Improvements to the Simplified Loads Methodology in IEC 61400-2

November 22, 2021 – November 21, 2022

David Wood

Department of Mechanical and Manufacturing Engineering, University of Calgary

NREL Technical Monitor: Brent Summerville

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Errata

The following changes were included as of May 3, 2023.

- Page v. Added definition for DEL (damage equivalent load) to the list of acronyms.
- Page vi. Included "a simple and quick calculation" on line 1 of the Executive Summary.
- Page 3. Added a sentence to line 4 of Section 2.1: "In modern parlance, that makes it the equivalent of a "damage equivalent load" or DEL."
- Page 6. Added a phrase to the first sentence of Section 2.3: "constrained from producing power, as opposed to not producing power because the wind speed is too low."
- Page 8. Added a sentence to line 3 of Section 4.1: "Freebury and Musial (2000) described the determination of the DEL for a 12-meter (m)-long blade." Also added "Downwind" as the rotor location for the UAE VI in Table 3.
- Page 10. Included the following:

To simplify the fatigue calculations for Load Case A, it is assumed that the loads cycle every blade revolution with a single frequency, $\omega_{n,design}$, which appears in Equation (19). To proceed with the application of Equation (18), it is necessary to derive the DEL, the single amplitude of fatigue loading that will be equivalent to the load spectrum, the methodology of Hayman (2012) can be applied:

$$\mathrm{DEL} = \frac{1}{2} M_{y,gyro} \left(\int_0^1 \left(1/x^s - 1\right)^m dx \right)^{1/m} \tag{21}$$

where m is the Wohler constant, the slope of the logarithmic S,N curve, such as shown in figures E.1 and E.2 of IEC 61400-2. For composites, m = 10 is a common value which will be used here. The integral in Equation (21) has a closed-form solution for integer values of m:

$$\left(\int_0^1 \left(1/x^s - 1\right)^m dx \right)^{1/m} = \left(\frac{(-1)^m m\Gamma(1-1/s)}{\Gamma(1+m-1/s)} \right)^{1/m} \tag{22}$$

where Γ is the standard Gamma function. The integral increases with increasing s. Interestingly, the integral becomes infinite as $s \to 1/m$. For the largest s = 0.062, considered by Evans et al. (2020), it has the value of 0.443. Rounding this up to ½, gives

$$\mathrm{DEL} = \frac{1}{4} M_{y,gyro} = \frac{1}{2} \omega_{\mathrm{yaw,max}} I_{\mathrm{B}} \omega_{\mathrm{n,design}} \tag{23}$$

This gives a DEL of approximately one-third that of Equation IEC23. Equation (19) implies that no other fatigue loads are significant for the blades. The transfer of the blade root bending moment to the shaft and other components depends on the number of blades, B.

Following Equation IEC29 and IEC30, the DEL for the shaft is Equation IECF.4 multiplied by 2 for B = 2, and $B/2$ for all other blade numbers. The shaft bending moment is assumed to be maximal at the first bearing. The shaft loads are directly transferred to the nacelle platform and the tower.

- Page 11. Replaced "Equations (19) and (20)" with the following: "The first recommendation is that the SLM fatigue loads assessment for free yaw turbines be replaced by Equation (23) and no other contribution to the fatigue load be considered."
  - Phrase added to first line of Section 4.2: "it was noted earlier that"

Page 13. Phrase added to the fourth line of second-to-last paragraph: "to the safety factor"

Page 14. New content added under the third recommendation:

"The final change to this load case concerns Equation (15, IEC41) for the maximum thrust on a parked rotor that is still rotating. If the turbine is producing no power when the extreme wind load is applied, then the maximum velocity at the blades will be $\sqrt{V_{e50}{}^2 + \lambda_{e50}^2 R^2}$ so to have a term in (IEC41) proportional to λ_{e50}^2 implies that $V_{e50} << \lambda_{e50} R$, which is likely to destroy the blades through centrifugal stresses in any case. The maximum rotation that can be allowed must make $V_{e50} >> \lambda_{e50} R$ in which case, (14, IEC40) is sufficient.

The fourth recommendation is that equations (IEC41,42) be removed from DLC H."

Page 16. Added in the fourth recommendation, which required reordering the previous number to five. Changes include:

- Adding in "equations (IEC41,42) be removed from DLC H." after "The fourth recommendation is that"
- Adding in "The last term in Equation (9, IEC28) be replaced by the last term in Equation (21), highlighted in red." After "The fifth recommendation is that"

Page 17. Added the following two new references:

- Freebury, G., and Musial, W. 2000. Determining equivalent damage loading for full-scale wind turbine blade fatigue tests. In 2000 ASME Wind Energy Symposium (p. 50).
- Hayman, G. 2012. MLife theory manual for version 1.00. National Renewable Energy Laboratory, Golden, CO, 74(75), 106.

List of Acronyms

DEL	damage equivalent load
DLC	design load case
IEC	International Electrotechnical Commission
kW	kilowatt
m	meter
MPa	megapascal
rad/s	radians per second
rpm	revolutions per minute
SLM	Simplified Loads Methodology
SWT	small wind turbine
W	watt

Executive Summary

The "Simplified Loads Model" (SLM) of IEC 61400-2 provides a simple and quick calculation of the design loads to assess the structural integrity of a small wind turbine (SWT). The SLM is unique to the small wind turbine standard. It was included to allow SWT manufacturers with limited resources to undertake integrity checks at a reasonable cost in time and resources and avoid the expense of detailed aeroelastic simulations. Unfortunately, the SLM has gained the reputation of being overly conservative, and this has reduced its value to the SWT community and its use in SWT design and certification. Conservatism in design standards is necessary, but excessive conservatism is not. The aim of this report is to address the principal areas of excessive conservatism and recommend changes to the SLM that preserve its simplicity but reduce the excess. The changes for the ultimate loads are consistent with their treatment in aeroelastic modeling for certification and with related codes for wind loading on structures. The recommendations for a new fatigue design load case are also based on aeroelastic simulations—in this case, of five SWTs of varying configurations with rated power from 2.4 to 50 kilowatts. It is also pointed out that the design load case for yawed operation omits an important term. The recommended inclusion of this term would make the SLM slightly more conservative for this case. This work is intended to inform the maintenance team for IEC 61400-2 (MT2) for consideration of possible changes to the standard in the upcoming 4th revision.

