Introducing Low Cycle Fatigue in IEC Standard Range Pair Spectra

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Abstract

State-of-the-art assessment of wind turbine fatigue loads concentrates on load cycles that are found within simulated or measured 10-minute realizations of the investigated load. The philosophy is based on a representative description of the wind turbine loading by means of a capture matrix that is expanded by the parameters of inflow turbulence intensity and average wind speed. In the data base created through simulations and measurements time series of 10 minutes duration for any possible combination of these two parameters are captured. The range pair spectra used in fatigue life calculations are found by superposition and extrapolation of the rainflow counted load cycles that can be found within each of the used time series. In this procedure the loading effect of the wind speed varying from one 10-minute average to another is neglected.

Already 1996 a method to take such low cycle fatigue loads into consideration has been suggested by Larsen and Thomsen from RISØ [1]. The proposed paper describes the application of the RISØ-method to a data set of measured flatwise fatigue loads. The resulting fatigue life range pair spectrum with low cycle fatigue content is discussed in comparison to a fatigue life range pair spectrum obtained by the standard technique. The comparison that is carried out on the basis of the rainflow range pair load spectra, 1-Hz equivalent load and even more complex damage calculations aims to give orientation in the question of how severe low cycle fatigue appears to be and whether or not it shall be considered in future design verifications.

1 Low Cycle Fatigue

In state-of-the-art assessment of wind turbine fatigue, loads are characterized using the load cycles that are found within representative simulated or measured 10-minute-time series of the investigated load. According to the Technical Specification IEC 61400-13 [2] the wind turbine loading shall be described by means of a capture matrix that is expanded by the parameters of inflow turbulence intensity and average wind speed for a given mode of operation i.e. normal power production, power production plus occurrence of fault, idling and transients. In this data base time series of 10 minutes duration for any possible combination of these two parameters are captured and requirements are given for a sufficient amount of data for each of these combinations.

In the fatigue analysis the wind turbine duty cycle [3] is described through the wind speed distribution and a specific number of transient events. In this philosophy each wind speed bin is considered as an individual measurement load case (MLC) that is to be weighted according to its frequency of occurrence throughout the turbine's service life. This frequency is given by a specific wind speed distribution which is normally chosen to be identical with which has been used in the design of the turbine e.g. a Rayleigh distribution with average wind speed of 8.5m/s as assumed for wind turbines class II in the International Standard IEC 61400-1 [4]. The fatigue load spectra are then found by superposition and extrapolation of the rainflow counted load cycles that can be found within each of the time series used to describe a given MLC. In this procedure the loading effect of the wind speed varying from one 10-minute average to another respectively from one measurement load case to another is neglected. The loading arising from these transitions between the load cases (MLCs) is in the following referred to as Low Cycle Fatigue (LCF).

2 The RISØ-Method

With respect to LCF the IEC Technical Specification 61400-13 refers to a method published by Kenneth Thomson and Gunnar Larsen from RISØ already in 1996 [1]. As it appears the application of this method is not formally requested and hence does not seem to be common practice. Nevertheless, as can be learned from load monitoring exercises [5] and from the following results, LCF can contribute considerably to the fatigue life consumption depending on the component and the material under examination.

To apply the RISØ-method an annual time series of 10-minute-average wind speeds is required. Having found such time series for a given site or class of sites for each 10-minute-average value of the wind speed a pair of extreme values from a load time series of the corresponding MLC is extracted from the data base (capture matrix) and added to an artificial annual load sequence of 105120 extreme

