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Fatigue reliability and effective turbulence models in wind farms

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ABSTRACT: Offshore wind farms with 100 or more wind turbines are expected to be installed many places during the next years. Behind a wind turbine a wake is formed where the mean wind speed decreases slightly and the turbulence intensity increases significantly. This increase in turbulence intensity in wakes behind wind turbines can imply a significant reduction in the fatigue lifetime of wind turbines placed in wakes. In this paper the design code model in the wind turbine code IEC 61400-1 (2005) is evaluated from a probabilistic point of view, including the importance of modeling the SN-curve by linear or bi-linear models. Further, the influence on the fatigue reliability is investigated from modeling the fatigue response by a stochastic part related to the ambient turbulence and the eigenfrequencies of the structure and a deterministic, sinusoidal part with frequency of revolution of the rotor.

1 INTRODUCTION

Wind turbines for electricity production have increased significantly the last years both in production capability and in size. This development is expected to continue also in the coming years. Offshore wind turbines with an installed capacity of 5–10 MW are planned. Typically, these large wind turbines are placed in offshore wind farms with 50–100 wind turbines. Behind a wind turbine a wake is formed where the mean wind speed decreases slightly and the turbulence intensity increases significantly. The change is dependent on the distance between the wind turbines.

In this paper fatigue reliability of main components in wind turbines in clusters is considered. The increase in turbulence intensity in wakes behind wind turbines can imply a significant reduction in the fatigue lifetime of wind turbine components. In the wind turbine code IEC 61400-1 (IEC 2005) and in (Frandsen 2005) are given a model to determine an effective turbulence intensity in wind farms. This model is based on fatigue strengths modeled by linear SN-curves without endurance limit.

The reliability level for fatigue failure for wind turbines in a wind farm is evaluated using the effective turbulence intensity model in IEC 61400-1 (IEC 2005) for deterministic design, and the uncertainty models in (Frandsen 2005) are used in the reliability analysis. The fatigue strength is assumed to be modeled using the SN-approach and Miners rule. The stochastic models recommended in the JCSS PMC (JCSS 2006) are used. Linear and bi-linear SN-curves are considered.

Further, the influence on the fatigue reliability in wind farms with wakes is considered in the case where the fatigue load spectrum is modeled not only by a stochastic part related to the ambient turbulence and the eigenfrequencies of the structure, but also additionally a deterministic, sinusoidal part with frequency of revolution of the rotor. This deterministic part is important for many fatigue sensitive details in wind turbine structures.

Devising the model for effective turbulence, the underlying assumption is a simple power law SN curve. However, when applying the effective turbulence that assumption shall not be propagated, and thus the load spectra should be derived from the response series by e.g. rainflow counting and the fatigue life should be derived by integrating with the actual SN curve. In this paper, the possible error/uncertainty introduced by the simple, one-slope power law SN curve, is investigated.

2 WAKES IN WIND FARMS

In figure 1 from (Frandsen, 2005) the change in turbulence intensity I (standard deviation of turbulence divided by mean 10-minutes wind speed) and mean 10-minutes wind speed U is illustrated.

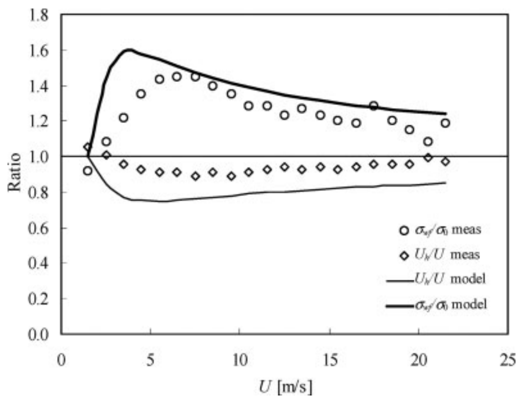

Figure 1. Illustrative ratios of wind velocity U at hub (rotor) height and turbulence σ_u inside (U_h and σ_{wf}) and outside (U and σ_0) a wind farm, as function of wind velocity. The full lines are the model predictions – from (Frandsen, 2005).

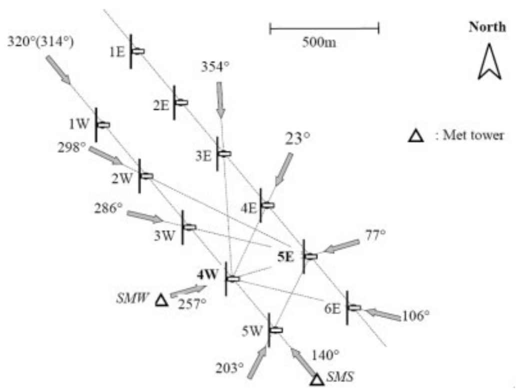

Figure 2. Layout of the Vindeby offshore wind farm – from (Frandsen, 2005).