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1 Introduction

This report discusses improvements to the "Simplified Load Model" (SLM) in International Electrotechnical Commission (IEC) standard 61400-2 (IEC 2013) for the analysis of turbine safety in the context of certification. The SLM combines simple equations for the critical design load cases (DLCs) and high safety factors to compensate for the uncertainty, which is assumed to be a consequence of the simplicity. There is no restriction on the turbine size for the applicability of the SLM in the current edition of IEC 61400-2, but the new U.S. standard (ANSI/ACP 2021) recommends that the SLM be restricted to small wind turbines (SWTs) less than 10 kilowatts (kW) in rated power. Most of the problems with the SLM occur for this turbine category, so the restriction does not evade the need to improve it. The SLM is recognized as being unduly conservative in:

- Requiring excessive load factors in some cases
- Overestimating the fatigue loads on SWT blades
- Overestimating the gyroscopic loads, which are often the major loads for the sub-10-kW class.

It is also shown that the SLM omits an important load in DLC B. Corrections for these deficiencies are developed.

The SLM is unique to the small wind turbine standard IEC 61400-2. It defines 10 DLCs, listed in Table 1. The cases for which this report argues the SLM should be modified are highlighted in red in the table. These include:

1. The only fatigue DLC, DLC A
2. DLC B where the yaw-activated gyroscopic loads are maximized as an SWT decreases in size
3. DLC H for parked wind loading, which typically produces the maximum load on the tower.

Table 1. The Design Load Cases of the Simplified Load Methodology[a]

Design Situation	Load Case	Description	Type of Analysis
Power production	A	Normal operation	Fatigue
	B	Yawing	Ultimate
	C	Yaw error	Ultimate
	D	Maximum thrust	Ultimate
Power production plus occurrence of fault	E	Maximum rotational speed	Ultimate
	F	Short at load connection	Ultimate
Shutdown	G	Shutdown (braking)	Ultimate
Parked (idling or standstill)	H	Parked wind loading	Ultimate
Parked at fault conditions	I	Parked wind loading (maximum exposure)	Ultimate
Transport, assembly, maintenance, and repair	J	To be stated by manufacturer	Ultimate

[a] The cases whose equations are recommended to be amended are shown in red

Throughout this report, any equation taken from IEC 61400-2 will be specified as (xx, IECyy) where “xx” is the equation number for this report and “yy’ is the equation number in the standard. Equations labeled “(xx)” only are unique to this report. Symbols are also taken from the standard, but the main ones are defined here to avoid continual reference to the standard. For further reference, it is noted that the derivations of the SLM equations are given in Annex F of IEC 61400-2. Two equations from the Annex are quoted in this report.

The DLCs recommended for amendment are described in the next section with limited commentary on their problems. This is followed by a description of the load safety factors, as these are the focus of the main recommendations of this report. In Section 4, DLC A for fatigue is assessed using aeroelastic simulations of five SWTs of rated power up to 50 kW, and DLCs B and H for ultimate loads are assessed for turbines of less than 10 kW in rated power. The omission in DLC B is considered in Section 5, and a suggested inclusion is presented. A summary of the recommended changes to the SLM is given in Section 6.

2 The Load Cases Recommended for Amending

2.1 Design Load Case A – Normal Operation

This DLC is the only fatigue load case. It is assumed to comprise a once-per-revolution variation of the root bending moment from 50% to 150% of the design value at the design wind speed. There is no consideration of gyroscopic loads or of other wind and blade speeds, so there is no continuous fatigue load spectrum. In modern parlance, that makes it the equivalent of a "damage equivalent load" or DEL. Further, the effects of high turbulence, which is often experienced by SWTs, are not included. The fatigue load has several components. The first is the centrifugal load, ΔF_{zB}, given by

$$\Delta F_{zB} \quad = \quad 2 m_B R_{cog}\, \omega_n^2 \qquad \text{(1, IEC21)}$$

where subscript z denotes the radial direction, as shown in Figure 1, subscript B indicates a value for the blades, and R_{cog} is the radius of the center of gravity (mass) of the blade of mass m_B rotating at ω_n. The next two equations give, in order, the lead-lag moment (in the direction of rotation) and flapwise moment (in the direction of the wind; alternatively, out of the plane of rotation):

$$\Delta M_{xB} \quad = \quad Q_{design} \big/ B \; + \; 2 m_B\, g\, R_{cog} \qquad \text{(2, IEC22)}$$

$$\Delta M_{yB} \quad = \quad \lambda_{design}\, Q_{design} \big/ B \qquad \text{(3, IEC23)}$$

where B is the number of blades, and Q_{design} and λ_{design} are the design torque and tip speed ratio, respectively. These moments are to be applied to that part of the blade root with the lowest ultimate strength. Note that most turbine blades are very stiff in the lead-lag direction, so the use of the term "bending" in conjunction with "moment" can be taken to imply bending in the flapwise direction only.