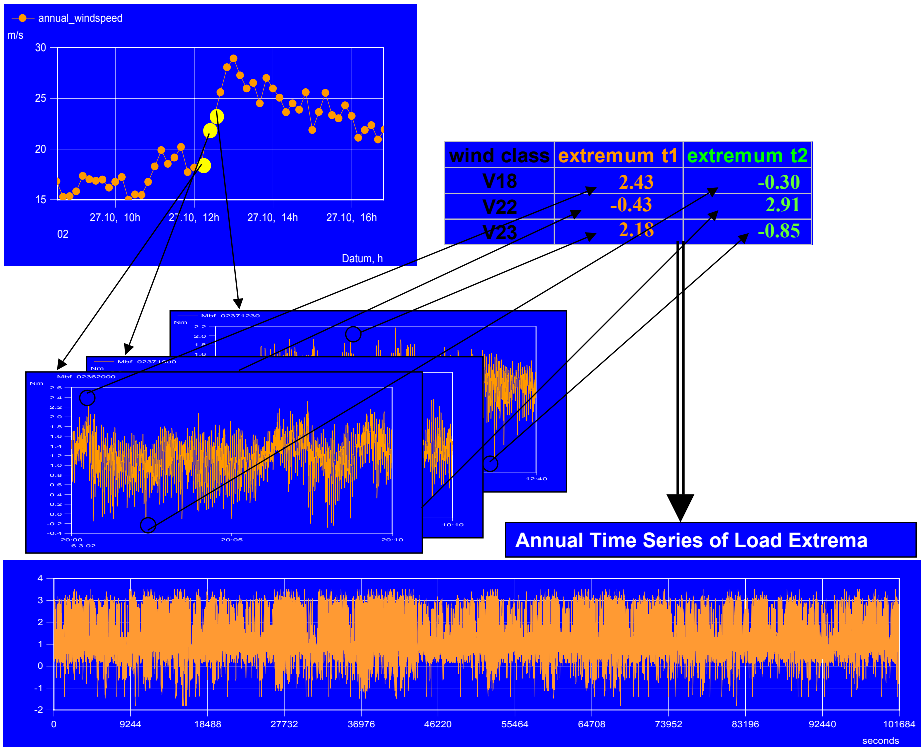
Normal Power Production

Windturbine: **1**
Wind speed bin size (x-axis): **1 m/s**
Turbulence bin size (y-axis) : **2%**

V(m/s) I(%)	0 3.5	3.5 4.5	4.5 5.5	5.5 6.5	6.5 7.5	7.5 8.5	8.5 9.5	9.5 10.5	10.5 11.5	11.5 12.5	12.5 13.5	13.5 14.5	14.5 15.5	15.5 16.5	16.5 17.5	17.5 18.5	18.5 19.5	19.5 20.5	20.5 21.5	>21.5 V out
0- <3			**2**	**6**	**3**	**3**	**5**	**3**												
3- 5			**6**	**4**	**15**	**4**	**7**	**1**												
5- 7		**1**	**4**	**9**	**23**	**11**	**8**	**1**												
7- 9	**1**	**2**	**9**	**17**	**11**	**7**	**5**	**6**	**6**	**2**		**4**								
9- 11	**3**		**4**	**5**	**3**	**6**	**19**	**31**	**21**	**16**	**11**	**7**	**4**	**1**	**1**	**2**	**2**			
11- 13		**2**	**7**	**2**	**1**	**6**	**21**	**25**	**18**	**21**	**20**	**20**	**18**	**6**	**6**		**4**	**1**		**1**
13- 15		**3**	**1**	**1**			**4**	**8**	**5**	**7**	**5**	**11**	**5**	**1**	**3**	**4**	**3**	**2**		
15- 17		**1**						**3**	**1**	**1**	**2**	**1**	**1**	**1**	**3**	**1**				
17- 19		**1**					**1**													
19- 21									**1**											
21- 23																				
23- 25																				
25- 27																				
27- 29																				
>29	**1**																			
	5	10	33	44	56	37	70	78	52	47	38	43	28	9	13	7	9	3	0	1

Datasets : **583**

Tab. 1: Capture Matrix for Flatwise Loading for Normal Power Production



wind class	extremum t1	extremum t2
V18	2.43	-0.30
V22	-0.43	2.91
V23	2.18	-0.85

Fig.1: The RISØ-method

values (see Fig. 1, for details of the method the reader is referred to [1]). This synthetic load sequence is then Rainflow-counted and the resulting load cycles are added to the standard Rainflow load statistics obtained from a the same capture matrix.

