INTEGRATED FATIGUE LOADING FOR WIND TURBINES IN WIND FARMS BY COMBINING AMBIENT TURBULENCE AND WAKES

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ABSTRACT

A study is presented of an offshore application of a fatigue model for wind turbines operating partly in ambient turbulence and partly wakes. In order limit the number of aeroelelastic calculations in design verification, it is necessary to reduce the measured distribution of turbulence intensities into specific design turbulence. In this study, the observation that the fatigue loading is proportional to the turbulence is used. Thus, turbulence is used as primary design parameter, substantially describing the fatigue effects. The design turbulence is defined as the turbulence that gives an equal amount of fatigue damage as the combination of true distribution of ambient turbulence and turbulence generated from wake effects. The single most important parameter responsible for the increase in fatigue loading is very short distances between turbines.

KEYWORDS

Turbulence, fatigue analysis, wakes, offshore, added turbulence, ambient turbulence.

NOMENCLATURE

a	Slope parameter for the turbulence standard deviation model
a	Constant in model for added turbulence "over" wind farm
b	Constant in model for added turbulence "over" wind farm
b	Constant in expression for "effective" width of wake
C_T	Thrust coefficient of wind turbine rotor
c_t	Drag coefficient for wind farm, corresponding to drag-per-m^2
e	Equivalent stress range [N/m^2]
f'	Coriolis parameter multiplied by e^4
$f(*)$	Normal distribution
f_0	Probability as function of wind direction
h	Hub-height [m]
$i_{addwf}(y)$	Added turbulence intensity as function of downstream distance to wind turbine row
I	Turbulence intensity
I'	Spatially averaged turbulence in wind farm
I_{15}	Characteristic value of hub-height turbulence intensity at a wind speed of 15 m/s
I_m	Fatigue-weighted turbulence
I_0	Mean turbulence intensity
I_0'	Spatial average of turbulence in wind farm
I_{wf}	Turbulence intensity over wind farm
I_{addwf}	Turbulence intensity "over" wind farm – added turbulence intensity
I_{eff}	Effective turbulence
κ	von Karman's contants (=0.4)
$-m$	Exponent of (exponential) Wöhler curve
$M_{vertical}$	Vertical momentum transport [kg m^{-1} s^{-2}]
N	Number of neighbouring wind turbines
p_w	Probability of wake condition
r	Coefficient of variation of turbulence (σ_u)

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s Separation between wind turbine rows, divided by rotor diameter
s_1 Separation between wind turbines in the row, divided by rotor diameter
u 10 min average wind speed [m/s]
u_0 Ambient 10 min average wind speed [m/s]
u_h Hub-height average wind speed in wind farm [m/s]
u_* Friction velocity [m/s]
u_{*0} Friction velocity above wind farm [m/s]
x Perturbation in turbulence intensity
y Distance downstream of wind turbine row, divided by rotor diameter
z_0 Terrain surface roughness [m]
z_{00} "Apparent" roughness of wind farm [m]
α Constant in model of wake turbulence
β Constant in model of wake turbulence
σ_u Standard deviation over 10 min period of wind speed fluctuations [m/s]
σ_1 Standard deviation over 10 min period of wind speed fluctuations in along-wind direction [m/s]
$\overline{\sigma}_1$ mean of σ_1 [m/s]
$\Delta\sigma_1$ Standard deviation of σ_1 [m/s]
σ_I Coefficient of variation in turbulence intensity [m/s]
σ_0 Standard deviation of wind speed fluctuations in ambient flow, hub-height [m/s]
σ_{wf} Standard deviation of wind speed fluctuations "over" wind farm [m/s]
σ_{addwf} Standard deviation of wind speed fluctuations "over" wind farm – added turbulence [m/s]
$\phi_T(y)$ Total turbulence in terms of standard deviation of wind speed fluctuations – the distance y downstream [m/s]
$\phi_0=\sigma_0$ Spatially averaged turbulence "over" wind farm [m/s]
$\phi_w(y)$ Perturbation in turbulence "over" wind farm [m/s]
θ Wind direction [deg]

INTRODUCTION

The paper is focusing on the fatigue effects imposed on operating wind turbines by ambient and wake turbulence. Also, a few remarks are offered as to extreme loading in wake situations. 'Ambient, non-obstrcucted, turbulence' is defined as the 'normal' turbulence at the site that would be experienced by a single, stand-alone, turbine.