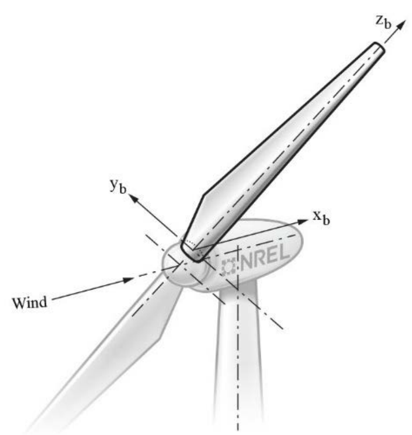

Figure 1. The co-ordinate system used in IEC 61400-2 and in this report. ***Image courtesy of the National Renewable Energy Laboratory (NREL), 62841***

The next three equations give the peak-to-peak fatigue loads as forces (ΔF) and moments (ΔM) on the turbine shaft. These loads are assumed to occur at the first shaft bearing (nearest to the rotor):

$$\Delta F_{x-shaft} = 3\lambda_{design} Q_{design} / (2R) \quad (4, \text{IEC24})$$

$$\Delta M_{x-shaft} = Q_{design} + 2m_r g e_r \quad (5, \text{IEC25})$$

$$\Delta M_{shaft} = 2m_r g L_{rb} + \frac{R}{6}\Delta F_{x-shaft} \quad (6, \text{IEC26})$$

where m_r is the rotor mass, and the rotor eccentricity, e_r, is to be taken as $0.005R$ unless it can be proven otherwise. L_{rb} is the distance from the rotor to the first bearing, usually on the front end of the generator. The loads on the blades and shaft that comprise this DLC will be transmitted to the tower.

IEC 61400-2 stipulates that the fatigue damage is to be assessed using Miner's rule. The damage calculation is

$$Damage = \sum_i \frac{n_i}{N_{cycles}\left(\gamma_f \gamma_m s_i\right)} \leq 1 \quad (7, \text{IEC47})$$

where n_i is the number of fatigue cycles in bin i of the characteristic load spectrum; s_i is the stress level of the fatigue cycles, including effects from both mean and cyclic stress levels; and N_{cycles} is the number of cycles to failure as a function of the stress. The term in parenthesis in the denominator is called the "associated stress level." For the SLM, there is only one "bin," for which the number of fatigue cycles is calculated as

$$n = B n_{design} T_d / 60 \quad (8, \text{IEC48})$$

where T_d is the design life of the turbine in seconds. Note that IEC 61400-2 uses both n (in revolutions per minute [rpm]) and ω (radians per second [rad/s]) to denote blade angular velocity.

By Miner's rule, a component fails when the accumulated damage reaches unity It is also worth noting that the cyclic gyroscopic moment also causes fatigue loads, particularly if the tower has a resonant frequency matching the blade passing frequency or the natural frequency of yaw. There is no specific load case in the SLM covering tail fin fatigue, but the author is unaware of any failures in practice where the tail fin does not furl (which can introduce additional high loads that are not considered here on the grounds that furling is becoming much less common for SWTs).

2.2 Design Load Case B – Yawing

The maximum blade root bending moment, M_{yB}, is given by

$$M_{yB} = m_B \omega^2_{yaw,\max} L_{rt} R_{cog} + 2\omega_{yaw,\max} I_B \, \omega_{n,design} + \frac{R}{9} \Delta F_{x-shaft} \quad (9, \text{IEC28})$$

where L_{rt} is the distance from the rotor to the yaw (tower) axis, the maximum yaw rate as seen by a stationary observer, which is considered in detail in Section 4.1. The first term is the centrifugal term. The second term gives the maximum of the cyclic gyroscopic load which changes with the azimuthal position of the blade. The last term approximates the effect of wind shear. A glaring omission is a term accounting for the blade thrust, for which the recommended remedy is discussed in Section 5. For two-bladed turbines, the shaft loading is:

$$M_{shaft} = 4\omega_{yaw,\max} \, \omega_{n,design} I_B + m_r g L_{rb} + \frac{R}{6} \Delta F_{x-shaft} \quad (10, \text{IEC29})$$

For a turbine with $B > 2$:

$$M_{shaft} = B\omega_{yaw,\max} \, \omega_{n,design} I_B + m_r g L_{rb} + \frac{R}{6} \Delta F_{x-shaft} \quad (11, \text{IEC30})$$

For $B > 1$, there is no contribution from the average blade thrust to the shaft moment. Experience has shown that the gyroscopic terms involving ω_{max} are dominant. The difference between Equations (10, IEC29) and (11, IEC30) indicates a significant difference between a two-bladed and a three-or-more-bladed turbine—the standard specifically excludes single-blade rotors from using the SLM. The difference arises from the variation in the rotor's moment of inertia about the yaw axis with the azimuthal position of the blades. This is most easily seen for a two-bladed rotor by considering the yaw inertia for the two extreme cases: when the blades are vertical, the blade inertia, I_B, about its axis contributes minimally to the yaw moment of inertia, whereas horizontal blades cause the maximum yaw inertia. The significant variation in inertia alters the maximum loads on the blade and shaft in the manner reflected by the first term in Equation (10, IEC29). For $B > 2$, the inertia varies much less with azimuthal position of the blades and the variation can usually be ignored. This statement implies that Equation (11, IEC30) approximates both the average and maximum moment on the shaft of a turbine with three or more blades, whereas Equation (10, IEC29) gives the maximum moment for a two-bladed turbine.