In figures 3–4 from (Frandsen, 2005) data are shown, obtained from the Vindeby wind park (south of Denmark). It is seen that the standard deviation of the turbulence and the wind load (flapwise blade bending moment) increase significantly behind other wind turbines. For wind turbine W4 the directions 23°, 77°, 106°, 140°, 320° and 354°, and for wind turbine E5 the directions 140°, 203°, 257°, 286°, 298° and 320°.

3 EQUIVALENT FATIGUE LOAD

The fatigue load spectrum for fatigue critical details in wind turbines is modeled not only by a stochastic part related to the ambient turbulence and the eigenfrequencies of the structure, but also additionally a deterministic, sinusoidal part with frequency of revolution of the rotor, see figure 5.

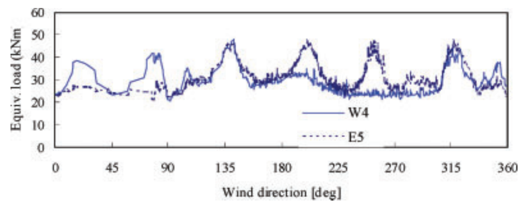

Figure 3. Equivalent load (flap-wise bending) for two wind turbines, 4W and 5E in figure 2, as function of wind direction, in the Vindeby wind farm, $8 < U < 9$ m/s – from (Frandsen, 2005).

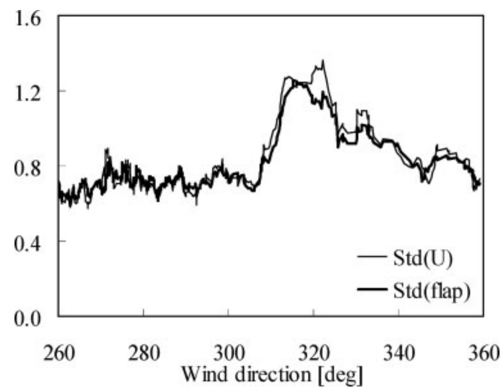

Figure 4. Vindeby data: Standard deviation of wind velocity measured at hub height and flapwise blade bending moment (normalized with free flow conditions in 260–300°) of wind turbine 4W – from (Frandsen, 2005). The bending moment is scaled to fit at free-flow conditions at wind directions 260–300°. Scale of ordinate is arbitrary.

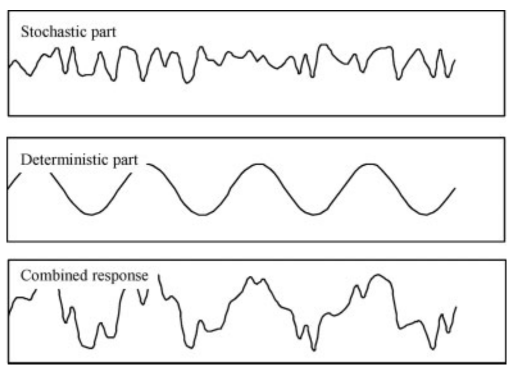

Figure 5. Typical response time series for fatigue analysis (from Frandsen 2005).

In case the response is Gaussian and narrow-banded/cyclic, e.g. if the response is dominated by an eigenfrequency, the stress ranges becomes Rayleigh distributed and the number of fatigue load cycles typically $\nu = 10^7$/year.

A linear SN relation is assumed:

$$N = KS^{-m} \tag{1}$$

where S is the fatigue load stress range, N is the number of stress cycles to failure with constant stress range S and K, m are material parameters.