A model for an "effective" turbulence is devised. This model integrates load situations with ambient turbulence and load situations under wake conditions to give the total effective turbulence. When applying the effective turbulence, instead of the usual ambient turbulence for stand-alone wind turbines, no further actions have to taken to account for increased loading in wind farms due to increased turbulence from the other machines. Firstly, the effect of ambient turbulence on fatigue loading is evaluated, including the possible effect of the wind farm on the local climate. Next, the impact of individual wakes is considered. Finally, the combined action of wake and non-wake load cases is evaluated, and a proposal made for future standards' revisions.

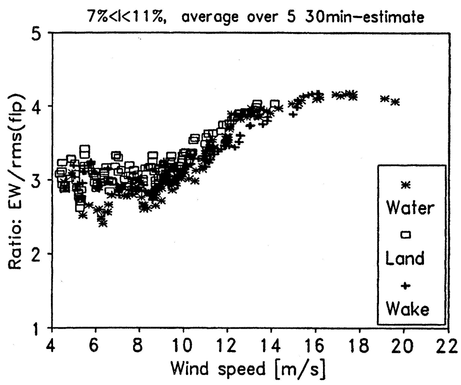

Figure 1: Ratio (non-dimensional) of measured equivalent stress range to standard deviation of wind speed as a function of the wind speed. Figure from Frandsen et. al (1996).

The response – in terms of cross-sectional forces or materials stress range - is known to be proportional in magnitude to the magnitude of wind speed fluctuations. The *equivalent* stress range[1] is proportional to the standard deviation of response fluctuations. I.e. for a fixed wind speed, the ratio between the equivalent stress range and the standard deviation of the load is constant. The validity of this statement is illustrated by the limited *scatter* of the ratio between the two quantities in Figure 1. Thus, it can be assumed that fatigue effects – in terms of equivalent stress range – is proportional to the standard deviation, σ_u, of wind speed, u:

$$e \propto \sigma_u \quad \Rightarrow \quad (\text{for fixed } u) \quad e \propto I \, . \qquad (1)$$

Measurements show that also under wake or part-wake conditions, the proportionality holds. This is understood and *justified by the fact that in most cases, other possible "input variables", such as vertical shear and wake deficit in mean wind speed are strongly (negatively or positively) correlated with turbulence*, Frandsen and Thomsen (1997).

For the approach to be valid, also the response of different structural components (output) must be correlated with each other, and again experimental evidence supports the model, Frandsen and Thomsen (1997).

In this paper the turbulence at hub height is chosen as reference, but the validity of the approach does not depend on which height reference is used.

FATIGUE IN AMBIENT FLOW

Firstly, the model of the IEC61400-1 standard is reviewed. Hereafter, the implications of the non-linearity of fatigue are investigated, and this section is finalised with considerations as to the interaction between very large wind farms and the local climate, in terms of increased "ambient" turbulence.

Ambient Flow, no Wind Farm

In the IEC 61400-1, the turbulence, σ_1, to apply in design calculations is given by the following expression (see symbols list for definitions and units of paramenters):

$$\sigma_1 = I_{15}(15 + a \cdot u)/(a+1) \qquad (1)$$

Here I_{15} is a characteristic value of hub-height turbulence intensity at wind speed of 15 m/s, a is the slope parameter for the turbulence standard deviation model, and u is the unperturbed wind speed.

The IEC 61400-1 operates with two turbulence levels, where $(I_{15};a)=(0.16;3)$ for "low" turbulence and $(I_{15};a)=(0.18;2)$ for "high" turbulence. The expression presumably is the best estimate of the average turbulence, as experienced/measured in nature, plus one standard deviation. The standard deviation *of* σ_1 is specified as

$$\Delta\sigma_1 = 2I_{15} \qquad (2)$$

Thus, the coefficient of variation for the turbulence is

$$r = \frac{\Delta\sigma_1}{\sigma_1 - \Delta\sigma_1} \qquad (3)$$

The quantity is plotted in Figure 2, for the low turbulence case. Note that for 10<u<20 m/s, the relative standard deviation decreases from approx. 20% to 10%.

