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

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1. Introduction

In the process of extending the validation of the Dynamic Wake Meander (DWM) model[1,2], several load comparisons between simulations and measurement in wake operation have been carried out in the past[2,3,6,10,11] together with other types of validation studies[7,8,12]. One of the most comprehensive comparisons was the Egmond Aan Zee study[3] where a very fine agreement between model and measurements was seen for the ambient mean wind speed regime between 3m/s and 14m/s. This study consisted of full-scale measurements from a Vestas V90 turbine located in the Dutch Egmond aan Zee Wind farm[3] for a *specific wind direction*, where the turbine in focus was located as 6'th turbine in a row spaced with 7 rotor diameters (D).

A new load comparison study has now been carried out for the simulated and measured fatigue loads for the Swedish Lillgrund off-shore wind farm[4]. This wind farm has a layout characterized by exceptionally small wind turbine (WT) inter-spacings. Measurements from this wind farm have previously been presented, but this has only concerned power production effects below rated power[5,11]. In the study[4] predicted flapwise fatigue loads for a *full polar* were shown to agree very satisfactorily for single turbine wake situations as well as 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 this paper an update to the DWM model is proposed for multiple wake operation in high ambient wind speeds, and the present paper deals with the performance of the updated model concerning both flapwise fatigue loads associated with high wind deep array cases and tower fatigue loads in general. Simulation and fullscale measurement are compared. As the DWM is about to be included in the new edition of the IEC61400-1 ed. 4 standard, this is expected to be of major importance for future wind farm projects.

These results are further subsequently compared to load predictions as based on the existing recommended practice in the IEC61400-1 ed. 4 standard[9] (to appear in the final paper).

2. Approach

The DWM model basically simulates the *non-stationary* wind farm flow field, which is required for wind farm load predictions, by treating WT wakes as passive tracers transported downstream by the mean flow field superimposed by a meandering process driven by the large scale cross wind turbulence components[1]. This model has been integrated with the DTU aeroelastic code HAWC2 in order to facilitate load and production predictions of wind farms. Compared to the DWM version applied in the former Lillgrund study[4], the DWM sub-model used to determine the aggregated deficit from upstream turbines has been revised in the present study.

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

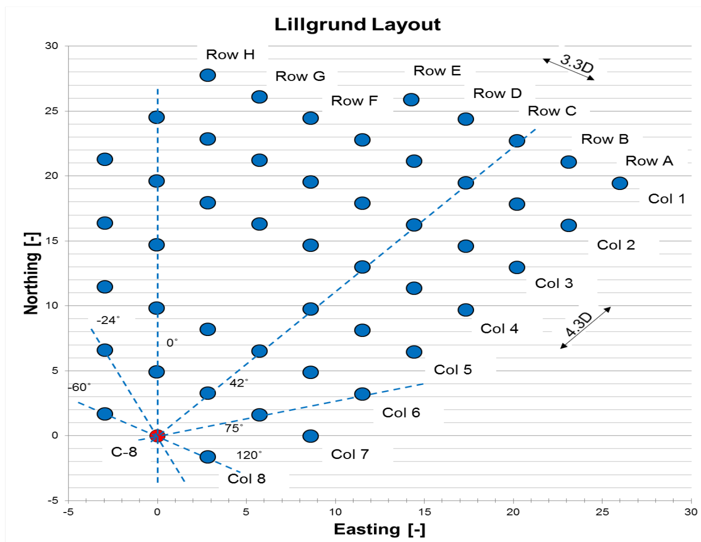


Figure 1: The Layout of the Lillgrund wind farm and location of WT C8.

Whereas the Egmond ann 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 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 4 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 6m/s to 25m/s. Six mean wind speed bin regimes were considered: 6m/s-8m/s; 8m/s-10m/s; 10m/s-12m/s; 12m/s-14m/s; 14m/s-16m/s; and 16m/s-25m/s. A measured wind speed dependent turbulence intensity (TI) was used, reflecting the offshore wind speed dependent "surface" roughness. However, no attempt was done to resolve TI as function of upstream fetch (i.e. direction). In the mean wind speed regime 6m/s-14m/s a TI of 5.8% was used - gradually increasing to 9.5% at 25m/s.

Simulated and measured fatigue equivalent moments have been compared bin wise for a complete direction rose, which includes a multitude of load cases ranging from ambient inflow conditions over single wake cases to various types of multiple wake inflow cases.

3. Results

For wind speeds below the rated mean wind speed previous investigations have demonstrated an excellent agreement between measured and simulated fatigue loads[4]. This was seen both for the 3.3D single wake situation and for the multiple wake situations associated with the North-Eastern direction sector. This is illustrated in Figure 2 for the mean wind speed regime 8 – 10m/s and 10-12m/s.