Assuming a linear SN curve, it has been demonstrated by (Rice 1944), (Crandall and Mark 1963) and adopted by (Frandsen 2005) that an equivalent load measure of fatigue loading for a combined Gaussian, narrow-banded stochastic and deterministic load may be written as

$$e(\sigma, A, m) = 2\sqrt{2}\cdot\sigma_x\cdot \left[\Gamma\left(1+\frac{m}{2}\right)\cdot \mathrm{M}\left(-\frac{m}{2};1;-\left(\frac{A}{\sqrt{2}\sigma_x}\right)^2\right)\right]^{1/m} \tag{2}$$

where e is the double-amplitude of the sinusoidal with the process' up-crossing frequency, that causes the same damage as the combined process. A is the amplitude of the deterministic part, and σ_x is the standard deviation of the zero mean-value stochastic part. $\Gamma(*)$ is the gamma function, and $M(*;*;*)$ is the confluent hypergeometric function. The function e has the following asymptotic values for vanishing random and sinusoidal component, respectively:

$$e \to 2\cdot A \text{ for } \sigma_x \to 0 \quad \text{and}$$
$$e \to 2\sqrt{2}\sigma_x\left(\Gamma(1+\frac{m}{2})\right)^{1/m} \quad \text{for } A \to 0 \tag{3}$$

It is noted that for zero amplitude of the deterministic component and conditioned on m the characteristic amplitude e is simply proportional to the standard deviation, σ_x, of the response of the stochastic component alone.

For wake and non-wake conditions, the model for effective turbulence implies that a design turbulence standard deviation may be calculated as, see also section 4.1.2

$$\sigma_{e,m} = \left((1-N_w p_w)\sigma_0^m + N_w p_w \sigma_w^m\right)^{1/m} \tag{4}$$

where σ_0 is turbulence standard deviation under free flow conditions, σ_w is the maximum wake turbulence, p_w(=0.06) is the probability of wake condition and N_w is the number of wakes to which the considered wind turbine is exposed to. We assume that the standard deviation of response is proportionnal to the standard deviation of turbulence (a constant between the two quantities have no consequence for the arguments to follow).

Is the model for effective turbulence sensitive to whether there is a super imposed deterministic load

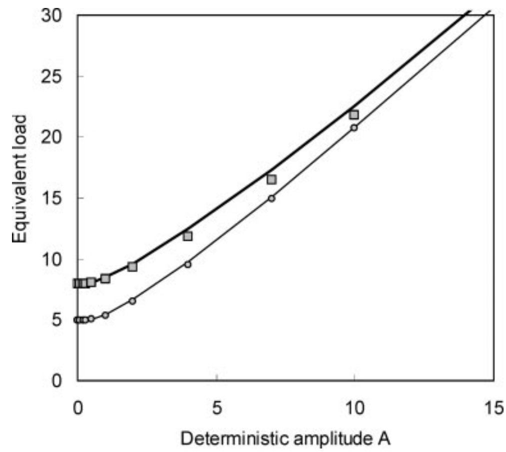

Figure 6. Equivalent load as function of deterministic amplitude. Circles are with SN-curve exponent $m = 4$ and squares $m = 10$. The full lines are with the application of the model for effective turbulence.

component? This is tested by calculating directly the equivalent loads for the two levels of turbulence and subsequently weighting these similarly to (4):

$$e_{direct,m} = \left((1-N_w p_w)e(\sigma_0, A, m)^m + N_w p_w e(\sigma_w, A, m)^m\right)^{1/m} \tag{5}$$

On the other hand, according to the model for effective turbulence, the same quantity may be approximated by $e_{e,m} = e(\sigma_{e,m}, A, m)$.

For the cases $N_W = 4, p_W = 0.06, \sigma_0 = 1, \sigma_w = 2$ and $m = 4$ and 10, the two quantities are plotted in Figure 6. The model for effective turbulence is slightly conservative (with up to 3–4%), mostly so when the stochastic and deterministic component have approximately the same weight.

4 PROBABILISTIC MODELS FOR FATIGUE FAILURE

Design and analysis for fatigue are assumed to be performed using linear and bilinear SN-curves, eventually with lower cut-off limit as e.g. used in (Eurocode 3, 2003).

It is assumed that Miner's rule with linear damage accumulation can be used. Further, fatigue contributions from events as start and stop of the wind turbine are not included.

In the following first a linear SN-curve described by equation (1) is considered, and next a bi-linear SN-curve.

4.1 *Linear SN-curve*

4.1.1 *Free wind flow*

For a wind turbine in free wind flow the design equation in deterministic design is written:

$$G(z) = 1 - \int_{U_{in}}^{U_{out}} \frac{\nu \cdot FDF \cdot T_L}{K_C} \cdot D_L\left(m; \alpha_{\Delta\sigma}(U)\hat{\sigma}_u(U)/z\right) f_U(U) dU = 0 \tag{6}$$

where

$$D_L(m; \sigma_{\Delta\sigma}) = \int_0^\infty s^m f_{\Delta\sigma}\left(s \middle| \sigma_{\Delta\sigma}(U)\right) ds \tag{7}$$

is the expected value of $\Delta\sigma^m$ given standard deviation $\sigma_{\Delta\sigma}$ and mean wind speed U, and