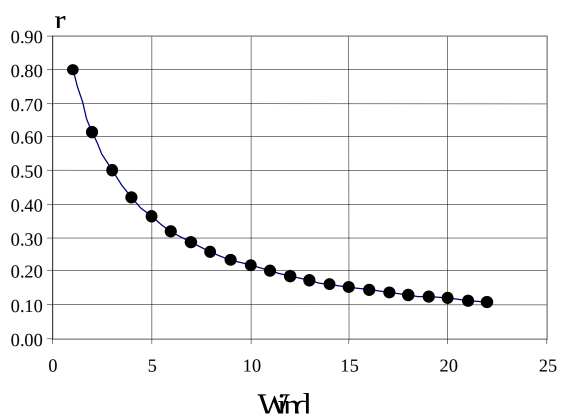

Figure 2 Coefficient of variation, r, of σ_1 as function of wind speed.

Thus, the 'design turbulence' of the IEC standard is composed of a mean turbulence and one standard deviation:

[1] The equivalent stress range is defined as the stress range amplitude at a fixed frequency that would cause the same fatigue damage as the real sequence of (random) variations, see e.g. Frandsen and Thomsen (1997).

$$\sigma_1 = \overline{\sigma}_1 + \Delta\sigma_1 \qquad (4)$$

Assuming that the turbulence is normal distributed, the above value constitutes a percentile of approximately 80%, i.e. for a given wind speed and a given 10 min. period, there is 80% probability the turbulence is smaller than σ_1.

Implication of the non-linearity of fatigue

As discussed above, ambient turbulence is, for a given wind speed and height, not constant, but varies due to terrain features and atmospheric stratification conditions. By introduction of the concept of equivalent stress range, sequences of dynamic turbulent loading of the structure can be added to estimate the integrated lifetime. Alternatively, the effective fixed turbulence intensity may be derived that gives the same fatigue life consumption as the real-life sequence of varying turbulence intensities, Frandsen and Thomsen (1997):

$$I_m = \left[\int_{-\infty}^{\infty} I^m f(I) dI \right]^{1/m} = \left[\int_{-\infty}^{\infty} (I_o + x)^m f(x) dx \right]^{1/m}, \quad I = I_0 + x \qquad (5)$$

where I_0 is the mean turbulence intensity (at the considered fixed wind speed), x the perturbation of turbulence intensity, $-m$ is the Wöhler[2] curve exponent of the materials of the structural component in question, and $f(*)$ is the Normal distribution,

$$f(x) = \frac{1}{\sigma_I \sqrt{2\pi}} \exp\left(-\tfrac{1}{2} \left(\frac{x}{\sigma_I} \right)^2 \right) \qquad (6)$$

where $\sigma_I = rms\{\sigma_1/u\}$ is the coefficient of variation of the turbulence intensity.

The integral of Eq. 5 is

$$I_m^m = I_0^m \left[1 + \binom{1}{m} \left[\frac{\sigma_I}{I_0} \right] + \binom{2}{m} \left[\frac{\sigma_I}{I_0} \right]^2 + \ldots\ldots\ldots + \binom{m}{m} \left[\frac{\sigma_I}{I_0} \right]^m \right] \qquad (7)$$

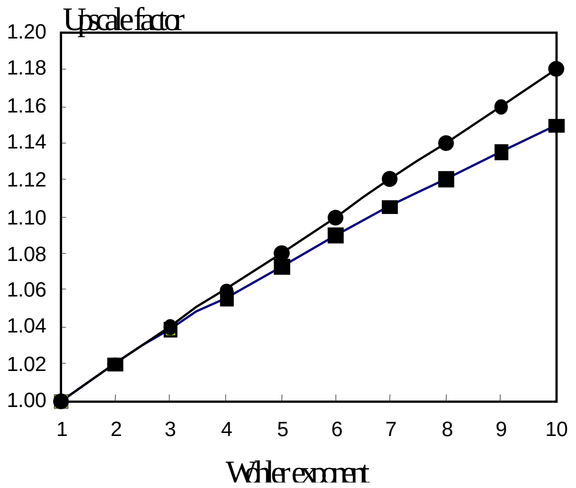

Figure 3 Effective turbulence for a coefficient of variation of turbulencence intensity of 20%. The line with the circles is the approximation. Both abscissa and ordinate are non-dimensional.