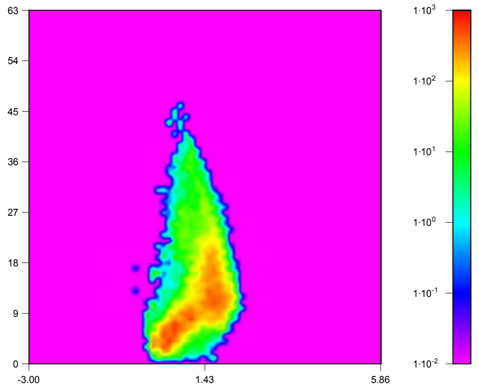


Fig. 2 : Averaged Normalized Flatwise Blade Bending Rainflow Matrix LCF Portion

3 Load Spectra Containing LCF

In the further course of the investigation 5 normalized load data bases of the flatwise blade bending from the NEW WISPER Task within the Optimat Blades project [5] have been used together with a year-round 10-minute-average wind speed time series complying with the wind speed distribution of the IEC wind turbine class II. This wind speed sequence thus characterizes a typical annual course of the wind speed in a Northern Europe Flat terrain site. Applying the RISØ-method on these data and adding 400 starts/stops at cut-in, some 10 starts/stops at cut-out, 40 emergency stops and other transients acc. to their determined frequency of occurrence delivered 5 fatigue load spectra with LCF contribution. For comparison the same data bases have been evaluated without LCF. From both sets an averaged flatwise blade bending load spectra are derived and the difference is computed. Figure 2 presents the LCF portion of the averaged flatwise blade bending Rainflow matrix (range mean).

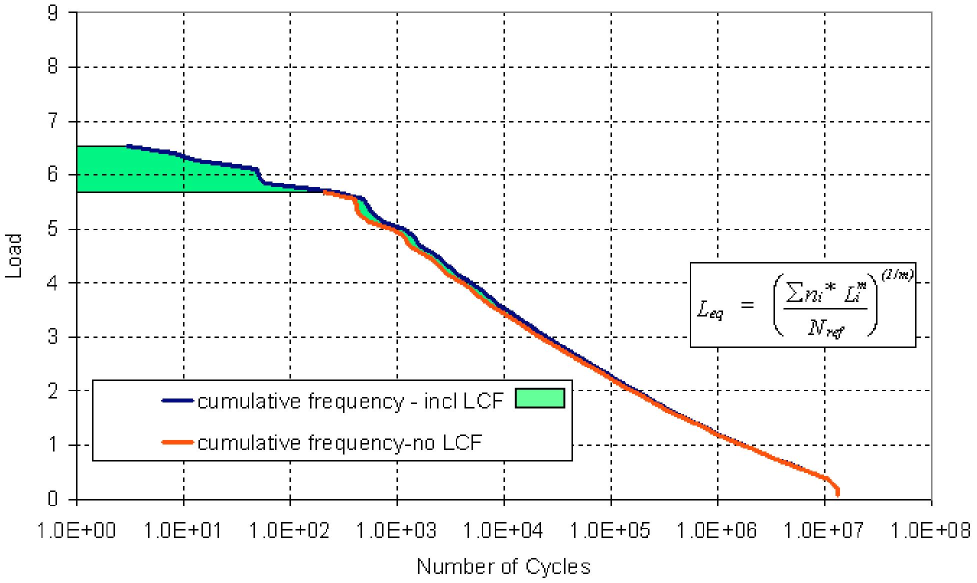


Fig. 3: Averaged Normalized Cumulative Flatwise Blade Load Spectra With/Without LCF

As could be expected the most prominent part of the LCF cycles are visible in the region of large load ranges as depicted in the cumulative range pair spectra of Figure 3. This impression is mainly due to the logarithmic scale of the frequency axis. Looking at the LCF Rainflow count considerable numbers of load cycles are also found with rather small ranges. To asses the contribution of these LCF cycles to the total damage of the flatwise loading on a rotor blade root several damage qualifiers of varying complexity have been applied.