ν total number of fatigue load cycles per year (determined by e.g. Rainflow counting)
T_L design life time
FDF Fatigue Design Factor (equal to $(\gamma_f \gamma_m)^m$ where γ_f and γ_m are partial safety factors for fatigue load and fatigue strength)
K_C characteristic value of K (obtained from $\log K_C$ equal to mean of $\log K$ minus two standard deviations of $\log K$)
U_{in} cut-in wind speed (typically 5 m/s)
U_{out} cut-out wind speed (typically 25 m/s)
$f_{\Delta\sigma}$ $(s|\sigma_{\Delta\sigma}(U))$ density function for stress ranges given standard deviation of $\sigma_{\Delta\sigma}(U)$ at mean wind speed U. This distribution function can be obtained by e.g. Rainflow counting of response, and can e.g. be assumed to be Weibull distributed. It is assumed that the standard deviation $\sigma_{\Delta\sigma}(U)$ can be written:

$$\sigma_{\Delta\sigma}(U) = \alpha_{\Delta\sigma}(U) \frac{\sigma_u(U)}{z} \tag{8}$$

with

$\alpha_{\Delta\sigma}(U)$ influence coefficient for stress ranges given mean wind speed U
$\sigma_u(U)$ standard deviation of turbulence given mean wind speed U
z design parameter (e.g. proportional to cross sectional area)

The characteristic value of the standard deviation of turbulence, $\hat{\sigma}_u(U)$ given average wind speed U is modeled by, see (IEC 2005):

$$\hat{\sigma}_u(U) = I_{ref} \cdot (0.75 \cdot U + b) \;\; ; \; b = 5.6 \text{ m/s} \tag{9}$$

where I_{ref} is the reference turbulence intensity (equal to 0.14 for medium turbulence characteristics) and $\hat{\sigma}_u$ is denoted the ambient turbulence.

The corresponding limit state equation is written

$$g(t) = \Delta - \int_{U_{in}}^{U_{out}} \int_0^\infty \frac{\nu \cdot t}{K} (X_W X_{SCF})^m D_L\left(m; \alpha_{\Delta\sigma}(U)\sigma_u(U)/z\right) f_{\sigma_u}(\sigma_u|U) f_U(U) d\sigma_u dU \tag{10}$$

where

Δ is a stochastic variable modeling the model uncertainty related to the Miner rule for linear damage accumulation
t time in years
X_W model uncertainty related to wind load effects (exposure, assessment of lift and drag coefficients, dynamic response calculations)
X_{SCF} model uncertainty related to local stress analysis
$\sigma_u(U)$ standard deviation of turbulence given average wind speed $U \cdot$ $\sigma_u(U)$ is modeled as LogNormal distributed with characteristic value $\hat{\sigma}_u(U)$ defined as the 90% quantile and standard deviation equal to $I_{ref} \cdot 1.4$ [m/s]:

The design parameter z is determined from the design equation (6) and next used in the limit state equation (10) to estimate the reliability index or probability of failure with the reference time interval $[0; t]$.

4.1.2 *Wind turbines in clusters*

For a wind turbine in a farm the design equation based on IEC 61400-1 (IEC 2005) can be written:

$$G(z) = 1 - \int_{U_{in}}^{U_{out}} \frac{\nu \cdot FDF \cdot T_L}{K_C} \cdot \left\{ \begin{array}{l} (1 - N_W \cdot p_W) D_L\left(m; \alpha_{\Delta\sigma}(U)\hat{\sigma}_u(U)/z\right) + \\ p_W \sum_{j=1}^{N_W} D_L\left(m; \alpha_{\Delta\sigma}(U)\hat{\sigma}_{u,j}(U)/z\right) \end{array} \right\} f_U(U) dU = 0 \tag{11}$$

where

N_W number of neighboring wind turbines
p_W probability of wake from a neighboring wind turbine (equal to 0.06)
$\hat{\sigma}_u$ standard deviation of turbulence given by (9)
$\hat{\sigma}_{u,j}$ standard deviation of turbulence from neighboring wind turbine no j

$$\hat{\sigma}_{u,j}(U) = \sqrt{\frac{0.9 \cdot U^2}{\left(1.5 + 0.3 d_j \sqrt{U/c}\right)^2} + \hat{\sigma}_u^2} \tag{12}$$

where d_j is the distance normalized by rotor diameter to neighboring wind turbine no j and c constant equal to 1 m/s.