Keeping only the first two terms of the expansion, the following approximation is obtained:

$$I_m^m \approx I_0^m \left[1 + \tfrac{1}{2} m(m-1) \left(\frac{\sigma_I}{I_0} \right)^2 \right] \Rightarrow$$

$$I_m \approx I_0 \left(1 + \tfrac{1}{2}(m-1) \left(\frac{\sigma_I}{I_0} \right)^2 \right) \qquad (8)$$

The approximation is compared in Figure 3 with the exact solution as a function of the Wöhler exponent, for $\sigma_I/I_0 = 0.2$ (chosen as the typical value viz. the preceding section). The approximation is somewhat conservative for larger values of m.

[2] The Wöhler curve is the relation between the stress amplitude and the number of load cycles at which fatigue failure occur. Here, the simplification is applied that the curve is an exponential.

The following is noted:

- For $m \le 10$ and $\sigma_I / I_0 \le 0.2$, the effective turbulence intensity is lower that the percentile value applied for the extreme evaluation (IEC).
- A percentile value of I_m is linked to the certainty with which I_0 and σ_I have been determined, presumably by means of measurements. If e.g. 100 measurements of I_0 forms the basis and $\sigma_I / I_0 \approx 0.2$, then the relative standard deviation of I_0 is 2% - small compared to the 20%.
- For the free turbulence, the addition of one standard deviation already applied in the IEC-standard also accounts for fatigue type calculations.

"Ambient" Turbulence, within the Wind Farm

For "large wind farms" it will be necessary to re-evaluate the concept of *ambient turbulence*. Deep inside the wind farm, total turbulence will be composed by an average component, where the sources are reminiscences of the wakes, and turbulence generated by the ground friction, Templin (1974), Frandsen (1992), Emeis and Frandsen (1993). In addition, there is a component representing the well-defined nearer wakes, which is discussed later. Effectively, the wind turbines themselves will appear as roughness elements, and thus reduce the mean flow speed. In this respect, it is presently not well clarified how large is "large", Crespo et al (1999).

However, there are indications, Frandsen and Christensen (1994) and Frandsen and Thomsen (1997), that turbulence quickly reaches a level of balance. As far as turbulence is concerned, this justifies that the *spatially average* of hub height turbulence is estimated by means of a model that simply considers the wind turbines as roughness elements.

Applying the geostrophic drag law, Frandsen (1992) and Emeis and Frandsen (1993), the spatially averaged vertical wind profile down to hub height in the wind farm can be described as

$$\frac{u_h}{u_{*o}} = \frac{1}{\kappa} \ln\left(\frac{h}{z_{00}}\right) \qquad (9)$$

where the apparent, combined roughness of the ground and the wind turbines is

$$z_{00} = h \cdot \exp\left(-\frac{\kappa}{\sqrt{c_t + (\kappa / \ln(h/z_0))^2}}\right),\ c_t = \frac{\pi C_T}{8 s s_1} \qquad (10)$$

where h is hub height, z_0 is the roughness length of the ground, κ is von Karman's constant (=0.4), C_T is the wind speed-dependent thrust coefficient of the wind turbines, and s_1 and s are distances between the units in the rows and the separation between the rows, normalised with the rotor diameter[3]. The above-wind-farm friction velocity and the hub height wind speed are found as

$$u_{*0} = \frac{\kappa G}{\ln\left(\frac{G}{f' h}\right) + \frac{\kappa}{\sqrt{c_t + (\kappa / \ln(h/z_0))^2}}} \qquad (11)$$

and

$$u_h = \frac{G}{1 + \ln\left(\frac{G}{f' h}\right) \frac{\sqrt{c_t + (\kappa / \ln(h/z_0))^2}}{\kappa}} \qquad (12)$$

where G is the geostrophic wind speed and $f' \approx 1.2 \cdot 10^{-4} \cdot e^4 = 6.5 \cdot 10^{-3}$ at latitudes corresponding to Northern Europe. The friction velocity is assumed constant above hub height. Turbulence, σ_u, is assumed proportional to the friction velocity.

