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

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Many thanks to the reviewers for their detailed comments and feedback to improve the article. Please find below the response to each of the specific questions or feedback comment provided by the reviewers.

<u>Reviewer 1</u>

in this paper, long-term fatigue damage analysis was considered using 10-min DEL and the probability distribution of wind conditions to formulate a Weibull long-term 10-min DEL distribution, which agrees better with the results from the measurements. The 10-min DEL for each wind condition was obtained using a level-crossing fatigue cycle counting method assuming a Gaussian process.

The topic of this paper is interesting and the results are well presented.

1) Some of the details to justify the level-crossing method considering the Vanmarcke correction for very narrow band process should be given. It is not very clear to the current reviewer that whether it is the wide-band correction that was equivalently considered or not.

   The basis for fatigue damage calculation for each wind condition is to use the rainflow cycle counting method for the obtained stress time series (or cross-sectional loads in this paper). The outcome of the rainflow cycle counting are both counted number of cycles (which equals to the number of peaks Np) and stress ranges. A narrow band assumption of the fatigue damage calculation is to assume a Rayleigh distribution of the stress range and to use the number of cycles as the number of global peaks (Ngp) for the stress time series. the global peaks are defined as the maximum value of two consecutive up-crossing of the mean level of the stress. Therefore Ngp is smaller than Np for a wide band process. moreover, a wide-band correction factor is multiplied with the damage under narrow-band assumption to obtain the true damage.

   Then, the question is whether the corrections proposed by the author is similar as this type of correction for wide-band processes? on the other hand, as the author discussed, the Vanmarcke correction is for very narrow band process for up-crossing rate analysis. is the response process is a very narrow band process? it is better to show the spectral density function of the response process to check this.

A: The method of level-crossings is employed in the article to derive the DEL, by using the results of the simplified analytical expressions provided for Gaussian processes. As stated in page 4 of the original article, for wide-band Gaussian processes or Poisson processes, the methods of Cramer-Leadbetter [Cramer and Leadbetter (1967)] can be used to determine the number of level-crossings of specific barriers. For the wind farm analyzed in this article, it did not require the use of wide-band process methods. The blade root flap moments are assessed at the P (rotational speed) frequency, for which a regular narrow-band Gaussian process assumption was found satisfactory. A very-narrow band correction (Vanmarcke correction) was needed to represent the tower-base fore-aft moments. The Vanmarcke correction is similar to the corrections applied for wide-band processes that the reviewer refers to, except that it is used to restrict the number of peaks crossing a given level. The α parameter in the Vanmarcke equation controls this and as described in the paper, this parameter is taken to approach unity for highly damped systems. This is needed to account for the reduced energy of the spectrum of tower base fore-aft moment due to the high damping present during turbine operation. This is also explained in page 7 of the original article. This implies that the energy in the spectrum at the first natural frequency is significantly low. A sentence clarifying this is now added to section 4.2. A spectrum of blade flap moment and tower base moment without marked frequencies is shown in the revised manuscript, as requested, which shows that the first peak in the tower fore-aft moment spectrum is much lower than the corresponding peak in the blade flap moment spectrum.

2) It can be discussed whether the Vanmarcke correction is relevant for fatigue damage calculation. in principle, for fatigue damage calculation, one has to consider all the stress peaks. however, for extreme value analysis, one should consider independent peaks in order to impose the Poisson assumption for extreme value prediction, as a result, one may use this correction method.

A: While it is correct that for fatigue damage computations, all stress peaks must be considered, the Vanmarcke correction provides a constraint to the upcrossings of the Gaussian process and does not neglect any upcrossing. The Vanmarcke formula essentially corrects the number of upcrossings of the Gaussian process with lowered energy content as characterizing a highly damped dynamic system. This correction can also be used to identify extreme loads of highly damped dynamical systems.

3) Another question is whether this Vanmarcke correction is used for the measured data? On the other hand, one may also check the use of SN-curves, with one-slope or two-slope curves. wind turbine response might have large moderate frequency loads plus very small high frequency loads. as a result, the number of high-frequency cycles is very large, but the amplitudes are small. therefore they might be very important for fatigue damage calculation.

