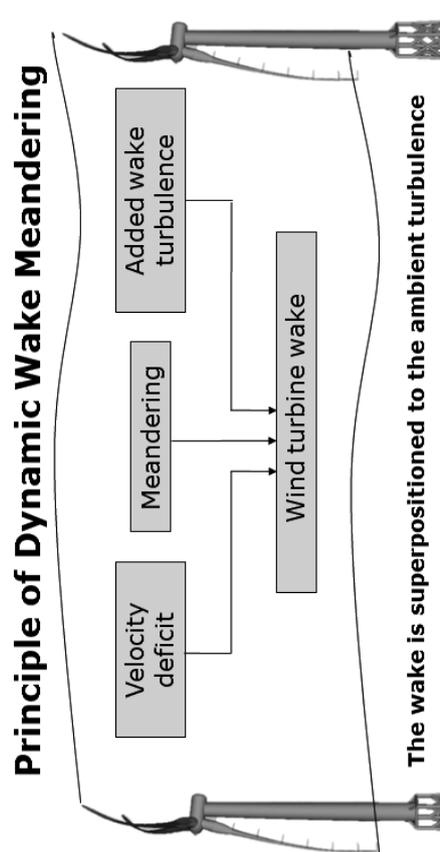


Figure 1: Illustration of the main components of the DWM method. A cascade of deficits are transported downstream in a process governed by the large scale turbulent flow field.

The wake self-induced small scale turbulence is denoted by  $(U_{w,i}, V_{w,i}, W_{w,i})$ , and as the wake deficit flow field component in the longitudinal flow direction is by far the dominating component and further the most load critical, only this deficit component is included.

**Above rated wind speed:** Using the nomenclature introduced above, (1) is replaced by a linear summation of wake contributions from all upstream turbines, i.e.

$$U_w(r, \theta, t|x) = \sum_i U_{w,i}(r, \theta, t|x) \quad (2)$$

This linear perturbation approach is consistent with WT's being more "flow transparent" for higher wind speeds, which in turn results in relatively smaller wake deficit magnitudes and thereby improving the accuracy of a linear flow field approximation.

**Below rated wind speed:** For a WT with the rotor centre located at the spatial position,  $\mathbf{x}$ , within the WF, the temporally varying wake flow contribution at the rotor polar coordinate  $(r, \theta)$  is determined by the dominating wake among wake contributions from all upstream turbines at any time.

$$U_w(r, \theta, t|x) = \min_i(U_{w,i}(r, \theta, t|x)) \quad (1)$$

where  $(r, \theta, t|x)$  denotes a temporal coordinate  $t$  combined with a spatial coordinate in a polar frame of reference centered at the spatial position  $\mathbf{x}$ , and where each individual upstream emitted wake flow field is given by  $U_{w,i} = (U_{w,i} + U_{w,i})\mathbf{e}_1 + V_{w,i}\mathbf{e}_2 + W_{w,i}\mathbf{e}_3$ , with  $\mathbf{e}_j, j = 1, 2, 3$ , being unit normal vectors in respectively the longitudinal, transversal and vertical mean flow directions. The parameter  $i$  includes all upstream turbines relative to the spatial position  $\mathbf{x}$  for a given mean wind direction.