Alternatively, an effective/equivalent turbulence model can be used, where the same model as used for a single wind turbine is used, but with an effective turbulence standard deviation. In (Frandsen 2005) and implemented in IEC 61400-1 (IEC 2005) the model for effective turbulence is presented. It is conditioned on wind speed and SN-curve slope m, i.e. fatigue load calculations should be carried out separately for a number of wind speed bins, and for each wind speed bin the effective turbulence intensity should be established. Further, it is in the equivalent model assumed that the standard deviation of turbulent wind speed fluctuations, $\hat{\sigma}_u(\theta, U)$, is a deterministic function of wind direction θ with a superimposed, wind-direction independent random component. The model is based on the assumption that the SN curve is linear: $N = KS^{-m}$.

Disregarding other flow variables than standard deviation of wind speed fluctuations, the equivalent load (stress ranges) is assumed to be written as

$$e(U,\theta) = \alpha_{\Delta\sigma}(U) \cdot \sigma_{u,eff}(U,\theta) \tag{13}$$

where

$$\sigma_{u,eff}(U,\theta) = \left[\int_0^\infty (\sigma_u(\theta,U))^m f_{\sigma_u}(\sigma_u|U,\theta) d\sigma_u \right]^{\frac{1}{m}} \tag{14}$$

where $\alpha_{\Delta\sigma}(U)$ is the influence coefficient for wind speed fluctuations $f_{\sigma_u}(\sigma_u|U,\theta)$ is the density function σ_u, conditioned of mean wind speed and direction. $\sigma_{u,eff}(U,\theta)$ is the fixed standard deviation of wind speed that causes the same fatigue as the varying quantity. Denominating the distribution of wind direction conditioned on wind speed $f_{wd}(\theta|U)$, the integrated equivalent load at wind speed U becomes

$$e(U) = \alpha_{\Delta\sigma}(U) \cdot \sigma_{u,eff}(U) \tag{15}$$

where

$$\sigma_{u,eff}(U) = \left[\int_{-180}^{180} \left(\sigma_{u,eff}(U,\theta) \right)^m f_{wd}(\theta|U) d\theta \right]^{\frac{1}{m}} \tag{16}$$

is the effective turbulence intensity for mean wind speed U. Through a set of assumptions on the shape of the wake turbulence profile and by assuming the density function of wind direction uniform, $f_{wd} = \frac{1}{360}[\deg^{-1}]$, and the ambient turbulence intensity is independent of wind direction, (16) reduces to, see (Frandsen 2005)

$$\sigma_{u,eff}(U) \cong \left[(1 - N_w \cdot p_w)\sigma_u^m + \sum_{j=1}^{N_W} p_w \sigma_{u,j}^m \right]^{\frac{1}{m}} \tag{17}$$

where $\sigma_{u,j}$ is maximum turbulence standard deviation for wake number j and N_w is the number of neighboring wind turbines taken into account and $p_w \approx 0.06$.

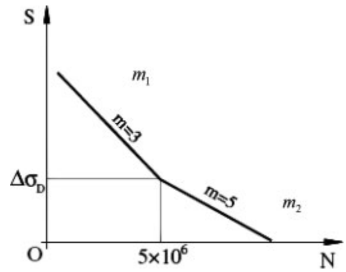

Figure 7. Bilinear SN-curve.

The resulting design equation is written:

$$G(z) = 1 - \int_{U_{in}}^{U_{out}} \frac{\nu \cdot FDF \cdot T_L}{K_C} D_L\left(m; \alpha_{\Delta\sigma}(U)\hat{\sigma}_{u,eff}(U)/z\right) f_U(U) dU = 0 \tag{18}$$

Note that for linear SN-curves equations (11) and (18) are identical.

The limit state equation corresponding to either the of the above design equations is written:

$$g(t) = \Delta - \int_{U_{in}}^{U_{out}} \int_0^\infty \frac{\nu \cdot t}{K} (X_{wake} X_{SCF})^m \times \left\{ \begin{aligned} &(1 - N_W \cdot p_W) D_L\left(m; \alpha_{\Delta\sigma}(U)\sigma_u(U)/z\right) \\ &+ p_W \sum_{j=1}^{N_W} D_L\left(m; \alpha_{\Delta\sigma}(U)\sigma_{u,j}(U)/z\right) \end{aligned} \right\} \times f_{\sigma_u}(\sigma_u|U) f_U(U) d\sigma_u dU \tag{19}$$

where

$$\sigma_{u,j}(U) = \sqrt{X_W \frac{U^2}{\left(1.5 + 0.3 d_j \sqrt{U/c}\right)^2} + \sigma_u^2} \tag{20}$$

X_U model uncertainty related to wake generated turbulence model.