[3] If the wind turbine units are located in an irregular way, then s and s_1 should be taken as averages in the wind farm.

In the ambient flow, at height h, turbulence σ_0 and turbulence intensity I_0 are:

$$\sigma_0 \approx \frac{u_0}{\ln(h/z_0)} = \frac{u_*}{\kappa}, \quad I_0 = \frac{\sigma_0}{u_0} \tag{13}$$

Similarly, turbulence "over" the wind farm can be estimated as

$$\sigma_{wf} = \frac{u_{*0}}{\kappa} \tag{14}$$

This expression may in general be assumed valid some distance above the wind farm. As an approximation, it is assumed that the expression is valid all the way down to hub height. In the following, the turbulence intensity in the wind farm is defined as (referring to ambient hub height wind speed, u_0):

$$I_{wf} = \frac{\sigma_{wf}}{u_0} \tag{15}$$

The above-wind-farm turbulence is decomposed in a component from "ambient roughness" and component from wind turbines:

$$\sigma_{wf}^2 = \sigma_0^2 + \sigma_{addwf}^2, \quad I_{wf}^2 = I_0^2 + I_{addwf}^2 \Rightarrow \quad I_{addwf} = \sqrt{I_{wf}^2 - I_0^2} \tag{16}$$

The above set of equations are fairly complex and a simplification is useful. It is found that the added wind farm turbulence, I_{addwf}, is well modelled by the expression:

$$I_{addwf} \approx \frac{a\sqrt{C_T}}{b\sqrt{C_T} + \sqrt{s_1 s}} = \frac{0.36}{1 + 0.2\sqrt{s_1 s / C_T}}, \quad \text{where} \quad a = 1.8 \text{ and } b = 5 \quad . \tag{17}$$

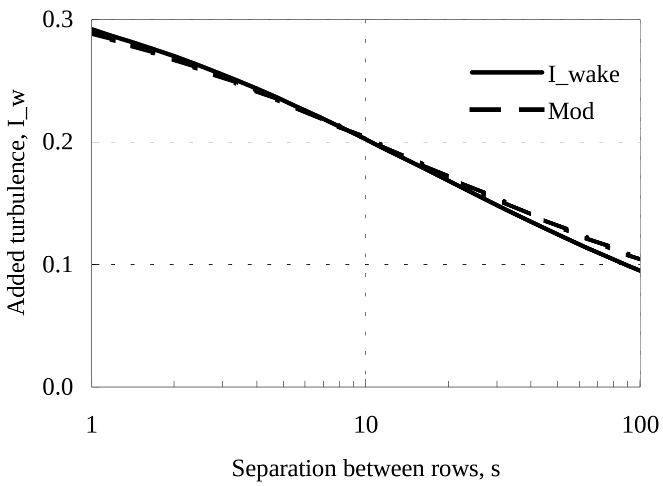

Figure 4: Horizontal average of added turbulence, as function of separation between rows. The solid is from basic equations, the red line corresponds to the proposed simplified model (s_1=1.5, C_T=1, h=50m, z_0=0.01m, G=15m/s). Both abscissa and ordinate are non-dimensional.

(The constants a and b are empirical . The approximation is tested in Figure 4. As seen from Eq. (17), the model has a maximum value of 0.36 for the separation tending toward zero, which is – probably accidental – similar in magnitude to the maximum near-wake turbulence argued by Crespo and Hernandez (1996).