A: The Vanmarcke correction is used to compute the DELs using the measured 10-minute load statistics (std. deviation, min, max) and the resulting computed DEL is compared with the measured DEL to validate the result in Fig. 10 of the original paper. The use of two slope SN curves is relevant for the tower and may result in higher-damage for high frequency loads. However, the measured DEL for the tower of the instrumented turbine was computed at a slope = 4 and that was also used in the computed DEL using the Vanmarcke correction. This explanation has been added in to section 4.2.

4) Figure 3: What is the main reason for the scatter for a given mean wind speed? because of a different turbulence?

A: This is correct. Figure 3 represents the 10-minute DELs over different wind turbulence intensities encountered by the wind turbine over a year. The reasons for the varying wind turbulence are due to the wake situations prevalent in a given wind direction, as well as atmospheric effects.

5) The main difference between figure 4 and figure 3 are for the wind speeds larger than the rated value. the simulated results seem to show a larger scatter. it will be interesting to look at the reasons. Do you have the same measured wind and wave conditions in your simulations?

A: Measured wind conditions are used in this study and Fig. 3 shows the measured loads obtained at different measured wind conditions. There are no wave conditions used as these wind turbines are mounted on gravity based foundations, which are assumed rigid. Figure 4 shows the results of twelve aeroelastic simulations at each mean wind speed bin over all IEC turbulence classes (Class A, B, C). The scatter observed in Fig. 4 is due to the different turbulence levels and due to the random seed of turbulence used. However in Figure 3, there are much fewer measurements obtained at the higher mean wind speeds as compared to the lower mean wind speeds. Further at higher mean wind speeds, the wake effects are reduced due to the lower thrust in the upstream wind turbine and therefore the effective turbulence seen by the measurement turbine is also smaller. These two factors reduce the scatter at higher mean wind speeds in Fig. 3. This reduced turbulence at higher mean wind speeds is not simulated in Fig. 4. This explanation is added to the revised manuscript.

6) Can you also present the results for a case with mean wind speed larger than the rated value, for example with 18m/s?

A: A result at a higher mean wind speed is now added to Fig. 8 instead of the result at 10 m/s that is shown now.

7) Is the Vanmarcke correction applied here (Fig. 8)?

A: No, the blade flap moment does not require the Vanmarcke correction as it is not highly damped and the DELs computed using the regular narrow-band Gaussian process assumption show very good match with measurements.

8) It will be interesting to compare the time series of the tower base moment in the first place.

A: The actual time series of the tower base moment cannot be shown due to confidentiality reasons. The comparison of measured DELs versus the simulated DELs using the Vanmarcke correction for the tower base FA moment was shown in Fig. 10.

Reviewer 2

1. The use of a 3-parameter Weibull distribution for extrapolations of fatigue loads has already been conducted by Moriarty et al. “Extrapolation of Extreme and Fatigue Loads Using Probabilistic Methods” in 2004. They fit the distribution to the cycles directly and not the 10-min DELs. Nonetheless, this work and subsequent publications on fatigue damage extrapolations have to be discussed. Otherwise, the innovation of the “extrapolation part” of this work remains unclear.

A: This article by Moriarty et.al. is now added as a reference in the introduction. As noted in the introduction of the revised article, “The work by Moriarty et.al. uses extrapolation similarly for extreme loads and fatigue loads, whereby the load amplitude is extrapolated and combined with the corresponding expected number of cycles to determine the damage equivalent load. Since the load amplitude is extrapolated, the probability of the load amplitude and number of cycles is conditional on the joint distribution of turbulence and mean wind speed. In the present work, the aggregated DEL itself is extrapolated as a stochastic variable and taken to be fully correlated to the wind turbulence. The DEL being an aggregated quantity is not affected by isolated changes in load amplitudes over 10-minutes, but the change in DEL that is modelled is due to change in turbulence at a given mean wind speed. Therefore the probability distribution of DEL is conditional only on the mean wind speed, as is the case with wind turbulence. This approach for modelling the DEL as a stochastic variable is validated with DEL measurements in a wind farm in the presence of wake effects. This is thus novel and allows direct assessment of the long-term fatigue damage from measurements even when high frequency wind velocity time series measurements from a met-mast are not available, as is the case for many wind farms. “

2. For me, the relevance of 1-year extreme DELs (or even longer return periods) is not clear. Surely, high cycles tend to dominate the overall fatigue behaviour, especially for blades featuring a high material exponent m. Nonetheless, especially for steel components, a single high DEL is normally not design driving. For the overall fatigue, the sum of DELs ($\sum DEL\ m$) is important. Hence many medium DELs can be much more relevant compared to a single high DEL, if m is moderate. For example, in Fig. 5, the underestimation of DELs around 1 might lead to an underestimation of the overall DEL. Please, comment on this and show how good $\sum DEL\ m$ is approximated. For blades with high m, I believe that this procedure will give accurate approximations for $\sum DEL\ m$, but for steel components with low m, I doubt it.