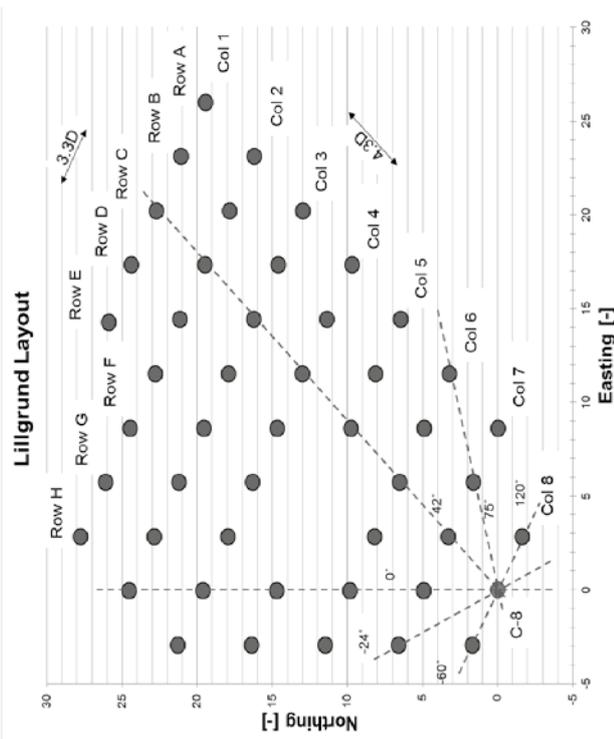


Figure 2: The Layout of the Lillgrund wind farm and location of WT C-8. Distances are non-dimensionalised with the rotor diameter

supplement to the DWM validation, the investigation includes also comparative load simulations as based on the existing recommended practice in the IEC61400-1 ed. 4 standard [9]. This consist of a set of loads obtained using the IEC class 1A, as most offshore turbine are approved for such conditions, as well as the wake simulation method suggested by Frandsen [13], where the thrust coefficient  $C_T$  is approximated with  $7/U_{amb}$  for the sectors where increased background turbulence from the entire farm is expected.  $U_{amb}$  represents the ambient mean wind speed.

All presented fatigue loads have been normalized with the fatigue load representing the respective sensors at 9m/s in the free sector.

The results for the blade load comparison can be seen in Figure 3. Results are presented as function of the wind direction for each wind speed bin covered. In the left column of the figure is shown the results from comparing the measurements, IEC class 1A and the Frandsen method to results obtained with the DWM approach using the maximum deficit operator (1). In the right column a similar comparison to the DWM approach using a linear superposition for multiple wake situations (2) is shown. A similar comparison for the tower bottom bending moment is shown in Figure 4.

An excellent agreement between measurements and the DWM approach with the maximum deficit operator is seen for the flapwise bending moment at low wind speeds, where the turbine thrust is high. The Frandsen method results in blade loads in the slightly conservative region of measured load levels. The highest loads are seen in the sector with the closest located upstream wind turbine. In this case the single wake situation with 3.3D spacing.

At 10-12 m/s, the agreement between measurements and the DWM approach using the maximum deficit operator still shows an excellent agreement for the 3.3D single wake situation. A slight increased load level can be seen in the measurements for the multi-wake sector, which is however still in fine agreement with the simulation results.

Note, that before the model update superposition of wakes emitted by upstream turbines was treated according to the algorithm described by equation (1) for the entire the wind regime.

### 3. Validation Case

The Lillgrund wind farm consists of 48 Siemens SWT-2.3-93 turbines, and one of these (C-8) is instrumented with strain gauges resolving blade, main shaft and tower loads, see Figure 2. The present DWM model validation is based on recordings from this turbine.

Whereas the Egmond aan Zee wind farm is characterized by a "conventional" turbine inter spacing, the layout of the Lillgrund wind farm is, as mentioned, characterized by very small turbine inter spacing's; i.e. down to 3.3 D. This makes the present Lillgrund load validation case a unique supplement to the former validation based on the Egmond ann Zee wind farm.

Measured and predicted fatigue loads are quantified as fatigue equivalent moments using the Palmgren-Miner approach; and Wöhler exponents of 5 and 10 were assumed for the tower and blade composite structures, respectively.

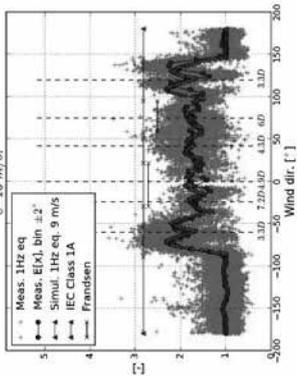
The validation scenarios include load cases associated with normal turbine operation with mean wind speeds ranging from 8m/s to 16m/s. Measured wind speed dependent turbulence intensities (TI's) are used, reflecting the offshore wind speed dependent "surface" roughness. However, no attempt is done to resolve TI as function of upstream fetch (i.e. direction). Thus, in the mean wind speed regime 6m/s-14m/s a TI of 5.8% is used - gradually increasing to 6.2% at 16m/s.