The average of wind-farm generated contribution to ambient turbulence between the below-rotor-turbulence level, I_0, and the above-rotor-turbulence, Frandsen and Christensen (1994), is applied:

$$I' = \tfrac{1}{2}\left(\sqrt{I_{addwf}^2 + I_0^2} + I_0\right) \tag{18}$$

FATIGUE DUE TO NEAR-WAKE CONDITIONS

In an attempt to link the above model for the spatially-averaged turbulence to the near-wake turbulence, the case of wind turbines narrowly-spaced perpendicular to the wind direction is studied first.

Variation of turbulence between closely spaced machines

In the particular case of wind farms with narrowly spaced units in the rows facing the wind front, it is possible with few assumptions to deduct from the above global-flow considerations the variation of turbulence between the rows. Therefore, what is presented in this section applies for wind farms with machines closely spaced in the rows facing the wind, and larger spacing downwind between rows.

Turbulence varies between rows, being the largest immediately behind each wind turbine row. In that case it can be assumed that the wakes are significantly overlapping when reaching the next row, i.e. turbulence does not vary laterally at hub height just in front of each row. Assume next that vertical (downward) momentum transport is proportional to the variance of turbulence[4]:

$$M_{vertical} \propto u_*^2 \propto \sigma_u^2 \, . \tag{19}$$

For that reason is seems reasonable to find the "effective" value of turbulence (σ_u) by averaging the variance of turbulence, which we denominate ϕ^2. Thus, the variance of turbulence at distance y downstream of a row of turbines can be written as

$$\phi_T^2(y) = \phi_0^2 + \phi_w^2(y) = \sigma_0^2 + \phi_w^2(y) \tag{20}$$

The average of the variance is taken between two rows:

$$\sigma_T^2 = (\frac{1}{s})\int_0^s \phi_T^2(y)dy = \sigma_0^2 + (\frac{1}{s})\int_0^s \phi_w^2(y)dy \tag{21}$$

The last term on the right side of the equation corresponds to the added turbulence in the global considerations, Eq. 17:

$$a^2 C_T \frac{s}{(b\sqrt{C_T} + \sqrt{s_1 s})^2} = \int_0^s i_{addwf}^2(y)dy, \quad \text{where} \quad i_{addwf}(y) = \frac{\phi_w(y)}{u_0} \tag{22}$$

Differentiating with respect to s (s_1 is held constant) we get

$$\begin{aligned} i_{addwf}^2(s) &= \frac{d}{ds}\left(a^2 C_T \frac{s}{(b\sqrt{C_T} + \sqrt{s_1 s})^2} \right) \quad \Rightarrow \\ i_{addwf}^2(y) &= \frac{a^2}{b^2} \cdot \left\{ \frac{b\sqrt{C_T}}{b\sqrt{C_T} + \sqrt{s_1 y}} \right\}^3 \quad 0 < y < s \end{aligned} \tag{23}$$

Thus, an estimate of wake turbulence intensity as function of downstream distance from a row of wind turbines is

$$i_T(s) = \sqrt{\frac{a^2}{b^2} \cdot \left\{ \frac{b\sqrt{C_T}}{b\sqrt{C_T} + \sqrt{s_1 y}} \right\}^3 + I_0^2} \tag{24}$$

[4] This is the usual assumption in the logarithmic boundary layer.

This result is applied in the following, adopting the *form* for a model of single-wake, added turbulence – as an alternative to the form proposed previously, Frandsen et al (1996) and Frandsen and Thomsen (1997).

Single (multiple) wake turbulence

In cases where the wind turbine units are sufficiently separated for the neighbouring units to experience definite wakes, the modelling presently applied is mostly empirical.

