Comparison of methods for load simulation for wind turbines operating in wake

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Abstract. For simulation of load response for a wind turbine operating in wake conditions, two different approaches exist. One method – the equivalent turbulence method – is based on the assumption that all load generating mechanisms causing increased loads in wake operation can be merged into an equivalent value of increased turbulence intensity [1]. This method is specified in the IEC61400-1 safety standard [2]. The other method (the new dynamic wake meandering model [3], [4], [5]) is a recently developed more physical approach, taking into account the transversal and vertical dynamics of the wake (i.e. wake meandering). The objective of the work is to compare these two methods for a specific turbine in a specific wind farm environment. Both fatigue loads and ultimate loads are considered. The turbine is a 2.0 MW variable speed/pitch controlled turbine. The aeroelastic model HAWC has been used for the investigation. A number of fatigue load cases are analyzed using the Rainflow counting method, and the combined life time fatigue loads are compared for the two different wake simulation methods at mean wind speeds 10m/s and 20m/s, respectively. The difference in fatigue load is within 20% for most load sensors. Concerning the extreme loads, no differences are expected for the stand still/idling 50-year load case; however, for extreme loads occurring during normal operation the wake method applied influences the results significantly. The main differences between the two wake simulations methods are seen for the extreme yaw loads during operation.

1. Introduction

Most wind turbines are installed in wind farms and during the past years, much focus has been put on the difference in the loading for wind turbines operating in wake compared with wind turbines operating in free inflow. The traditionally used concept is to adjust the free flow turbulence intensity to account for increased loads in wind farms – a methodology that might be suitable for fatigue load simulation. For extreme response during operation the success of this simplified approach depends significantly on the physical mechanism causing the extremes. If the physical mechanism creating increased loads in wake operation differs from increased turbulence intensity, the resulting extremes might be erroneous. Regarding blade loads the traditionally used simplified approach works better than for integrated rotor loads - where the instantaneous load gradient across the rotor disc, is causing the extreme loads.

Usually, separate methods for prediction of power loss and load response for wind turbines in wind farms are used. For the estimation of production, models describing the average deficit for a specific turbine are used, while turbulence equivalent models often are used to predict the increased loading. The simplicity is an advantage of both types of models, and usually the computational work is small. If there is a need for more detailed response prediction (simultaneous power and load prediction), it can be difficult to combine these two types of methods. One example can be the prediction of extreme response of an operating turbine or cases where simultaneous analysis of production and load responses is carried out, e.g. as basis for establishing an operational strategy based on the trade off between loads and power production. For such cases, a more physical detailed modelling is needed.
Another example is when advanced individual pitch control is used to reduce rotor loads in wake operation.

For these cases, a more physical approach must be followed and recently a dynamic wake meandering model was suggested [3], [4], [5]. This method differs from previous work in being a more detailed physical modelling of the wind speed deficit in the wake of the upwind turbine. The region with reduced wind speed moves transversal depending on the large scale free turbulence transversal components and it is used as inflow for the actual turbine. Thus, this turbine will experience periods with varying shear profile across the rotor disc, caused by the upstream created wake deficit, in combination with the free turbulence field.

In this paper the two different model types are compared for a 2.0MW variable speed/pitch controlled wind turbine operating in wind farm conditions. The analyzed load cases are normal operation at 10m/s and 20m/s, and both fatigue and extreme loads are compared. The layout of wind farm considered is a square wind farm, and the actual turbine has four neighbouring turbines. Two different values of inter-turbine spacing – 3 diameters and 8 diameters – are considered.

2. Description of the methods
Two different approaches are considered for handling of the increased loading in wind farm operation, the method of equivalent turbulence intensity and the dynamic wake meandering model. These are described in this section.

2.1. The method of equivalent turbulence intensity.
The method of equivalent turbulence forms the basis of an informative annex in the recent IEC standard [2]. In the method of equivalent turbulence, the effects of all load generating mechanisms are condensed into a modification of the intensity of the free flow turbulence. The method has primarily been calibrated in order to obtain correct values for flapwise blade bending fatigue loads.