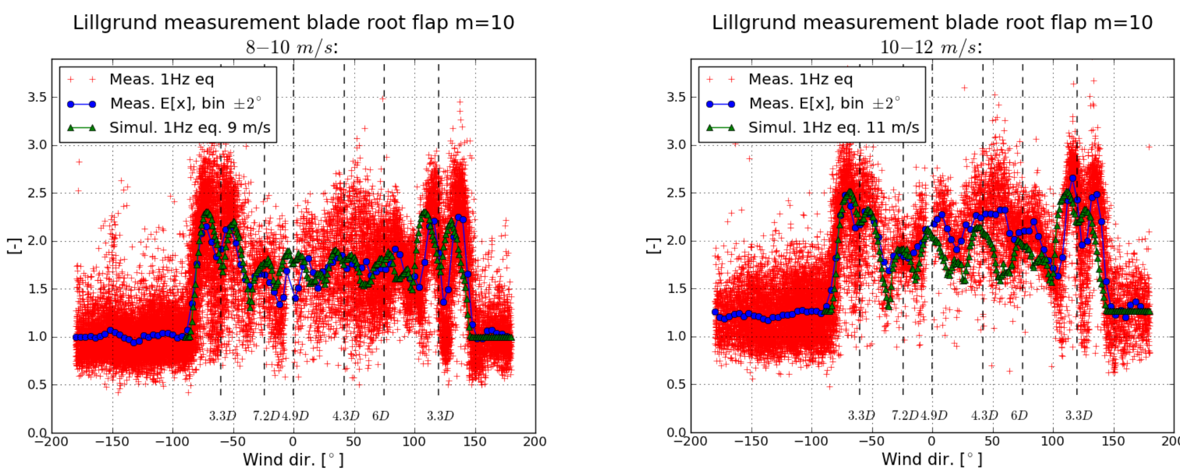
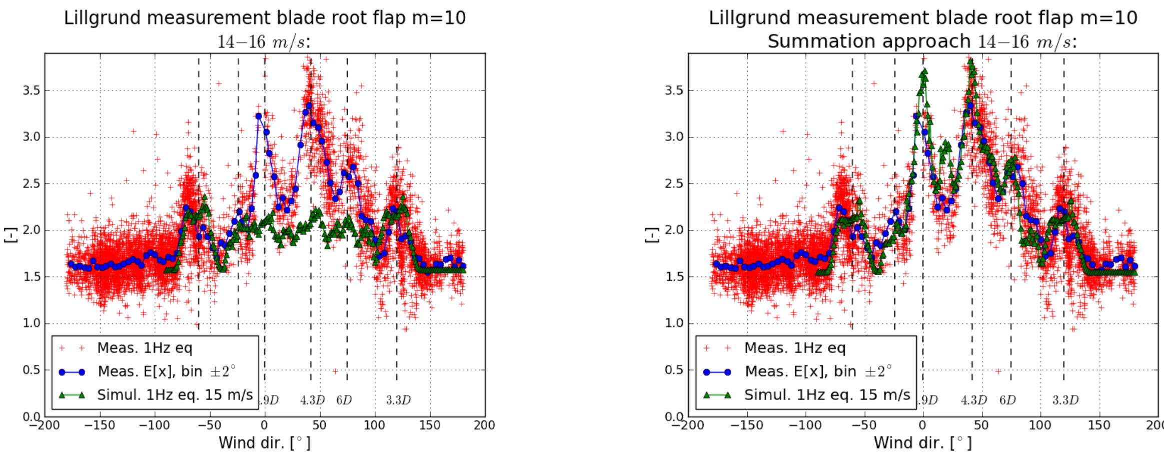


Figure 2: Measured and predicted blade flap fatigue equivalent polar. a) 8-10m/s; b) 10-12m/s.

For wind speeds above the rated mean wind speed the previous Lillgrund study demonstrated a significant deviation between full-scale and predicted flap wise fatigue loads associated with the multiple wake direction sector. With the recent DWM model update, the model predictions are now in excellent agreement with the measured fatigue loads also for these wake load case scenarios as shown in Figure 3.



a) b)

Figure 3: Measured and predicted blade flap fatigue equivalent polar. a) Old[4] DWM version; b) revised DWM version.

4. Conclusion

Excellent agreement between DWM fatigue load predictions and full-scale measurements has previously been demonstrated for the ambient mean wind speed regime *below* rated wind speed, whereas significant differences between model predictions and measurement was 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.

5. Learning objectives

- DWM model prediction in excellent agreement with full scale measurements from the Lillgrund wind farm for all wind speed regimes and all wake cases (i.e. the full polar);
- Blade fatigue load levels increase in wake situations. Below rated wind speed the nearest turbine is the most important contributor. Above rated wind speed load levels the

importance of handling multiple wake situations is much more important. Loads in multiple wake situations are significantly higher than in single wake operation.

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