Damage Equivalent Load Synthesis, Stochastic Extrapolation and Validation for Fatigue Life prediction

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Many thanks to the reviewer for the specific comments provided to the revised article. Please find below the response to the technical clarifications sought by the reviewer.

Response to Reviewer comments

1) For me, the relevance of 1-year extreme DELs (or even longer return periods) is still not completely clear. Perhaps, I just misunderstand your definition of 1-year DELs. If this is the case, the definition of it should be stated more clearly in the paper. And additional explanations are required. A detailed example has been provided by the reviewer.

A: Thanks a lot for providing the example to clarify the question much better. The example that has been provided by the reviewer demonstrates the sentence that was added to the revised manuscript on page 10 that the influence of the tail region is much greater for larger material exponents such as for blades. While, as the reviewer points out that the true 25-year DEL can be determined using extrapolation of blade root DELs, the methodology adopted in the article is not targeting the determination of the true 25-year DEL. The equation for the 25-year DEL stated by the reviewer and presented in Eq. (1) in the manuscript is not directly used in the manuscript in the assessment of integrity of the structure. It is to be noted that the method proposed by the author is focusing on the one-year DEL and not 25-year DEL. The main requirement is that measured 10-minute DEL magnitudes as shown in Fig. 3 of the article are verified to be within design limits over a target period, which is taken to be one-year in this article. The method proposed in the article as explained on page 10 is that the weighted probability of the extrapolated 10-minute DEL over one year at each mean wind speed is compared with the corresponding weighted probability of the extrapolated 10-minute DEL over a year using aeroelastic simulation results to enable a definite assessment of the margin of safety available of the turbine structure. This is significantly more accurate than assuming that the average 10-minute DEL over a limited number of aeroelastic simulations is a constant over the full year as is done in the conventional design practice, when using Eq. (1).

The limitation regarding the lower Wohler exponent of steel to not allow exact reproduction of the long-term DEL is also applicable to the extrapolation using DEL results from aeroelastic simulations. Hence the two DEL extrapolations, one using measurement results and the other using aeroelastic simulation results are commensurate and can be used for direct comparison of the utilization of the structural fatigue margins. Hence this methodology is also applicable towards the structural integrity of towers as well as for blades. Moreover, the one-year extrapolated DEL using measurements can be continuously corrected over time with more measurements to reduce the error in the long-term DEL prediction. A clarification on this aspect is now provided on page 10 of the revised article. Further a sentence is added in page 4 as “Instead of assuming the same limited number of load cycles repeated for the lifetime of the turbine in Eq. (1), it is more realistic to determine the probability of exceedance of DELs over a period and thereby determine the number of cycles for each DEL magnitude.”

Minor points:

1) Perhaps it would help if you clearly differentiate between short-term DELs (e.g. based on 10 min intervals) and long-term DELs being the “sum” of many (n_{ST}) short-term DELs ($L_{LT}=(\Sigma \mathrm{j}=1..\mathrm{n}$

$(L_{ST,j}\hat{}m))\hat{}1/m$) over a longer time period. In my understanding an "aggregated DEL" is a long-term DEL, but it seems as if you use this expression differently.

A: The phrase "aggregated DEL" appears only on page 3 of the article and here the phrase implies that the DEL is a summation over a time interval, (herein taken over 10-minutes). The main reason the word "aggregated" is used, is to differentiate between a stochastic quantity that is a cumulation over several load amplitudes versus individual amplitudes that occur in a time series. To avoid any confusion, the phrase "aggregated DEL" is now replaced with just DEL on page 3.

2) L. 190 (of the revision): Perhaps refer to Fig. 9b.

A: A phrase is now added herein that states "…. as later explained through Fig. 9b".

3) L. 248-250 (of the revision): I am sorry, but you cannot see "that the extrapolation […] provides a good representation". It is true that in Fig. 5, it can be seen that the 1-year DEL is fitted well. However, in Fig. 5, you do not know which measurement corresponds to which line etc. Hence, please reformulate or remove this statement or make the figure clearer.

A: The statement referred to is modified to the following in the revised article, " It can be seen that extrapolation using the 3-parameter Weibull distribution reproduces the same trend as the empirical distribution using the measurements, while allowing for predicting the DEL magnitudes asymptotically to lower probabilities of exceedance"

4) Fig. 6 and 7: Different scales of the vertical axis make comparisons complicated.

A: While this may be the case, the intent here is not to make a direct comparison between these two figures, but to outline the process to be made for assessing the structural integrity in fatigue. This was already noted on page 10 that "while the process of verification of the structural integrity in fatigue is presented, the quantification of the structural reliability or remaining life of the specific operational turbine is not made herein, since the actual design loads of the specific turbine used in its design is not available."

5) In Fig. 9b, it would help if the first eigenfrequencies of the blade (flapwise) and the tower (FA) are marked, since the first peak for the tower moment is not clearly visible.

A: This is marked now in the revised manuscript with the label "1st frequency" on each FFT plot.

6) L. 291 (of the revision): You state that is it "possible to directly simulate multi-year damage equivalent moments". However, if I am correct, this is only possible if std. deviation, minimum and maximum load levels are available. This should be stated here again.

A: While it is true that std. deviation, minimum and maximum load levels are required to compute the DEL using GPA, the same can be generated using a random process, if a feasible domain for the range of these quantities is known, for example from past experience with similar turbine configurations. This is clarified on page 14 of the revised manuscript.

The minor format corrections suggested by the reviewer are implemented in the revised manuscript.