### 4. Results

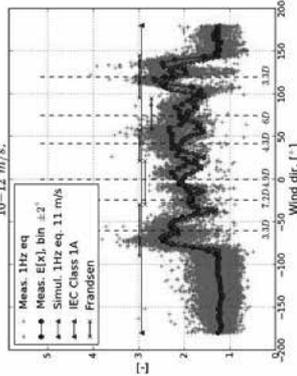
For a complete direction rose simulated and measured fatigue equivalent moments are compared (mean wind speed) bin wise for two WT main components - i.e. blade and tower. With the complete direction rose being represented, a multitude of load cases - ranging from ambient inflow conditions over single wake cases to various types of multiple wake inflow cases - are thus covered. Further, as a

**MAX DEFICIT OPERATOR**

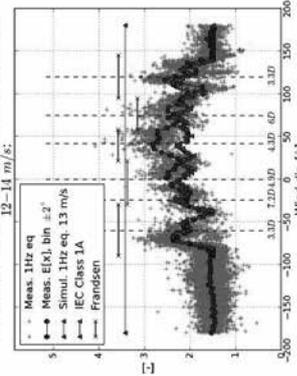
Lilgrund measurement blade root flap m=10  
8-10 m/s.



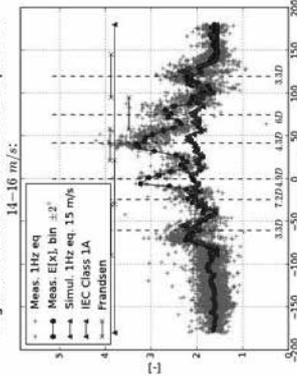
Lilgrund measurement blade root flap m=10  
10-12 m/s.



Lilgrund measurement blade root flap m=10  
12-14 m/s.

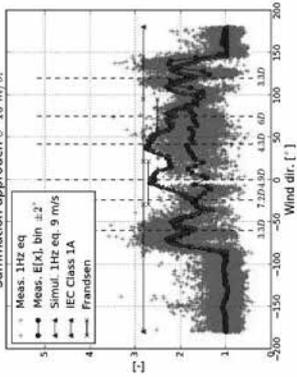


Lilgrund measurement blade root flap m=10  
14-16 m/s.

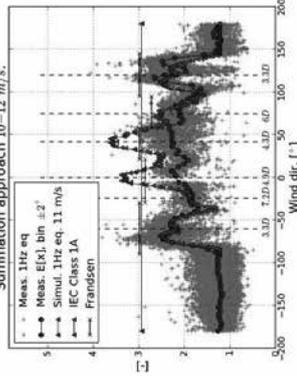


**DEFICIT SUMMATION**

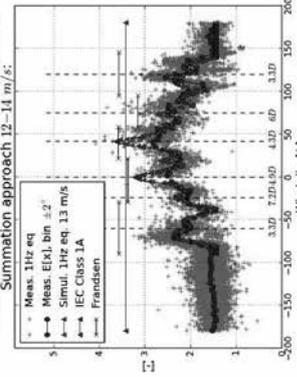
Lilgrund measurement blade root flap m=10  
8-10 m/s.



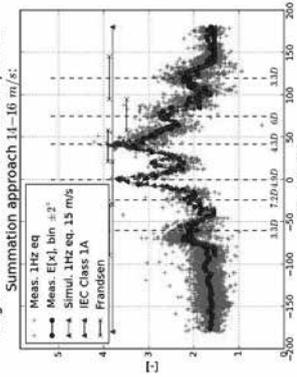
Lilgrund measurement blade root flap m=10  
10-12 m/s.



Lilgrund measurement blade root flap m=10  
12-14 m/s.