For a uniform wind directional distribution, the effective turbulence intensity can be calculated as:

\[ I_{\text{eff}} = \frac{1}{V_{\text{hub}}} \left( (1 - N p_w) \sigma^m + p_w \sum_{i=1}^{N} \sigma_T^m (d_i) \right)^{\frac{1}{m}} \]

where \( V_{\text{hub}} \) is the average wind speed at hub height, \( N \) is the number of neighbouring wind turbines, \( p_w \) is the probability density function of the wind direction (for a uniform distribution, \( p_w = 0.06 \) is used) and \( m \) is the relevant material SN-exponent. \( \sigma \) is the ambient wind speed standard deviation and \( \sigma_T \) is the maximum centre-wake wind speed standard deviation calculated as:

\[ \sigma_T = \sqrt{\frac{0.9 V_{\text{hub}}^2}{(1.5 + 0.3 d_i \sqrt{V_{\text{hub}}/c})^2} + \sigma^2} \]

where \( d_i \) is the distance to neighbouring turbines, normalized by the rotor diameter and \( c = 1 \) m/s.

More details on the model are given in references [1] and [2].

2.2. The dynamic wake meandering (DWM) model.
The dynamic wake meandering method [3], [4], [5] is based on two parts: a prediction of the deficit wind field in the wake of an upstream turbine and on the meandering of the deficit wind field due to transversal turbulence. The first part is basically a simulation of the wake deficit of the upwind turbine in steady flow. The full flow field for the upwind turbine is calculated, in this case with an axis-symmetrical actuator disc model using the CFD code FIDAP. Turbulence is modelled with a k-\( \varepsilon \) model. The calculation is carried out for different rotor loadings (wind speeds), and the deficit wind
field is determined from this flow field at the correct downwind position for the turbine operating in wake and for the actual loading on the upwind turbine. Using the actuator disc concept to model the rotor flow the discrete tip vortices are not modelled, but the turbulence generated in the shear layer of the deficit will cause an expansion of the deficit region downstream.

In the dynamic wake meandering method, it is assumed that the wake deficit of the upwind turbine is transported downstream as a passive tracer in a turbulent environment. The downwind turbine experience a cascade of wake deficits each transported individually downstream affected only by the local turbulence it experiences during the transport. In the particular implementation each volume of air passing the upwind turbine is transported downwind in the turbulent atmospheric boundary layer with a velocity corresponding to the mean wind speed. Thus, during a small time step the deficit moves a distance corresponding to the product of the wind speed and the time step in the longitudinal direction. At the same time it is assumed that a transversal movement of the wake centreline occur as a result of the cross turbulence components. Since the deficit has a considerable spatial size the transversal components are only affected by the large scale turbulent eddies. Therefore, the turbulence components affecting the transport are the spatially averaged over an area corresponding to the upstream turbine rotor diameter.

The movement is accumulated during time, and the resulting movement corresponding to one point in a 'movement'-series is later used in the full aeroelastic simulation. Since the wake moves and the characteristic lateral and vertical turbulence components are calculated in the actual position, it is necessary to use a large turbulence field for calculation of the movement.

At the present time the DWM model is still under development and different issues are investigated. One is the level of wake turbulence from the upstream turbine caused mainly by trailed vorticity which typically rolls up into tip and root vortices shortly after being released from the blades. An analysis of wake turbulence has been reported in [6] and [7], based on detailed inflow measurements with a five hole pitot tube on the rotating wing of a 2MW turbine operating in wake from a similar upstream turbine at a distance of about 3D. The analysis of the measurements and comparisons with the simulation results of the DWM model indicated wake turbulence intensity levels of 10-15%, but varying considerably in intensity across the wake with peak values at the edge of the wake. However, the analysis also indicated that the length scale in this wake turbulence is considerably lower than the length scale for the ambient turbulence, causing a high number of low amplitude cycles in the flapwise blade root moment response.

Another issue is the influence of the ambient turbulence on the development (expansion) of the wake deficits. Using a simple axis symmetric flow model with an eddy viscosity model for the turbulent stresses, Ainslie [8], [9] showed the considerable influence on the wake deficit development as function of ambient turbulence.
Figure 1 Illustration of the influence of the ambient turbulence on the development of the wake deficit profiles computed with an eddy viscosity (EV) model. Initial deficit from the actuator disc model.