The gyroscopic terms are mentioned very briefly in Burton et al. (2011) and treated in much more detail and complexity by Eggleston and Stoddard (1987). To complicate matters even further, the gyroscopic terms used in the SLM do not include any contributions from the yaw acceleration or the angular acceleration of the blades. The yaw acceleration contribution to M_{yB} is out of phase with the gyroscopic term and hence will not alter its magnitude. The angular acceleration contributes only to the lead-lag motion of the blade—that is, motion in the direction of the rotation where most blades are very stiff. Current knowledge of the extra terms is too poor to justify any attempt at quantification or inclusion in the SLM.

The gyroscopic moments acting on the main shaft will be transmitted to the generator, nacelle, and tower, but there are no equations in the standard for these components.

2.3 Design Load Case H – Parked Wind Loading

Several separate loads can act on a parked turbine—that is, a turbine whose rotor is constrained from producing power, as opposed to not producing power because the wind speed is too low. It is not necessary for the blades to be stationary while parked. The loads are calculated using a wind speed of V_{e50}, the 3-second, 50-year extreme wind speed. The main loading on a stationary rotor is due to drag:

$$M_{yB} = \tfrac{1}{4} C_d \rho V_{e50}^2 A_{proj,B} R \qquad (12, \text{IEC38})$$

where the drag coefficient C_d is taken as 1.5. If the blades are rotating, M_{yB} is from the lift created on the blades due to variations in the wind direction:

$$M_{yB} = \tfrac{1}{6} C_{l,\max} \rho V_{e50}^2 A_{proj,B} R \qquad (13, \text{IEC39})$$

If $C_{l,max}$ is not known, then a value of 2 is to be used. Next is the thrust caused by the wind loading on the blades. For a parked rotor, the analogue of Equation (12, IEC32) is

$$F_{x-shaft} = \tfrac{1}{2} B C_d \rho V_{e50}^2 A_{proj,B} \qquad (14, \text{IEC40})$$

For a spinning rotor

$$F_{x-shaft} = 0.17 B A_{proj,B} \lambda_{e50}^2 \rho V_{e50}^2 \qquad (15, \text{IEC41})$$

where

$$\lambda_{e50} = \omega_{\max} \pi R \big/ \left(30 V_{e50}\right) \qquad (16, \text{IEC42})$$

This load case also covers the maximum bending moment on the tower base due to the thrust loading on the turbine as calculated above. It must also include the wind load on the nacelle and tower and any other components from the same basic equation:

$$F = \tfrac{1}{2} C_f \rho V_{e50}^2 A_{proj} \qquad (17, \text{IEC43})$$

where A_{proj} is the perpendicular projected area of the component against the wind and C_f is the force coefficient from Table 9.4 of IEC 61400-2.

It is noted that DLC I is similar to DLC H with the difference that the latter uses the reference wind speed, which is a factor of 1.4 less than V_{e50}. Because wind loads depend on the square of the wind speed, it is unlikely that DLC I will give higher loads than DLC H, as was found by Dana, Damiani, and Van Dam (2018). DLC I is not considered here, but the recommendations for DLC H also apply to it.

3 The Partial Load Safety Factors and Their Significance for the SLM

Standards usually prescribe the load safety factors, γ_f, to be used in conjunction with the load equations such as those given in the previous section. IEC 61400-2 also specifies material load factors which depend on the knowledge of the material used in constructing each component. In the author's view, these factors are appropriate, and are the same for all methods for determining the loads, so the recommendations for changes to the SLM are restricted to the load safety factors.

Table 2 reproduces Table 7 from IEC 61400-2, which shows the significant difference between γ_f values for an aeroelastic simulation and those for the SLM. For many SLM equations, the high γ_f is justified, as Equations (5, IEC25) and (6, IEC26) are approximate and have not been checked for accuracy using the results of field testing.

Table 2. Partial Safety Factors for SLM Loads From IEC 61400-2

Load Determination Method	Safety Factor for Fatigue Loads, γ_f	Safety Factor for Ultimate Loads, γ_f
Simplified load calculation	1.0	3.0
Aeroelastic modeling with design data (rpm, power)	1.0	1.35
Load measurements with extrapolation	1.0	3.0

Other equations, or terms in the equations, such as the gyroscopic moment in Equation (9, IEC28) are exact, to the extent that $\omega_{yaw,\max}\ \omega_{n,design}$ is the maximum of the yaw rate multiplied by the turbine angular velocity. This important issue is addressed in Section 4.2. Like the equation for centrifugal force, the gyroscopic term is exact, as they both arise from a coordinate transformation. For the gyroscopic term, the transformation is from the earth-fixed inertial system to one rotating with the blades and yawing about the tower axis. An alternative viewpoint is that the gyroscopic load equation would appear in the same form as the term in Equation (9, IEC28) in an aeroelastic code, where it would attract $\gamma_f = 1.35$ instead of 3.0 for the SLM. This seems like discrimination against the SLM.

Other terms in the SLM equations that are not "exact" are analogues of terms used in other standards where they attract much lower load factors than in the SLM. The most important example is the drag equation used in DLC H for tower loading, which is, typically, the maximum tower load. Equations (15, IEC40) or (16, IEC41) determine the rotor contribution to the tower load. The tower drag equation is not specified, but the intention clearly is to use a simple drag equation of the form of Equation (18, IEC43) with the drag coefficients given in Table 3 of IEC 61400-2 and the wind speed, $V_{e,50}$, with no variation with distance above the ground. This is in conformity with most wind loading codes around the world, as described in Chapter 11 of Holmes and Bekele (2021) who state on page 55 that typical wind safety factors range from 1.4 to 1.6.