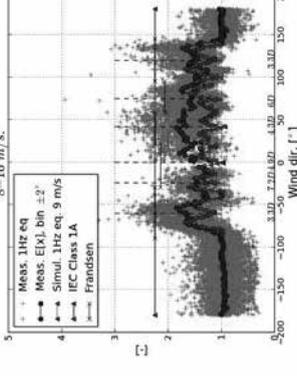


Lilgrund measurement blade root flap m=10  
14-16 m/s.

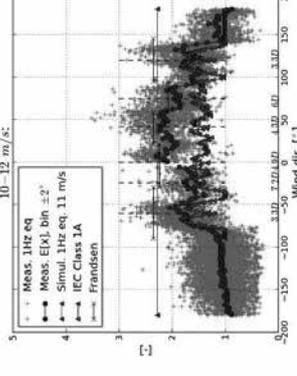


**MAX DEFICIT OPERATOR**

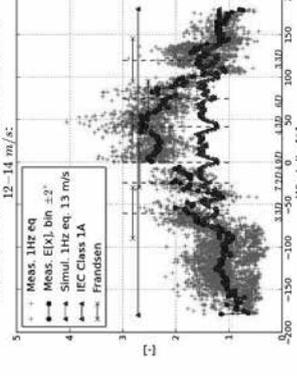
Lilgrund measurement tower bend, m=5  
8-10 m/s.



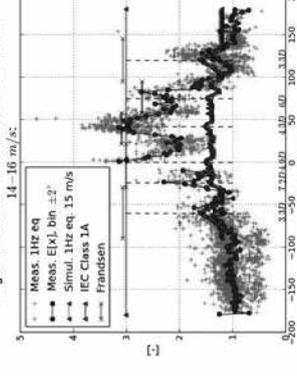
Lilgrund measurement tower bend, m=5  
10-12 m/s.



Lilgrund measurement tower bend, m=5  
12-14 m/s.

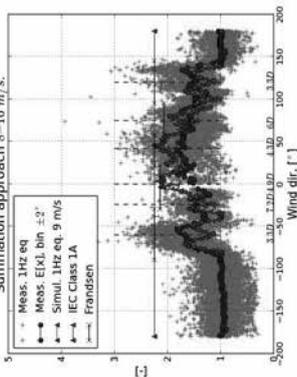


Lilgrund measurement tower bend, m=5  
14-16 m/s.

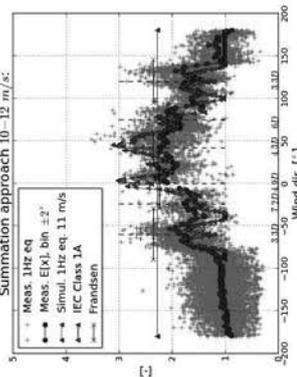


**DEFICIT SUMMATION**

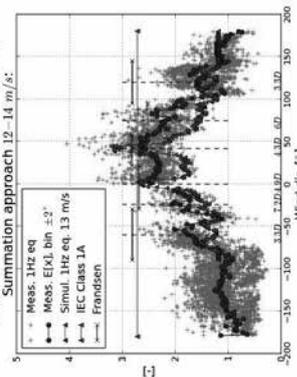
Lilgrund measurement tower bend, m=5  
8-10 m/s.



Lilgrund measurement tower bend, m=5  
10-12 m/s.



Lilgrund measurement tower bend, m=5  
12-14 m/s.



Lilgrund measurement tower bend, m=5  
14-16 m/s.

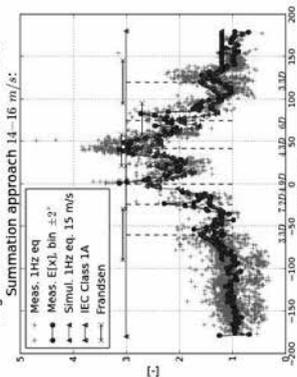


Figure 3: Comparison of blade root bending 1 Hz fatigue loads at wind speed from 8 to 16m/s. Left: DWM using max operator. Right: DWM using linear superposition.

Figure 4: Comparison of tower bottom bending 1 Hz fatigue loads at wind speed from 8 to 16m/s. Left: DWM using max operator. Right: DWM using linear superposition.

alternative, still simple, approach using linear wake deficit superposition was demonstrated to result in load levels in agreement with the measured levels and is thus recommended.