A: The integrity of wind turbine structures is based on maintaining an annual reliability level in fatigue, which implies that the annual fatigue damage accumulation does not result in exceeding an annual probability of failure. The DEL is the physical equivalent of fatigue damage and therefore the probability of exceeding a DEL value over an year is proposed herein as a verification mechanism to maintain the desired annual reliability level. This is applicable for both blades and steel structures like towers. The method proposed here is applicable for any number of DELs from different load components that are strongly dependent on wind turbulence. While it is true that the influence of the tail region is greater for larger material exponents such as for blades, it is not negligible for towers. What is important in the long-term DEL estimation (whether one or several components) is that the magnitude of the DEL is bounded with increase in time and that the tail can be accurately represented, which is shown in Figure 5. As can be seen, the rate of increase of DEL reduces significantly with reduction in the probability of exceedance and asymptotically approaches the empirical distribution from the measured DELs. This implies that the desired annual or long-term probability of failure (Not exceeding a DEL target) can be actively measured. This explanation has been added to the revised paper in section 4.1.

3. The assumption that the underlying stochastic process is a Gaussian process is a strong assumption. It has to be justified somehow. For example, the variation in loads might change of time (no longer a stationary Gaussian process) or it is due to several superimposed effects (e.g., different Gaussian processes for different wind directions).

A: The validation of the simulated DELs shown in Fig. 8 and Fig. 10 (taken over a year) is the justification that the underlying process is Gaussian. This is also consistent with the assumption that the stochastic process of DELs is driven by wind turbulence, which is Gaussian at larger scales. While, the variation in loads can change over time, the DEL is an aggregated quantity over 10-minutes. Variations in loads or wind speed fluctuations within 10-minutes do not affect the DEL. It is the variation in wind turbulence (10-min std. deviation) over time that affects the DEL magnitude. While there may be different Gaussian processes in different wind directions, that would still allow the same methods shown in the article to be used in each wind direction bin.

4. Regarding the simulations, many information are missing. For example, in line 145-150 or line 185- 189: how many simulations for the fitting?, what is changed (seed only or wind shear, turbulence intensity, etc. as well)?, settings of the aero-elastic model?

A: This information is now added in section 4.1. All 3 IEC wind turbulence classes, A, B and C are simulated and there are 12 simulations for each mean wind speed bin. The aeroelastic model uses the parameters of the actual 2.3 MW wind turbine with the DTU controller.

5. L. 156 and Fig 3 and 4: You state that simulated DELs do not feature the same variations. However, if we look at Fig. 3 and 4, for some wind speeds (e.g. 23 m/s), the variation is even higher for simulation data. Hence, the "larger variation" for measurement data for medium wind speeds, which is visible in Fig. 3 and 4, could also be only due to more data points, i.e. visual effect. Please comment on this. It might also be useful to actually determine the variation (overall and for different wind speeds) by calculating mean values etc. This would exclude visual effects.

A: The coefficient of variation is mentioned in the figure caption of the revised article. Figure 3 shows the measured loads obtained at different measured wind conditions. Figure 4 shows the results of twelve aeroelastic simulations at each mean wind speed bin over all IEC turbulence classes (Class A, B, C). The scatter observed in Fig. 4 is due to the different turbulence levels and due to the random seed of turbulence used. In Figure 3, there are much fewer measurements obtained at the higher mean wind speeds above 14 m/s as compared to lower mean wind speeds. Further at higher mean wind speeds, the wake effects in the measurements are reduced due to the lower thrust on the upstream wind turbine and therefore the variation in turbulence seen by the measurement turbine is smaller at higher mean wind speeds. This reduced turbulence at higher mean wind speeds is not simulated in Fig. 4 and the variation at higher wind speeds is consequently high. This explanation is added to the revised manuscript.