A similar model eddy viscosity (EV) model has been implemented at Risø, and the effect of varying the eddy viscosity due to the ambient turbulence is illustrated in Figure 1. The initial deficit is a deficit from the actuator disc model at 3D, and the deficits are now computed with the EV model at 8D for different values of the eddy viscosity $\epsilon_a$ from the ambient turbulence. The ambient turbulence is seen to increase the recovering of the velocities in the wake and at the same time increasing the wake width.

In the version of the DWM model used for the computations in the present paper no wake turbulence has been included, and further the wake deficits are computed without influence of ambient turbulence. The possible influence of neglecting these two parameters will be discussed later.

3. Assumptions for the comparison

The turbine considered is an 80m diameter, 2.0MW variable speed/pitch regulated turbine. Two different wind speeds are considered, 10m/s and 20m/s. For both wind speeds, the ambient turbulence intensity is assumed to be 0.125. All load simulations are carried out with the aeroelastic model HAWC.

Two wind farms with equal spacing between all turbines are used in the calculations. Except for the turbine spacing the two farms has identical layout, and in both cases the considered wind turbine is assumed to experience wake inflow from four neighbouring turbines. The inter-turbine spacing is either 3 rotor diameters or 8 diameters. The wind direction distribution is assumed uniform, and the number of operational hours at each wind speed is chosen according to a Weibull distribution with a scale parameter 8.67m/s and a shape parameter 1.76.

For the simulations with the dynamic wake meandering model, two different sets of turbulence boxes are needed for each simulation due to practical reasons; one for the meandering process with a large spatial size but coarse resolution, and one for the actual load simulation which is smaller in size but with a more detailed resolution. In order to reduce the statistical uncertainty, four different realizations are used for the meandering part. For the applied turbulence in the simulations, the same...
realization has been used in all simulations – both the ones with the dynamic wake meandering model and the ones with the method of increased turbulence intensity.

The resulting fatigue loads are compared at two wind speeds, 10m/s and 20m/s. The method of equivalent turbulence intensity is straightforward to apply; only one simulation is necessary for each material considered. In this case, \( m=12 \) and \( m=4 \) are used for blade loads and tower loads, respectively. The ambient turbulence intensity is 0.125, and the calculated turbulence intensities for the method of equivalent turbulence are given in Table 1.

| Case        | \( m=4 \) | \( m=12 \) |
|-------------|-----------|-----------|
| 10m/s, 3D   | 0.184     | 0.223     |
| 10m/s, 8D   | 0.137     | 0.146     |
| 20m/s, 3D   | 0.161     | 0.189     |
| 20m/s, 8D   | 0.131     | 0.135     |

For the dynamic wake meandering model, several simulations are needed in order to resolve the different degrees of wake operation. However, each of these covers all possible relevant materials in the investigated turbine. We have discretized the wake simulations into 17 angular sectors, ranging from -30\(^\circ\) view angle to +30\(^\circ\) view angle for the turbine considered. All four wakes from neighbouring turbines are considered identical, and the probability of each directional sector is calculated from a uniform distribution of wind directions.

4. Fatigue load results

The fatigue loads are compared for the two different methods as partial life time fatigue loads at each wind speed. Since only two distinct wind speeds are considered it is not possible to calculate the correct integrated life time fatigue loads corresponding to e.g. 10 millions cycles. However, for each wind speed, the partial integrated fatigue damage has been calculated and turned into a representative partial life time equivalent load at each wind speed, using the proper number of operational hours at the wind speed. For the normalization, a load cycles number corresponding to 1Hz has been applied.

The overall results from the fatigue load analysis are given in Table 2 for a number of selected load sensors. The results from the method of increased turbulence intensity (MET) originates from one simulation (actually two – corresponding to the two different \( m \)-values) while the results from the dynamic wake meandering model originates from 17 simulations integrated over the directional distribution.

The results illustrate that the MET model is under-estimating the fatigue loads generally at 10m/s for both spacing values. At 3 diameter spacing the under-estimation is approximately 5-15%, and the value is slightly larger at 8 diameter spacing. At 20m/s with 3D spacing the MET model over-estimates the fatigue loads whereas the agreement is better for the 8D spacing. However, as mentioned in the description of the DWM model the influence of wake turbulence and the influence of ambient turbulence have not been modelled in the present results. Adding the wake turbulence will increase the fatigue loading further, but as mentioned the length scale of this turbulence seems to be smaller than the length scale of the atmospheric turbulence and is thus relatively less important for fatigue loads. The other parameter not included in the present results is the influence of the ambient turbulence on the wake deficit development. The general tendency of ambient turbulence is as shown previously a faster recovery of the wake deficit profiles and this will tend to reduce the fatigue loads.