A "bell-shape" of turbulence has been observed and the following model for wake turbulence of one wake (or multiple-wake) is applied:

$$I = I_0(1+\alpha)\exp\left(-\left[\frac{x}{\beta}\right]^2\right) \tag{25}$$

where I_0 is ambient turbulence[5], x is the angle between the line from the wake-generating and the wake affected wind turbines and the wind direction. β is a characteristic wake width, found to be well described by:

$$\beta \cong \tfrac{1}{2}\left(\tfrac{180}{\pi}\cdot\tan^{-1}(1/s)+10^\circ\right) \approx \frac{25}{s} \quad [\mathrm{deg}] \tag{26}$$

where s is the distance between the wind turbines. The integrated effect of ambient turbulence and turbulence from one wake, assuming uniform distribution of wind direction and fixed wind speed, is

$$I_{eff} = \left[\int_{-180}^{180} f_0(\theta) I^m(\theta)\,d\theta\right]^{1/m} = \left[\int_{-180}^{180} \frac{1}{360}\left(I_0(1+\alpha)\exp(-\left(\frac{\theta}{\beta}\right)^2\right)^m d\theta\right]^{1/m} \tag{27}$$

where m is the Wöhler curve slope of the material under loading. Alternatively, the equation can be written as

$$I_{eff} = \left[\left(\frac{360-2b\beta}{360}\right) I_0^m + \frac{2b\beta}{360} I_T^m\right]^{1/m} \tag{28}$$

where I_T is maximum wake turbulence. Comparing the two expressions, it is found that the quantity b can be approximated by

$$b \cong \frac{\pi}{2}\frac{3+\sqrt{m}\alpha^{1.25}}{3+m\alpha^{1.25}} \tag{29}$$

The constant α can be expressed by the ambient turbulence and maximum added wake turbulence (note again that the turbulence intensities all refer to ambient wind speed):

$$I_T = I_0(1+\alpha) = \sqrt{I_w^2 + I_0^2} \quad \Rightarrow \quad \alpha = \sqrt{\left(\frac{I_w}{I_0}\right)^2 + 1} \;\; -1 \tag{30}$$

[5] Or the deduced effective ambient turbulence, I_m.

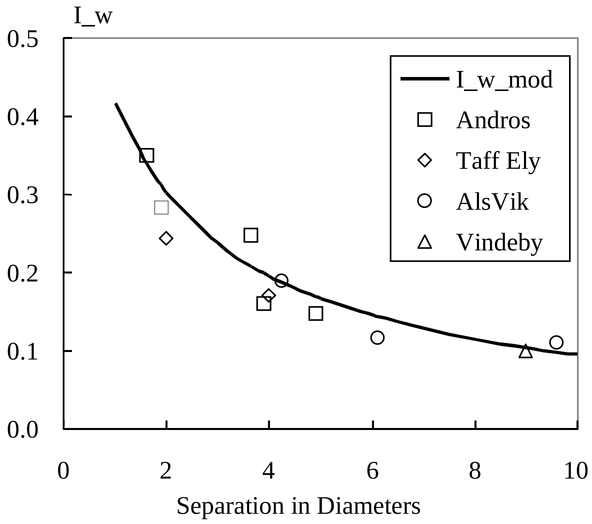

Figure 5: Maximum, additional wake turbulence I_w, measured at four site compared with the model. Both absisca and ordinate are non-dimensional. The measurement results was compiled by S. Ghaie (1997).

The drag coefficient is modelled as

$$C_T = \frac{3.5(2u-3.5)}{u^2} \approx \frac{7\text{ m/s}}{u} \qquad (31)$$

(C_T is non-dimensional)

Obviously, the approximation fits poorly at low wind speeds. However, loads at low wind speeds have little impact when summing up lifetime consumption and therefore the simple expression is acceptable. For the added turbulence, the following expression is adapted:

$$I_w = \frac{1}{1.5 + 0.1\frac{s}{\sqrt{C_T}}} \approx \frac{1}{1.5 + 0.3 \cdot s \cdot \sqrt{u}} \qquad (32)$$

The constants are chosen to best fit the data. The expression is similar in form to the model for spatially averaged turbulence and to the case of closely spaced wind turbines[6].

As it turns out, the quality of the model for I_w is important for the quality of the result. The model is compared with data in the above Figure 5 and there is good agreement, with the majority of measurements below the model-curve.