4 Examples of Excessive Conservatism in the SLM

4.1 Design Load Case A – Normal Operation

The literature on fatigue loads for SWTs is limited. Sutherland and Kelley (1995) modeled the fatigue loads of two 65-kW turbines using measurements of the turbine wind speed and deduced the fatigue life. Freebury and Musial (2000) described the determination of the DEL for a 12-meter (m)-long blade. Evans et al. (2020) simulated the fatigue loads from all sources for the five SWTs listed in Table 3 using Version 7 of the well-known aeroelastic software FAST. All the turbines rely on "free-yaw" for yaw alignment and, hence, are subject to possibly large gyroscopic loads, which are not considered in the SLM. Four of the five are upwind turbines which requires the tail fin module that was removed after Version 7 of FAST. The calculations were done for the number of fatigue cycles given by (8, IEC48 in IEC 61400-2 (IEC 2013) for an assumed 20-year life and listed in the last column.

Table 3. Small Wind Turbines Used in the Fatigue Study by Evans et al. (2020)

Turbine	Rated Power (kW)	Design Rotor Speed (*n*, rpm)	*R* (m)	*B*	Rotor Location	No. Fatigue Cycles
SkyStream	2.4	280	3.7	3	Downwind	1.07×10^{10}
Aerogenesis	5	320	5	2	Upwind	6.73×10^{9}
NREL SWRT	10	340	7	3	Upwind	8.83×10^{9}
UAE VI	20	72	10	2	Upwind, Downwind	1.51×10^{9}
AOC-15/50	50	65	15	3	Upwind	2.05×10^{9}

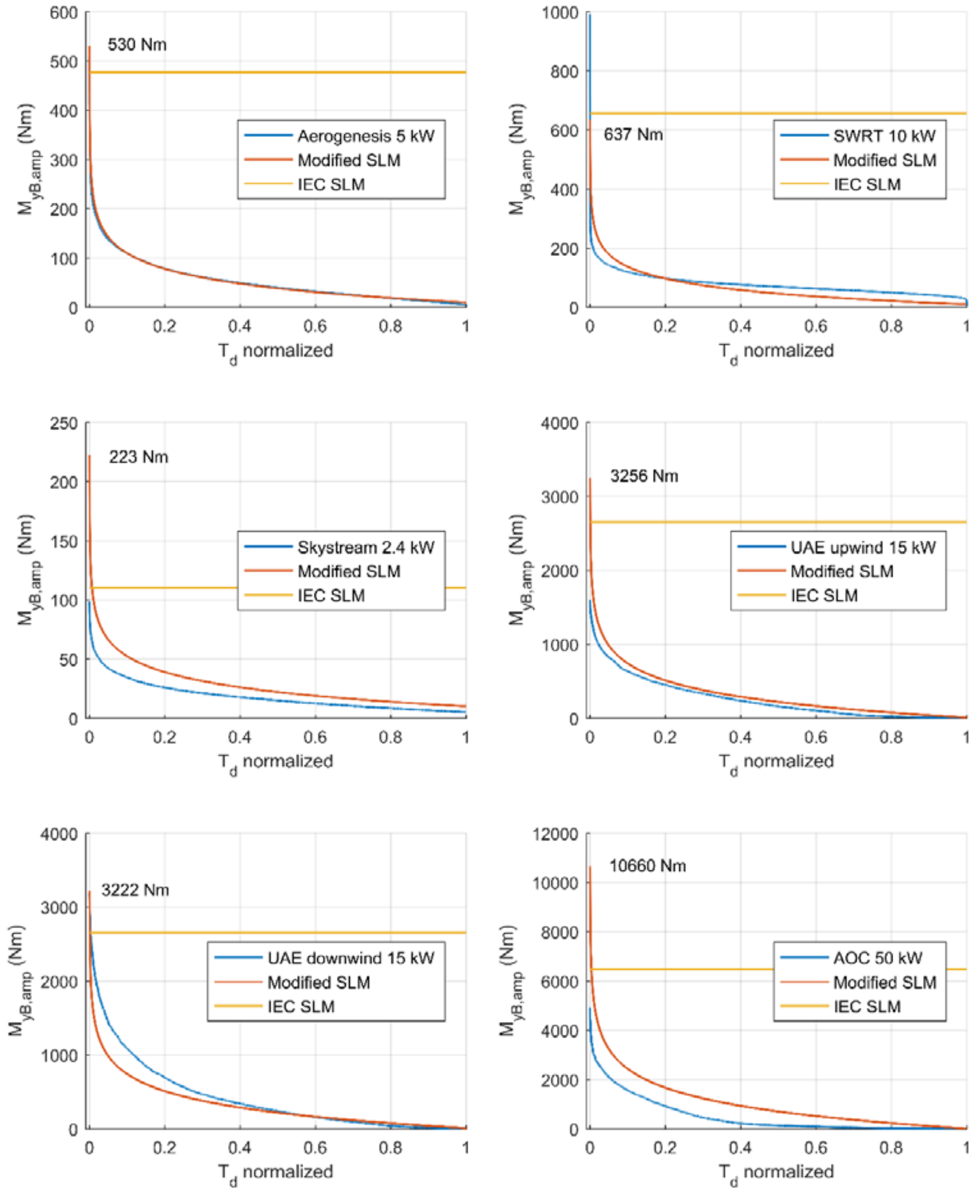

Figure 2. The fatigue loads as specified by the IEC SLM (yellow), the aeroelastic simulations (blue) and Equations (19) and (20) proposed by Evans et al. (2020) (red)