The design parameter z is determined from the design equation (10) or (17) and next used in the limit state equation (18) to estimate the reliability index or probability of failure with the reference time interval $[0; t]$.

4.2 *Bilinear SN-curve*

Next, it is assumed that the SN-curve is bilinear, see figure 7 (thickness effect not included) with slope change at $N_D = 5 \cdot 10^6$:

$$N = K_1 S^{-m_1} \text{ for } S \geq \Delta\sigma_D \tag{21}$$

$$N = K_2 S^{-m_2} \text{ for } S < \Delta\sigma_D \tag{22}$$

where
K_1, m_1 material parameters for $S \geq \Delta\sigma_D$
K_2, m_2 material parameters for $S < \Delta\sigma_D$

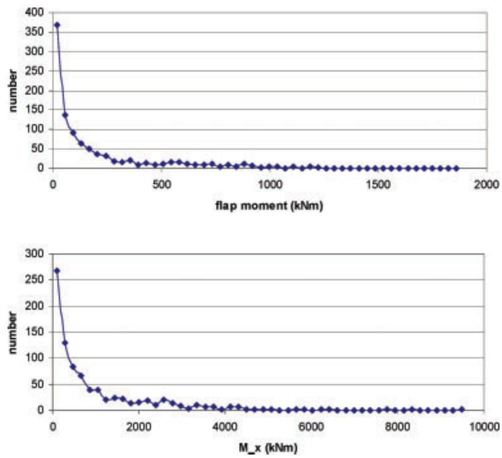

Figure 8. Number of load cycles in 10 minutes period for flap moment and mudline bending moment. Mean wind speed equal to 14 m/s.

$$\Delta\sigma_D = \left(\frac{K_1}{5\cdot 10^6}\right)^{1/m_1} \tag{23}$$

In case the SN-curve is bilinear $D_L(m;\sigma_{\Delta\sigma})$ in design equations and limit state equations in section 4.1 is exchanged with

$$D_{BL}(m_1, m_2, \Delta\sigma_D; \sigma_{\Delta\sigma}) = \int_0^{\Delta\sigma_D} s^{m_2} f_{\Delta\sigma}\left(s \middle| \sigma_{\Delta\sigma}(U)\right) ds + \int_{\Delta\sigma_D}^{\infty} s^{m_1} f_{\Delta\sigma}\left(s \middle| \sigma_{\Delta\sigma}(U)\right) ds \tag{24}$$

(24) can easily be modified to include a lower threshold $\Delta\sigma_{th}$.

5 EXAMPLES

Wind turbines are considered with a design life time $T_L = 20$ years and fatigue life time $T_F = 60$ years, corresponding to $FDF = 60/20 = 3$. The mean wind speed is assumed to be Weibull distributed:

$$F_U(u) = 1 - \exp\left(-\left(\frac{u}{A}\right)^k\right) \tag{25}$$

with $A = 10.0$ m/s and $k = 2.3$. It is assumed that the reference turbulence intensity is $I_{ref} = 0.14$, and that 5 wind turbines are close to the wind turbine considered with $d_i = 4$.

5.1 *Modeling of stress ranges*

The stress ranges are assumed to be Weibull distributed. In figure 8 is shown typical distributions of stress ranges for a pitch controlled wind turbine for flap and mudline bending moments. The corresponding Weibull shape coefficient k is typical in the range 0.8–1.0. These results are for cases where the response

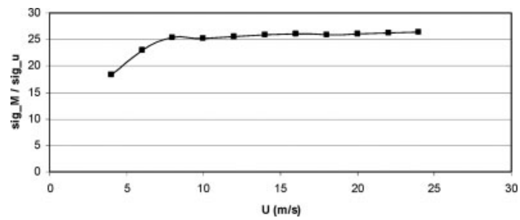

Figure 9. $\sigma_{\Delta\sigma}(U)/\sigma_u(U)$ for rotor tilt moment – stall controlled wind turbine.