It turns out that the probability of wake condition may, without significant loss of accuracy, be simplified:

$$p_w = \frac{2b\beta}{360} \cong 0.06, \quad \text{for any values of } s, I \text{ and } m \qquad (33)$$

The proposed model (instead of the best fit) takes small separations more into account than the larger separations. For separations less than 4D, for every data point above the line (20%) , there are 4 data points (80%) under the line.

CONCLUSION: PROPOSAL FOR MODEL FOR EFFECTIVE TURBULENCE

The developed model framework is used for the following proposal of how to include increased fatigue loading in wind farms.

Fatigue loading

The formulas apply for fatigue load calculations under normal operating conditions.

Wake effects from neighbouring wind turbines may be taken into account the following way: if the smallest wind turbine separation is larger than 20 rotor diameters, wake effects do not have to be included in the load calculations. If the minimum wind turbine separation is less than 20 rotor diameters, wake effects may be taken into account solely by replacing relevant turbulence intensities with

$$I_{eff} = \left[(1 - N \cdot p_w) I_0^m + p_w \sum_{i=1}^{N} I_T^m(s_i) \right]^{1/m} \qquad (34)$$

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[6] For the closely spaced wind turbines, the expression was raised to the power 3/2, and the constants were different. Here, the applied expression fits the data better.

where $p_w = 0.06$,

$I_T = \sqrt{\dfrac{1}{(1.5 + 0.3 \cdot s_i \cdot \sqrt{u}\,)^2} + I_0^2}$ is the maximum centre-wake, hub height turbulence,

s_i is the distance to neighbouring wind turbine no. *i*,
I_0 (or I_0', see below) is the ambient turbulence,
I_{eff} is the turbulence intensity to be employed instead of the turbulence used for non-wake conditions, IEC61400-1
N is the number of neighbouring wind turbines,
-m is the Wöhler curve exponent corresponding to the material of the considered structural component, and
u is mean ambient hub height wind speed.

Applying the formulas, no reduction in mean wind speed inside the wind farm can be assumed.

Wake effects from wind turbines "hidden" behind other machines need not be considered, e.g. in a row only wakes from the two units closest to the machine in question are to be taken into account.

Depending on the wind farm configuration, the number of nearest wind turbines to be included in the calculation of I_{eff} is given in the below table.

Wind farm configuration	N
2 wind turbines	1
1 row	2
2 rows	5
Inside a wind farm with more than 2 rows	8

The wind farm configurations are illustrated in the below Figure 6 for the case "Inside a wind farm with more than 2 rows".

Inside large wind farms, the wind turbines tend to generate their own ambient turbulence. Thus, when (1) the number of wind turbines from the considered unit to the "edge" of the wind farm is more than 5, or (2) the spacing in the rows perpendicular to the predominant wind direction is less than 3D, then the following ambient turbulence shall be assumed:

$$I_0' = \tfrac{1}{2}\left(\sqrt{I_{addwf}^2 + I_0^2} + I_0\right) \qquad (35)$$

where

$$I_{addwf} = \frac{0.36}{1 + 0.2\sqrt{s\ s_1 / C_T}} ..$$

In the above formulas circular distribution of wind direction is assumed. It is acceptable to adjust the formulas to other than circular distribution of wind direction.

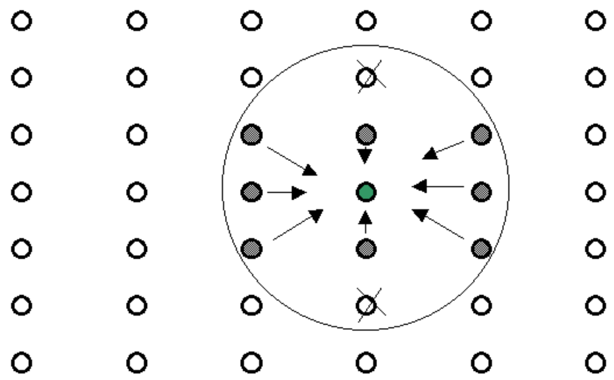

Figure 6: The situation within a wind farm.

Ultimate loads

Possible ultimate loads during normal operation should be investigated differently, depicting the load case with most severe wake condition or the load case where wake condition and ambient turbulence in combination constitute to most severe load condition.

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