Figure 2 reproduces Figure 2 of Evans et al. (2020) to show that the SLM significantly overestimates the flapwise root bending moment for most of the turbine life. The "modified SLM" curve is given by

$$\Delta M_{y,B}\left(x\right)=\frac{1}{2}M_{gyro}\left(1/x^{s}-1\right) \tag{18}$$

where $\Delta M_{y,B}$ is the fatigue root bending moment in IEC nomenclature. It is plotted on the *y*-axis in Figure 2. $x = t/T_d$ where t is the time and T_d is the turbine lifetime (both in *s*), is the fractional design life, and the exponent s is discussed below. $M_{y,gyro}$ is the gyroscopic moment used in Equation (9, IEC28):

$$M_{y,gyro} = 2\omega_{yaw,\max} I_B \, \omega_{n,design} \tag{19}$$

which will be discussed in more detail in the next subsection. The maximum yaw rate, $\omega_{yaw,max}$ in radians per second, is specified as a function of projected rotor area, A_{proj}:

$$\begin{aligned} \omega_{yaw,\max} &= 3 && \text{if} \quad A_{proj} \le 2\,m^2 \\ &= 3 - 0.01(A_{proj} - 2) && \text{otherwise} \end{aligned} \tag{20, IEC27}$$

Since the FAST simulations inherently consider all sources of fatigue loads, the scaling of the results on the gyroscopic contribution implies its significance.

To simplify the fatigue calculations for Load Case A, it is assumed that the loads cycle every blade revolution with a single frequency, $\omega_{n,design}$, which appears in Equation (19). To proceed with the application of Equation (18), it is necessary to derive the DEL, the single amplitude of fatigue loading that will be equivalent to the load spectrum, the methodology of Hayman (2012) can be applied:

$$\text{DEL} = \frac{1}{2} M_{y,gyro} \left(\int_0^1 \left(1/x^s - 1\right)^m dx \right)^{1/m} \tag{21}$$

where m is the Wohler constant, the slope of the logarithmic S,N curve, such as shown in figures E.1 and E.2 of IEC 61400-2. For composites, m = 10 is a common value that will be used here. The integral in Equation (21) has a closed-form solution for integer values of m:

$$\left(\int_0^1 \left(1/x^s - 1\right)^m dx \right)^{1/m} = \left(\frac{(-1)^m \, m\Gamma(1-1/s)}{\Gamma(1+m-1/s)} \right)^{1/m} \tag{22}$$

where Γ is the standard Gamma function. The integral increases with increasing s. Interestingly, the integral becomes infinite as $s \to 1/m$. For the largest $s = 0.062$, considered by Evans et al. (2020), it has the value of 0.443. Rounding this up to ½, gives:

$$\text{DEL} = \frac{1}{4} M_{y,gyro} = \frac{1}{2} \omega_{\text{yaw,max}} I_{\text{B}} \omega_{\text{n,design}} \tag{23}$$

This gives a DEL of approximately one-third that of Equation IEC23. Equation (19) implies that no other fatigue loads are significant for the blades. The transfer of the blade root bending moment to the shaft and other components depends on the number of blades, B. Following Equations IEC29 and IEC30, the DEL for the shaft is Equation IECF.4 multiplied by 2 for B = 2, and B/2 for all other blade numbers. The shaft bending moment is assumed to be maximal at the first bearing. The shaft loads are directly transferred to the nacelle platform and the tower.

The first recommendation is that the SLM fatigue loads assessment for free yaw turbines be replaced by Equation (23) and no other contribution to the fatigue load be considered.

4.2 Design Load Case B – Yawing

As a rotating rotor yaws with wind direction changes, it was noted earlier that a cyclic gyroscopic root bending moment is generated. The only measurements of this moment that are known to the author, are by Wilson, Clausen, and Wood (2008). The left side of Figure 3 shows the 1.94-m diameter, 500-watt (W) turbine with its usual blades. To measure the gyroscopic loads, one blade was fitted with flush-mounted strain gauges on the upwind side, from which the root bending moment was determined. Typical results are shown at the right where the origin for time is arbitrary. The red and green envelopes centered on the running averages of the root bending moment are the magnitudes of the gyroscopic loads given by $2\omega_{yaw}I_B\omega_n$ where I_B is labeled J in the legend. The variations in the gyroscopic moments are well captured by the envelopes. Further, when ω_{yaw} goes through zero at around 2.7 s, the gyroscopic moment goes to zero as it should. The accuracy of the envelope is to be expected because the gyroscopic loads result from the imposition of two non-inertial coordinate systems—the rotating rotor and the yaw about the tower—in much the same way that centrifugal loads appear in rotating (non-inertial) systems. In other words, the gyroscopic root bending moment, like the centrifugal force equation, is exact.

There are two critical issues in the SLM regarding the gyroscopic moments. The first is that this exact term must be used with the same safety factor as the other two approximate terms in Equation (9, IEC28). To put this another way, the gyroscopic equation is also used in aeroelastic codes such as OpenFAST with a safety factor of 1.35 instead of 3 in the SLM, Table 2. In Wood's (2011) SLM analysis of the turbine in Figure 3 the gyroscopic load dominates Equation (9, IEC28) and the turbine fails the load case despite there being no damage to the blades over several years of operation.