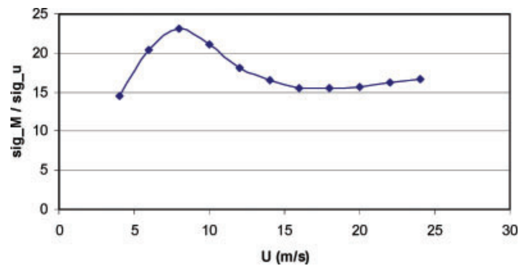

Figure 10. $\sigma_{\Delta\sigma}(U)/\sigma_u(U)$ for blade flap moment – stall controlled wind turbine.

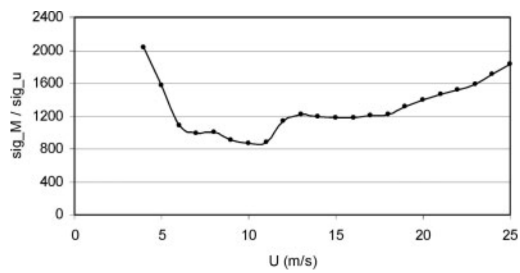

Figure 11. $\sigma_{\Delta\sigma}(U)/\sigma_u(U)$ for mudline bending moment – pitch controlled wind turbine.

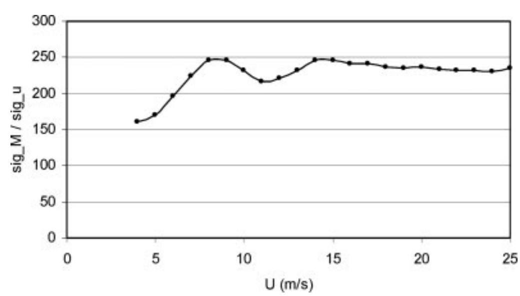

Figure 12. $\sigma_{\Delta\sigma}(U)/\sigma_u(U)$ for blade flap moment – pitch controlled wind turbine.

Table 1. Stochastic model.

Variable	Distribution	Expected value	Standard deviation
Δ	N	1	0.10
X_W	LN	1	0.15
X_{SCF}	LN	1	0.10
X_{wake}	LN	1	0.15
m_1	D	3	
$\log K_1$	N	determined from $\Delta\sigma_D$	0.22
m_2	D	5	
$\log K_2$	N	determined from $\Delta\sigma_D$	0.29
$\Delta\sigma_D$	D	71 MPa	

$\log K_1$ and $\log K_2$ are fully correlated.

is dominated by the "background" turbulence in the wind load. The corresponding number of load cycles per year is typically $\nu = 5 \cdot 10^7$.

5.2 *Modeling of influence function*

In figures 9–12 are shown typical examples of the ratio $\sigma_{\Delta\sigma}(U)/\sigma_u(U)$. The ratio is seen to be highly non-linear, especially for pitch controlled wind turbines. It is also seen that stall and pitch controlled wind turbines have significant different behaviors – due to the control systems.

5.3 *Stochastic model*

In table 1 is shown a typical example of a stochastic model for a welded steel detail, based partly on (Sørensen et al. 2005) and (Tarp-Johansen et al. 2004).

6 RESULTS

In the following examples a wind turbine in a wind farm is considered. Pitch and stall control, and different fatigue critical details are considered.

6.1 *Example 1 – pitch – blade flap moment*

In this example the flap blade moment in a picth controlled wind turbine is considered. The stress range is assumed Weibull distributed with shape parameter $k = 0.8$, and the number of load cycles per year $\nu = 5 \cdot 10^7$. The results are shown in table 2 and figure 13. α_1, α_2 are the parts of fatigue damage from SN-curve with slopes m_1 and m_2 ($\alpha_1 + \alpha_2 = 1$), $\Delta\beta(20)$ and $\beta(20)$ are the annual reliability index in year 20 and the reliability index corresponding to the accumulated probability of failure in 20 years. $\Delta\beta(20) = -\Phi^{-1}(\Phi(-\beta(20) - \Phi(-\beta(19))$ where $\Phi(\cdot)$ is the standardized Normal distribution function.

Table 2. Results – example 1. *) design value from Linear SN-curve; #) β the same as for Linear SN-curve.

SN-curve	Design equation	z	$\Delta\beta$	β	α_1
Linear	(11)	0.568	3.58	3.15	1
Bi-linear	(11)	0.406	2.96	2.27	0.34
Bi-linear	(18)(eqv)	0.399	2.93	2.21	0.30
Bi-linear	#	0.511		3.15	
Bi-linear	*	0.568	3.99	3.55	

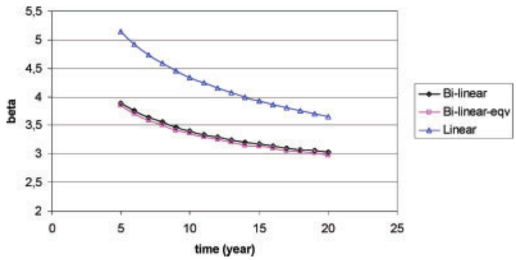

Figure 13. Annual reliability index as function of time.