The results are illustrated in Figure 2 - Figure 4 for three selected structural sensors. Here, the fatigue loads resulting from the method of equivalent turbulence is compared to the fatigue loads calculated at different degrees of wake operation. The difference between the values associated with
the method of equivalent turbulence intensity and the dynamic wake meandering, respectively, are obvious. Furthermore, it can be seen that the wake deficit has a characteristic double peak bell shape at a spacing of 3 diameters. This has disappeared further downstream at 8 diameter spacing – where the wake width also seems less than at 3 diameters downstream distance. The actual wake is wider for further downstream distances, but in these presentations the load are plotted versus the angular width seen from the turbine in question. Thus, the apparently lower width for larger spacing is caused by the fact that the angular section where the turbine is visible reduces – when observed at the specific turbine location.

The corresponding comparison of average power production is illustrated in Figure 5 for the 10m/s case and it illustrates another important difference between the approaches. For the method of equivalent turbulence, no change in average power is seen, while the dynamic wake meandering model reproduce the correct simultaneous reduction in power production for wake operation.

![Flapwise fatigue loads for different inflow angles from the DWM model compared to the results of the MET model. The integrated values from the DWM model are not shown.](image-url)
Figure 3  Tower bottom bending fatigue loads for different inflow angles from the DWM model compared to the results of the MET model. The integrated values from the DWM model are not shown.

Figure 4 Yaw moment fatigue loads for different inflow angles from the DWM model compared to the results of the MET model. The integrated values from the DWM model are not shown.
Table 2 Comparison of 1Hz equivalent loads for the method of increased turbulence (MET) and the dynamic wake meandering model (DWM).

| Load                     | m | MET  | DWM  | ratio |
|--------------------------|---|------|------|-------|
| 3D Flapwise blade bending| 12| 1832 | 1964 | 0.93  |
| U=10m/s Edgewise blade bending | 12| 3407 | 3523 | 0.97  |
| Tower bottom long.       | 4 | 2699 | 3401 | 0.79  |
| Tower top tilt           | 4 | 1059 | 1171 | 0.90  |
| Tower top yaw            | 4 | 936  | 1103 | 0.85  |
| 3D Flapwise blade bending| 12| 3202 | 2531 | 1.27  |
| U=20m/s Edgewise blade bending | 12| 3185 | 2682 | 1.19  |
| Tower bottom long.       | 4 | 6229 | 5105 | 1.22  |
| Tower top tilt           | 4 | 1652 | 1358 | 1.22  |
| Tower top yaw            | 4 | 1630 | 1374 | 1.19  |
| 8D Flapwise blade bending| 12| 1347 | 1669 | 0.81  |
| U=10m/s Edgewise blade bending | 12| 3606 | 3545 | 1.02  |
| Tower bottom long.       | 4 | 2015 | 3180 | 0.63  |
| Tower top tilt           | 4 | 725  | 941  | 0.77  |
| Tower top yaw            | 4 | 646  | 879  | 0.73  |
| 8D Flapwise blade bending| 12| 2611 | 2464 | 1.06  |
| U=20m/s Edgewise blade bending | 12| 2703 | 2665 | 1.01  |
| Tower bottom long.       | 4 | 5240 | 5148 | 1.02  |
| Tower top tilt           | 4 | 1368 | 1326 | 1.03  |
| Tower top yaw            | 4 | 1368 | 1333 | 1.03  |

Figure 5 Average value of power at 10m/s for the two model approaches.
5. Extreme load results

The extreme loads are presented as absolute extreme values for a number of selected sensors in Table 3. Generally, a small under-estimation is seen for most load sensors using the method of equivalent turbulence intensity. For the yaw moment at 10m/s the extreme values are under-estimated with a factor of 2-3. This is as expected and due to the fact that the extreme values of the yaw moment occur in half wake operation, which causes a large load gradient across the rotor disc. Such gradients in loading are not part of the conventional turbulence fields and it is therefore not possible to simulate these events using an increased turbulence intensity value – at least not with a realistic value of the turbulence intensity.