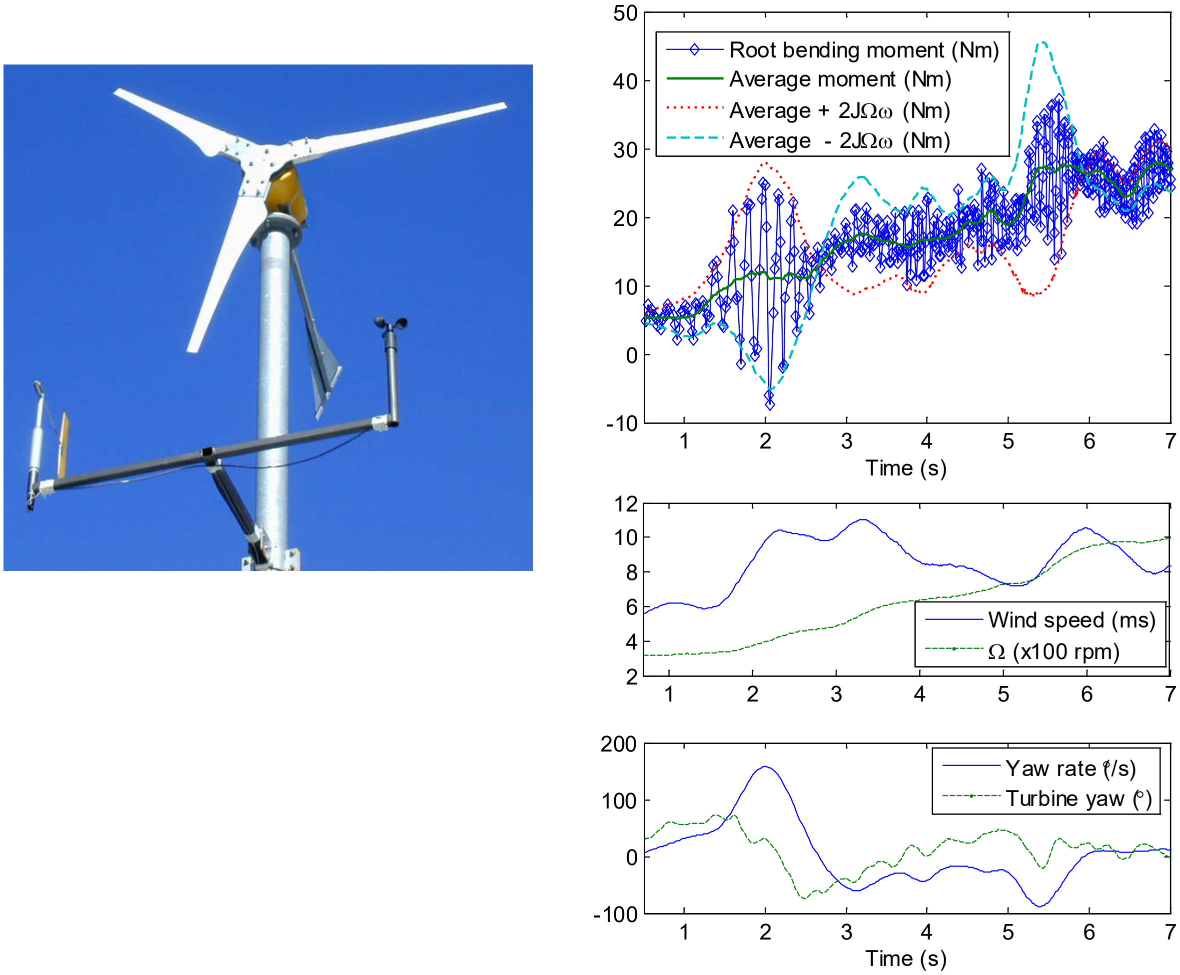

Figure 3. The gyroscopic root bending moment on a 1.94-m diameter, 500-W turbine. Please note that *J* in the figure legend is I_B in the text. Further, Ω is ω_n and ω is ω_{yaw}.

The second recommendation is that the gyroscopic term in Equation (9, IEC28) be applied with the same safety factor of 1.35 as allowed in aeroelastic simulations.

The second critical issue is the coupling of the rotor angular velocity, ω_n, and the yaw rate ω_{yaw}. The SLM stipulates that the former is the design angular velocity, and the latter is the maximum value from Equation (21, IEC27). There is accumulating evidence, however, that the maximum of $\omega_n\omega_{yaw}$ is less than $\omega_{n,design}\ \omega_{yaw,max}$. Plots of ω_{yaw} against ω for the turbine in Figure 3 are given in Wright and Wood (2007), from which it is clear that the maximum ω_{yaw} decreases with increasing ω_n. Measurements on the 5-kW Aerogenesis turbine, whose blade fatigue was analyzed above, show the same trend, and the FAST simulations reproduced this decreasing trend in ω_{yaw} (see Figure 4 of Evans, Bradney and Clausen [2018]). Another example can be seen in Figure 4: at 2 s, the turbine yaw rate is close to the maximum specified by Equation (21, IEC27), but n = 400 rpm compared to the design value of 700 rpm. At present, our knowledge of actual SWT yaw behavior is too poor to allow a recommendation about any change to the values of ω_n and ω_{yaw} to be used in DLC B. Hopefully this situation will not persist much longer.

4.3 Design Load Case H – Parked Wind Loading on the Tower

Figure 4 shows the Aerogenesis 5-kW wind turbine, one of the SWTs considered in Section 3.1 on fatigue loads, and its 18-m monopole, octagonal tower. The tower design is described in Chapter 10 of Wood (2011). Figure 5 is Wood's Figure 10.3, showing the stress distribution along the tower for three DLCs of the SLM. Clearly, DLC H is the most important and is the only one discussed here. The slip-fit tower was made in three 6-m sections with a larger thickness for the section closest to the ground, which causes the near-discontinuity in the calculated stress. The stresses were determined using the simple approximate method described in Wood (2011) as well as a detailed finite-element analysis also described by him. The turbine thrust was calculated using Equation (15, IEC40), and the drag due to the wind was found from an obvious modification to Equation (18, IEC43). The wind speed was assumed constant along the tower and equal to $V_{e,50}$. This conservative assumption is mandated in many wind loading codes. It can be seen from Figure 5 that the differences in stress between the two methods are small and negligible in the present context. The tower was made from structural steel with a yield strength of 350 megapascals (MPa). As expected, the maximum stress—around 200 MPa—occurs near the tower base (which is the main reason why a detailed finite-element analysis is needed). This means that the tower would fail DLC H spectacularly if the SLM safety factor of 3.0 were used. Instead, the tower was designed to the relevant Australian standard for wind loads on structures, which mandates a safety factor of 1.67. This was done for the very practical reason that using the SLM for design would have resulted in a tower of twice the weight. Another Aerogenesis SWT was erected at the University of Newcastle, Australia, in 2007 and has been operating intermittently ever since, implying that the SLM safety factor is excessive. Note that DLC H applies whether this turbine is operating or not, as the blades are stationary at high wind speed.