When using the equivalent turbulence model $m = m_1$ I used in (17) and (18).

It is seen that both the design value z and the reliability index β are smaller for the bi-linear SN-curve than for the linear SN-curve. The design value decreases since less fatigue is accumulated for the smaller stress ranges. The reliability decreases due to larger uncertainty on the lower part of the SN-curve and due to higher importance of the model uncertainties (X_W, X_{SCF}) at the lower part of the SN-curve (higher m value). As an interesting observation it can be seen that the design can be decreased by 11% (partial safety factor can be decreased 4%) if a bi-linear SN-model is used instead of a linear SN-model, but with the same reliability level.

If for bi-linear SN-curves the use for design of the equivalent turbulence model (equation (18) is compared to using the 'full' model (equation (11), it is seen that the equivalent model results in only a slightly smaller design value (2% less), which corresponds to a 7% higher accumulated fatigue damage. The reliability level is only slightly less when using the equivalent model.

6.2 *Example 2 – stall – blade flap moment*

The same parameters as in example 1 are used, except that stall control is considered. The results show the same tendency as for a pitch controlled wind turbine.

6.3 *Example 3 – pitch – blade flap moment – narrow-banded response*

In this example the flap blade moment in a pitch controlled wind turbine is considered. The stress range

Table 3. Results – example 2. *) design value from Linear SN-curve; #) β the same as for Linear SN-curve.

SN-curve	Design equation	z	$\Delta\beta$	β	α_1
Linear	(11)	0.667	3.59	3.16	1
Bi-linear	(11)	0.467	2.95	2.26	0.29
Bi-linear	(18)(eqv)	0.459	2.91	2.18	0.25
Bi-linear	#	0.592		3.16	
Bi-linear	*	0.667	3.89	3.61	

Table 4. Results – example 3. *) design value from Linear SN-curve; #) β the same as for Linear SN-curve.

SN-curve	Design equation	z	$\Delta\beta$	β	α_1
Linear	(11)	0.439	3.58	3.15	1
Bi-linear	(11)	0.295	2.83	2.04	0.10
Bi-linear	(18)(eqv)	0.288	2.77	1.95	0.05
Bi-linear	#	0.389		3.15	
Bi-linear	*	0.439	4.08	3.64	

Table 5. Results – example 2. *) design value from Linear SN-curve; #) β the same as for Linear SN-curve.

SN-curve	Design equation	z	$\Delta\beta$	β	α_1
Linear	(11)	0.577	3.57	3.14	1
Bi-linear	(11)	0.420	3.00	2.32	0.40
Bi-linear	(18)(eqv)	0.415	2.95	2.26	0.37
Bi-linear	#	0.522		3.14	
Bi-linear	*	0.577	3.96	3.52	

Weibull shape parameter is $k = 2$, and the number of load cycles per year is $\nu = 10^7$, corresponding to a situation where the response is dominated by a narrow-banded part with dominating frequency of revolution of the rotor. The results are shown in table 4. The results show the same tendency as in example 1 and 2, but a larger part of the fatigue damage is on the lower part of the SN-curve.

6.4 *Example 4 – pitch – mudline moment*

The same parameters as in example 1 except that the mudline moment is considered. The results show the same tendency as for a pitch controlled wind turbine.

7 CONCLUSIONS

The use of the effective turbulence model suggested by (Frandsen 2005) for design of single wind turbines in a wind farms is considered using a probabilistic approach, especially for bi-linear SN-curves.

In a situation where the fatigue load has both a stochastic part related to turbulence and a narrow-banded (sinusoidal) part related e.g. to eigenfrequancies of the wind turbine it is seen that the model for effective turbulence is good and only slightly conservative.

Using a probabilistic approach and using bi-linear SN-curves the results of different representative examples indicate that the model for effective turbulence is good and only slightly un-conservative. This indicates that the effective turbulence model is robust, and can be used in practical design also in cases where a bi-linear SN-curve is applied. The examples considered have been related to welded details e.g. in the wind turbine tower. More investigations are needed to see if the same conclusions hold for other fatigue details in a wind turbine, e.g. in cast components, and for other fatigue strength stochastic models.

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