4 LCF Effect on Damage Qualifiers

As the most simple damage qualifier the 1-Hz equivalent load (L_{eq} , formula given in Fig.3) has been computed for each of the 5 individual flatwise blade load spectra with and without LCF contribution. Additionally the L_{eq} –criterion has been determined for the averaged flatwise load spectra including/excluding LCF. Table 2 gives the results obtained for characteristic materials such as glass fiber (m=10), cast modular iron (m=7), welded steel (m=3):

Turbine		1	2	3	4	5	**averaged**
m=3	**EQL**	0.6095	0.5236	0.5101	0.8752	0.4641	**0.6338**
	EQL without LCF	0.5999	0.5150	0.5006	0.8628	0.4578	**0.6241**
	Ratio (%)	**101.60%**	**101.67%**	**101.90%**	**101.43%**	**101.37%**	**101.55%**
m=7	**EQL**	1.2366	1.0843	1.0244	1.8031	0.8812	**1.4572**
	EQL without LCF	1.1884	1.0319	0.9534	1.7576	0.8489	**1.4173**
	Ratio (%)	**104.06%**	**105.08%**	**107.45%**	**102.59%**	**103.80%**	**102.82%**
m=10	**EQL**	1.6598	1.4628	1.4676	2.3962	1.1542	**2.0481**
	EQL without LCF	1.5834	1.3639	1.2905	2.3326	1.0987	**1.9915**
	Ratio (%)	**104.83%**	**107.25%**	**113.73%**	**102.73%**	**105.05%**	**102.85%**
m = 10	**Miner Sum**						
	Ratio (%)	**160.24%**	**201.30%**	**361.93%**	**130.85%**	**163.67%**	**132.38%**

Tab. 2 : Results of LCF contribution rated by the L_{eq} –criterion

In general the LCF contribution rated by the L_{eq} –criterion is more important for larger material exponents m, i.e. for materials that are more sensitive for large range load cycles s. a. fiber reinforced plastics. The increase for m=10 for the different turbine data sets ranges from some 3% to roughly 14%. The averaged LCF range spectrum shows an increase of just 3%. This result is somewhat surprising but is caused by the rather large absolute contribution of turbine 4 when compared to the other turbines. Turbine 4 showed in general more and larger load cycles due to the site's complexity. This gives rise to the assumption that LCF is less important for complex sites.

These results look rather unspectacular when the LCF contribution is rated by the L_{eq} –criterion. As this criterion is a relative criterion it gives the load range that creates the same damage as the sum of all the different rainflow load cycles contained in a measured load spectrum when applied at a rate of 1Hz per cycle . However, no statement is made on the increase of the absolute damage on the material. To evaluate this effect the increase in the damage sum obtained with Palmgren-Miner's damage accumulation theory has been determined for m=10. For the average range pair spectrum the increase in the Miner sum is 32% this in fact means that the fatigue life of a blade root exposed to a load spectrum containing LCF is reduced by 25% compared to the fatigue life without consideration of LCF. When evaluating the Miner sum increase for the individual turbines values ranging from 130% to 362% are found. Using the translation into fatigue life reduction on the result of turbine 3 the dramatic message is that only 28% of the fatigue life as estimated without LCF will be reached!

The results described so far have been obtained using a rather simple description of the materials. In order to obtain a better understanding of the LCF effect and its importance DLR has joint the work in applying more complex fatigue damage calculations using more detailed material models.

5 LCF Effect Rated by DLR Damage Calculations

The damage calculations done by DLR employ experimental material data determined with a material that is typically applied wind turbine in rotor blades. The fatigue behavior of this material is characterized by means of several S-N curves at different R-ratios i.e. the ratio of the minimum applied strain to the maximum applied strain and static material parameters s.a. UTS (= ultimate tensile strength) and UCS (= ultimate compressive strength). Using these material data Goodman Diagrams or Constant Life Diagrams of specific materials are derived. From these material data for a given load cycle range the allowable number of load cycles is found through spatial interpolation and compared to the number of load cycles found in the fatigue load spectrum using linear Palmgren-Miner's Rule.

Table 3 presents the results of these computations in terms of the with-LCF/without-LCF ratio of the Miner sum.

The computations have been performed for several stress levels and employing experimental data for a typical wind turbine in rotor blade material. Only the averaged flatwise bending load spectra with/without LCF have been examined. The determined ratios clearly confirm the results of the L_{eq} –criterion almost up to the point. Again an extra damage in the size of 30% to 33% is found. As expected by DLR the surplus damage comes our slightly smaller with more exact but complex material descriptions.