Figure 4. The Aerogenesis 5-kW SWT on its monopile tower

The tower analysis in Wood (2011) showed that the turbine thrust contributed 20% to the horizontal force for DLC H and one-third of the base overturning moment. There have not been any direct measurements of these loads on a SWT, so it is not appropriate to change their treatment in the SLM. In other words, the recommended change to the safety factor for the calculation of the wind load on the tower only.

Equation (18, IEC43) is not an exact description of the wind loads on a tower but is sufficiently well-known and trusted to be used in a wide variety of international standards. Two standards that relate directly to wind turbines are ASCE/AWEA (2011) for large wind turbine towers and

ANSI/TIA (2011) for small ones. In applying the equivalent of IEC 61400-2 to large towers, the former recommends an effective safety factor of 1.52 and the latter suggests 1.6 for the use of IEC 61400-2.

The only direct measurements of SWT tower loads known to the author are by Dana, Damiani, and Van Dam (2018) who instrumented the tower of a Skystream 2.4-kW turbine (see Table 3) for a 6-month campaign. Their measurements of the tower bending moment were less than one-third the DLC H load calculated without a safety factor. It is concluded that the safety factor used for DLC H in the SLM is excessive.

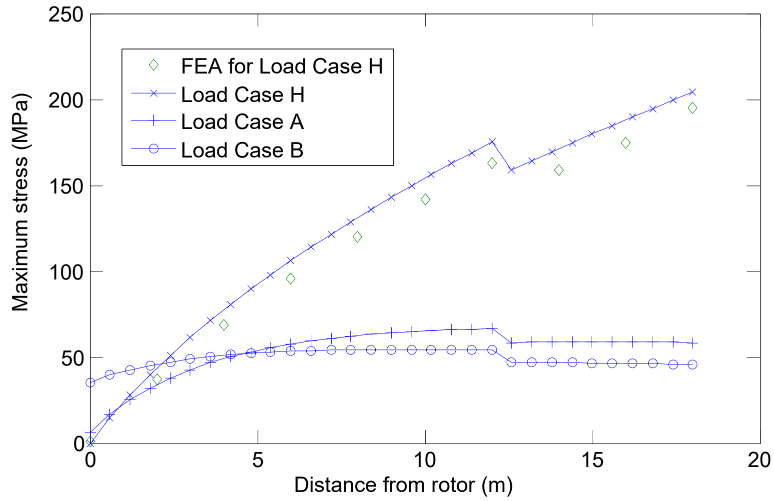

Figure 2. Stress distribution along the tower in Figure 3 for three DLCs

The third recommendation is that the safety factor for use in DLC H for the turbine tower be reduced to 1.6.

The final change to this load case concerns Equation (15, IEC41) for the maximum thrust on a parked rotor that is still rotating. If the turbine is producing no power when the extreme wind load is applied, then the maximum velocity at the blades will be $\sqrt{V_{e50}^{\ 2} + \lambda_{e50}^2 R^2}$ so to have a term in (IEC41) proportional to λ_{e50}^2 implies that $V_{e50} << \lambda_{e50} R$, which is likely to destroy the blades through centrifugal stresses in any case. The maximum rotation that can be allowed must make $V_{e50} >> \lambda_{e50} R$ in which case, (14, IEC40) is sufficient.

The fourth recommendation is that equations (IEC41,42) be removed from DLC H.

5 Error in the Equations for Design Load Case B

It was mentioned previously that Equation (9, IEC28) is in error because it does not include a contribution from the blade thrust. In the SLM context, this load is given by equation (F.11) in Annex F of IEC 61400-2, so the recommendation is to add that term to Equation (9, IEC28). Because the term at least twice as large as the last term in the original equation, that term can be neglected. This would replace Equation (9, IEC28) by

$$M_{yB} = m_B \omega_{yaw,\max}^2 L_{rt} R_{cog} + 2\omega_{yaw,\max} I_B \, \omega_{n,design} + \frac{\lambda_{design} Q_{design}}{B} \quad (21)$$

where the alteration is highlighted in red. Note that Equations (10, IEC29) and (11, IEC30) do not need changing, as the rotor thrust does not cause a moment on the shaft. Leaving the last term in both these equations can be viewed as inconsistent with Equation (21), but it can also be viewed as conservative and safe.

The fifth recommendation is that the last term in Equation (9, IEC28) be replaced by the last term in Equation (21), highlighted in red.

6 Summary of Recommendations for Changes to the Simplified Loads Model

These are:

1. The SLM fatigue loads assessment be replaced by Equations (18) and (19) and no other contribution to the fatigue load be considered.
2. The gyroscopic term in Equation (9, IEC28) be applied with the same safety factor of 1.35 as allowed in aeroelastic simulations.
3. The safety factor for use in DLC H for the turbine tower be reduced to 1.6 in line with civil design codes for wind loading.
4. Equations (IEC41,42) be removed from DLC H.
5. The last term in Equation (9, IEC28) be replaced by the last term in Equation (21), highlighted in red.

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