6. If I understand it correctly, GPA is mainly relevant, if load measurements are available, but neither times series nor cycle counts are stored, but only mean, max/min, and std. values are stored. If this is the case, this has to be stated more clearly in the abstract and/or introduction. This is a strong limitation and makes the approach much less relevant. In most cases, either no load measurements at all are available or time series are available.

A: This is already stated clearly in the introduction on page 2 of the original manuscript. There are several wind farms where only 10-minute statistics are available, even of loads, especially if the measurements cover several years. Even if time series measurements of loads are available for a year or two in the past, it would be productive to forecast fatigue damage from this to present time periods, knowing present 10-minute SCADA measurement statistics (wind speed, turbulence, power, etc.). Such a forecast requires the DEL to be computed for various periods with known 10-minute operating statistics. This can be achieved computationally fast, if the DEL can be processed without the need to generate load time series, but directly use 10-minute load statistics. Hence this is not a limitation of the approach, but a significant computational advantage.

7. L. 227: For me, it is not really clear how you determine the DEL using Eq. 4-7. Some more details would be nice, e.g. how exactly do you determine σL?

A: As explained in point 6 above, the σL is obtained from the load measurements in the paper. It can also be taken as any realistic 10-minute standard deviation of loads based on experience. It is also required to know the maximum and minimum load over 10-minutes. Then as stated in lines 119-121 of the original paper, these 10-minute statistics can be used to determine the level crossings of a random Gaussian process. Using several load level bins, the number of cycles of crossing of each load level can be determined, from which the DEL is determined.

8. Minor points:

1) Citations for Eq. 2 and 4 would be nice.

A: This is provided in the revised manuscript

2) L. 115: What value is used for α in this work?

A: As mentioned in page 4, α is taken to approach unity. So a value close to 1, such as 0.99 is used in the study.

3) L. 130: The assumption of using a 3-parameter Weibull distribution has to be justified.

A: The one-year return value of a stochastic process can be described by a probabilistic distribution such as a 3-parameter Weibull distribution that is able to capture the tail of the stochastic process. Also as mentioned in page 5, the reference Hoole et. al. have showed that fatigue life can be well represented by using a 3-parameter Weibull distribution.

4) L. 132: Additional explanations regarding the fitting process are required. If I am correct, Hoole et al. (2019) do not use suggest this method for the fitting itself, but for validation purposes. Moreover, in Section 4.1, you also state that you use the median rank for the validation. Hence, the question how you conduct the fitting itself arises.

A: The median rank is the empirical distribution. The explanation for fitting the 3-parameter Weibull distribution is further detailed in the revised manuscript in page 9 in "The measured turbulence variation at each mean wind speed is divided into 50 bins and one 10-minute DEL is taken from each bin to compute the median rank to which the 3-parameter Weibull distribution is fit. This distribution is extrapolated to the one-year exceedance level for each mean wind speed and compared with the empirical distribution using all measured DEL points over one year at that mean wind speed."

5) Eq. 8: I think, the equation is incorrect. The outer brackets have to be removed.'

A: Thanks for pointing this out. The outer bracket is removed.

6) L. 147: Why does Fig. 1 show that the "extrapolation is stable". The figure shows a fitted distribution. This has to be smooth. Either more information are needed or the statement should be reformulated.

A: The extrapolated distribution must asymptotically converge to a load value as the probability of exceedance approaches zero. This can be seen happening in Fig. 1. Under unstable extrapolation, the extrapolation results in a turning point, whereby after a certain probability, the extrapolated probability of exceedance starts to increase. This does not happen in Fig. 1 up to 1e-15, which is low enough to be zero for practical relevance. Therefore it is stated that the extrapolation is stable. This explanation is added to the revised manuscript.

7) Fig. 2: Please indicate the investigated turbine.
A: This is a 2.3 MW wind turbine, which is indicated in the revised article.

8) L. 170-172: Can you somehow show that the blade root moment is narrow band and the tower moment is very narrow band? Otherwise, the assumption remains mainly unjustified again.