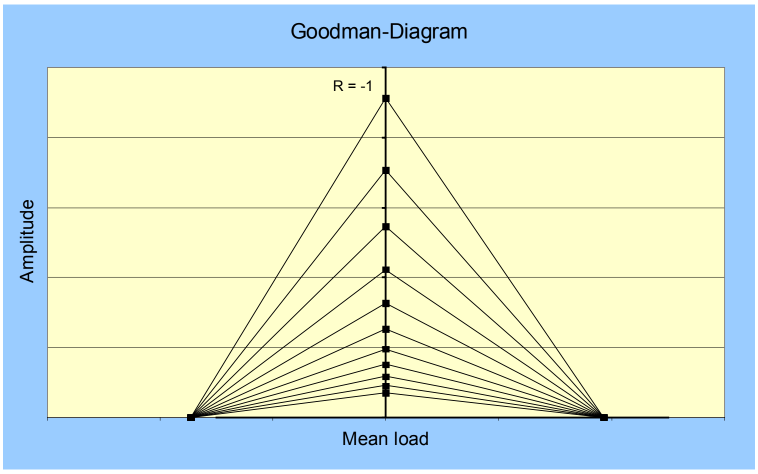


Fig. 4: Linear Goodman Diagram (Material data: S-N-Curves for R=-1, UTS,UCS - Linear interpolation between UCS/UTS and R= -1 for the individual load bins)

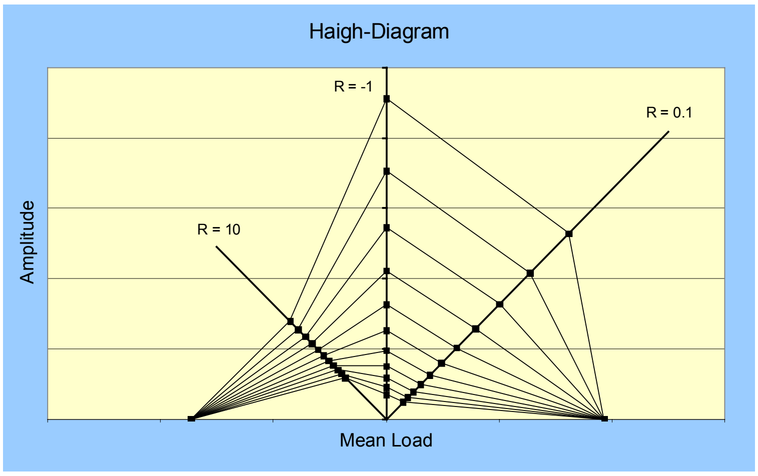


Fig. 5: Constant Life Diagram (Material data: S-N-Curves for R=-1, R=0.1, R=10, UTS,UCS - Linear interpolation between UCS/UTS and S-N-Curves for the individual load bins)

Stress Level	Ratio Damage Sum	
Mpa	Goodman	CLD
100	131.14%	130.19%
200	132.16%	129.91%
300	133.13%	129.72%

Tab. 3: Results of LCF contribution rated by DLR Damage Calculations

6 Conclusion

- Application of RISØ - Method for LCF on „real life" load data confirms the results reported in 1996 obtained on simulated load data.
- The LCF effect appreciated by different damage qualifiers becomes smaller when using more complex damage calculations employing more detailed material descriptions.
- LCF contributes significantly to structural damage in components made of materials with rather large sensitivity for load cycles with large ranges are concerned i.e. fiber plastics and cast modular iron components.

7 References

[1] Larsen, G.; Thomsen, K.: A simple approximative procedure for taking into account low cycle fatigue loads. Paper presented at IEA-Symposium on Wind Turbine Fatigue, Stuttgart, February 1-2, 1996

[2] IEC: Wind turbine Generator systems: Part 13: " Measurements of Mechanical Loads ": Technical Specification IEC 61400-13 (1. ed. 2001). Geneva, Switzerland: International Electrical Commission, 2001.

[3] IEA Recommended practices for wind turbine testing and evaluation. 3. Fatigue Loads, edition 1990

[4] IEC: Wind turbine Generator systems: Part 1: "Safety requirements": IEC International Standard 61400-1, 2. edition 1999. Geneva, Switzerland: International Electrical Commission, 1999.

[5] www.wmc.tudelft.nl/optimat_blades/