Table 3 Comparison of extreme loads for the two different approaches.

| Load                  | MET   | DWM   | ratio |
|-----------------------|-------|-------|-------|
| 3D Flapwise blade bending | 3330  | 3408  | 0.98  |
| U=10m/s Edgewise blade bending | 2567  | 2984  | 0.86  |
| Tower bottom long.     | 14980 | 16190 | 0.93  |
| Tower top tilt         | 3085  | 3912  | 0.79  |
| Tower top yaw          | 1205  | 2680  | 0.45  |
| 3D Flapwise blade bending | 3201  | 3108  | 1.03  |
| U=20m/s Edgewise blade bending | 2460  | 2058  | 1.20  |
| Tower bottom long.     | 13360 | 13840 | 0.97  |
| Tower top tilt         | 4221  | 4346  | 0.97  |
| Tower top yaw          | 2595  | 2615  | 0.99  |
| 8D Flapwise blade bending | 3047  | 3217  | 0.95  |
| U=10m/s Edgewise blade bending | 2784  | 3074  | 0.91  |
| Tower bottom long.     | 14460 | 17430 | 0.83  |
| Tower top tilt         | 2820  | 3770  | 0.75  |
| Tower top yaw          | 856   | 2448  | 0.35  |
| 8D Flapwise blade bending | 2802  | 3101  | 0.90  |
| U=20m/s Edgewise blade bending | 1847  | 2018  | 0.92  |
| Tower bottom long.     | 12430 | 14850 | 0.84  |
| Tower top tilt         | 3908  | 4289  | 0.91  |
| Tower top yaw          | 2012  | 2373  | 0.85  |

This point is emphasized in Figure 6 and Figure 7 illustrating the extreme values and mean value of the yaw moment at different degrees of wake operation. The extreme maximum value is seen for average half-wake operation to one side, while the extreme minimum value is seen for the half-wake operation to the other side. The general pattern is similar for both spacing values.

The reason for the difference is the different physics involved in the simulation approaches; see time series in Figure 8 and Figure 9. At half-wake operation, the rotating blade with sample a the large wind speed difference as a 1p variation, which in turn will result in a large load gradient across the rotor disc causing an offset in the yaw moment. This is not reproduces in the simulations with the increased turbulence method.
Figure 6 Extreme values for the yaw moment at different degrees of wake operation. Spacing is 3D.

Figure 7  Extreme values for the yaw moment at different degrees of wake operation. Spacing is 8D.
Figure 8 Time series of simulated flapwise root bending moment at 10m/s in 3D case. Upper plot is MET model, lower plot is the DWM model at a wake angle of -12deg (note that the flapwise moment is calculated positive towards the wind).

Figure 9 Time series of yaw moment for 10m/s 3D case. Upper plot is the MET model, lower plot is the DWM model at a wake angle of -12deg.
6. Conclusion

The method of equivalent turbulence intensity slightly underestimates the fatigue loads at 10m/s for both 3D and 8D separations. At 20 m/s and low spacing (3D), this model overestimates the fatigue loads with approximately 20-30%.

Generally, the method of equivalent turbulence intensity model slightly underestimates the extreme loads for both spacing values and both wind speeds. For the yaw moment at 10m/s, the MET model underestimates the extremes significantly with a factor of 2-3.

In the comparison of extreme loads, no load extrapolation has been applied. This is a requirement in the recent edition 3 of the IEC61400-1 standard [2], and this could possible increase the discrepancies for the yaw moment even further.

In the full description of the method of equivalent turbulence intensity [1], it is possible to use the thrust-coefficient of the specific turbine in question, and not a generic expression for this. This could change the results – in particular at high wind speeds, since the generic thrust-coefficient value used here are conservative in terms of fatigue loads. It should also be emphasized that two parameters, wake turbulence and influence of ambient turbulence on the wake deficit profiles have not yet been implemented in the DWM model. In general the first parameter will increase the loading and the other parameter will decrease the loading. A further development of the DWM model to include these two parameters is ongoing.

The comparison has illustrated some of the important differences in modeling of loads for wind turbines operating in wind farms. For future optimization of wind farm layout – and turbine design – it is crucial to be able to model the loads correctly, both with respect to extreme and fatigue loads. Furthermore, a simultaneous modeling of the reduction in power production is necessary – see Figure 5 – for a correct prediction of the trade off between loads and production.

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