A: This implies that the energy in the spectrum at the first natural frequency is significantly low for the tower base fore-aft moment. A sentence clarifying this is also added to section 4.2. The spectrum of blade flap moment and tower base moment without marked frequencies is shown in the revised manuscript, as requested, which shows that the first peak in the tower fore-aft moment spectrum is much lower than the corresponding peak in the blade flap moment spectrum. This is due to the influence of the strong damping in the tower moment signal.

9) L. 195: Why am I interested in extreme DELs and not aggregated DELs (cf. major point 2)

A: As shown in Fig. 3, the aggregated DEL has a high variation, which is correlated to the wind turbulence. As explained in the introduction of the paper, the wind turbine design uses aggregated DELs computed at the 90% quantile of turbulence, and requires that the annual reliability index in fatigue is greater than a design target (usually 3.3). This implies that the probability of the aggregated DELs exceeding a target value needs to be assessed. A procedure to assess this probability of the aggregated DEL exceeding a target DEL (herein taken as the one-year DEL value) is proposed here and this one-year DEL can be termed the extreme value of the DEL. It has nothing to do with extreme loads. A sentence to this effect is added in section 4 of the revised paper.

10) L. 198: How many measurements are a "small sample"?

A: 50 points are considered, each at different turbulence levels per mean wind speed bin.

11) L. 198: "over all turbulence levels": How do you guarantee that all turbulence levels are covered? Moreover, is it realistic that measurement data is available for all turbulence levels, if you state previously that you only use a "small sample"?
    A: The measurements are over a year. Hence all turbulence levels encountered in a year are considered. The turbulence is binned into 50 levels and one DEL measurement is taken from each turbulence bin to fit the 3-parameter Weibull distribution.

12) L. 205: This procedure of weighting gives you somehow a maximum lifetime DEL. However, this is not directly correlated with the lifetime (cf. major point 2)

The DEL is correlated to the lifetime of the structure and all wind farm designs require that the site specific DEL is lower than the design DEL for the lifetime of the wind turbine. This assessment is made deterministically in practise, but a better probabilistic procedure to quantify the margins in the DELs is proposed in this paper.

13) Fig. 5 and 6: The difference of these two figures is not clear to me. Is Fig. 6a just an extension of Fig. 5 for more wind speeds?

A: That is correct.

14) Fig. 6: A legend for the wind speeds would be nice

A: This is added in the caption of the figure in the revised paper.

15) Fig. 6 and l. 210: I cannot really see that there is a good fit. Perhaps zoom in; make clear which measurement data corresponds to which extrapolations; reduce the number of curves in the plot; etc.

A: This is the reason Fig. 5 is shown at two of the mean wind speeds (zoomed to cover only up to the one-year probability of exceedance), so that it can be seen that the one year DEL level is correctly captured with the extrapolation method. The same is shown over more mean wind speeds and to a lower probability of exceedance level in Fig. 6.

16) L. 229-231: You propose that simulation data can be used to determine the required data for GPA. However, details regarding the precise approach are missing, e.g., how much simulation data is required. Moreover, the question arises, whether this leads to a better extrapolation compared to the direct fit of a Weibull distribution to simulation data. Only if this is the case, the use of GPA in combination with simulation data is useful.

A: It is meant that aeroelastic simulation can be used to determine a range of applicable mean, std. deviations and minimum/maximum values of the load levels. The number of simulations required is turbine specific and depends on the experience of the designer. Given a upper and lower std. deviation of the load and maximum, minimum load levels, then a set of load levels and can be determined, from which GPA can be used to determine the number level crossings of each load level and thereby the DEL.

17) Fig. 11: Similar to Fig. 6, for me, it is not really clear how good the fit is. Especially, it is not possible to see whether GPA or the Weibull fit leads to better results. Please rethink the figure.

A: The purpose of GPA is to generate DEL values given the 10-minute load statistics. Figures 8 and 10 show that the generated DEL closely corresponds with the measured DELs. The purpose of Fig. 11 is to then also show that the extrapolation using the GPA generated DELs yields similar but not the same result as the extrapolation using the measured DELs. The difference in probabilities using the extrapolation from the GPA results with the extrapolation from the measurements data can be seen in Fig. 11. A quantification of the difference between the extrapolation curves at the one-year probability level is now added to the caption of Fig. 11. In the revised paper.

18) The minor editorial changes suggested by the reviewer is implemented in the revised paper.