Further, as a supplement to the DWM validation, the investigation includes also comparative load simulations as based on the existing recommended practice in the IEC61400-1 ed. 4 standard [9]. Here it can be concluded that the Frandsen approach is highly conservative for single wake situations, especially above rated wind speed. This in turn means that adopting the DWM approach, with site specific conditions allow for quantification of the build-in safety reserve in the existing IEC61400-1 recommended practice or, alternatively, use the DWM approach to reduce this safety reserve if appropriate. Even for a wind farm as the Lilgrund, with turbine spacings between 3 and 4D, a class 1A turbulence level still results in a conservative load level.

## 7. Acknowledgements

Siemens Wind Power has provided the unique measurements, which is gratefully acknowledged. The EUDP project "Impact of atmospheric stability conditions on wind farm loading and production" under contract 64010-0462 and the Danish PSO project "Wake affected offshore tower and foundation loads" under contract 2010-1-10546 are acknowledged for financial support and thus for making this study possible.

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ambient mean wind speed regime below rated wind speed, whereas significant differences between model predictions and measurement were observed above rated wind speed. A revision of the DWM sub-model for wake aggregation has improved the model/measurement agreement significantly and excellent agreement between DWM fatigue load predictions and full-scale measurements is now shown also for the ambient mean wind speed regime above rated wind speed.

For a complete direction rose simulated and measured fatigue equivalent moments are compared (mean wind speed) bin wise for two WT main components - i.e. blade and tower. With the complete direction rose being represented, a multitude of load cases - ranging from ambient inflow conditions over single wake cases to various types of multiple wake inflow cases - are thus covered.

Even though a fine agreement between the DWM approach and measurements can be achieved by using the maximum deficit operator below rated wind speed and the linear superposition above rated, it is also clear that multiple wake situations is a highly complex load situation. Especially the findings regarding the significantly increased load levels above rated wind speed, may (hopefully) cause increased attention for future studies. Especially large eddy CFD simulations could increase the insight in how to properly handle merging wakes.

## 6. Conclusion

A key finding in this study is that even though a wind turbine is more "aerodynamic transparent" above rated wind speed and therefore has a reduced wind speed deficit compared to below rated, the wake induced load levels increased significantly in multi-wake situations.

With this study it is also concluded that the DWM method can with great accuracy be used to predict the load level of wind turbines in wind farm conditions. However, when handling multiple wake situations above rated wind speed, the previous recommendation based on the Egmond aan Zee study [3] is NOI sufficient. An

At 12-14 m/s it becomes clear that the blade load for multiwake operation is not sufficiently captured by the DWM approach using the maximum deficit operator, and at 14-16 m/s the measurements show a significantly larger load level than the model predictions. It is consequently clear that *the maximum deficit approach cannot be used for high wind speeds!*

In the right hand column of the figure, the simulation results using the simple deficit superposition method is shown. This method seems slightly conservative regarding the blade loads for low wind speeds, but at high wind speeds the match is excellent.

A similar conclusion can be drawn when observing the tower bottom bending moments. The maximum deficit approach seems to result in a fine agreement for low wind speeds, but near rated and above only the superposition approach catches the load levels measured in the multi-wake sector.

Regarding the fatigue load levels obtained using the Frandsen method, it appears that this method is highly conservative for the low wind turbine spacings investigated in this study. Especially at wind speeds above rated in single wake situations, the method leads to a load levels 2-3 times higher than measured. As the measured loads increase significantly in multi-wake situations at high wind speeds, the load levels predicted by the Frandsen method actually fits quite well, but this is not caused by the modeled added ambient turbulence level, as this only has marginal influence of the modeled wake turbulence level.

The fatigue load level obtained from the class 1A site conditions appears to result in a conservative and safe design of the turbine compared to the measured load conditions.

## 5. Discussion

In general a very fine agreement between the DWM simulations and measurements is seen below rated wind speed. Excellent agreement between DWM fatigue load predictions and full-scale measurements has previously been demonstrated for the