Damage Equivalent Load Synthesis and Stochastic Extrapolation for Fatigue Life Validation

Anand Natarajan[1]

[1]Department of Wind Energy, Technical University of Denmark, Frederiksborgvej 399, Roskilde 4000, Denmark
Correspondence: Anand Natarajan (anand_nk@hotmail.com)

Abstract. Present verification of the fatigue life margins on wind turbine structures utilizes damage equivalent load (DEL) computations over limited time duration. In this article, a procedure to determine long term fatigue damage and remaining life is presented as a combination of stochastic extrapolation of the 10-minute DEL to determine its probability of exceedance and through computationally fast synthesis of DELs using level-crossings of a Gaussian process. Both the synthesis of DELs and long-term stochastic extrapolation are validated using measured loads from a wind farm. The extrapolation for the blade root flap and tower base fore-aft damage equivalent moment is presented using a three-parameter Weibull distribution, whereby the long term damage equivalent load levels are forecast for both simulated and measured values. The damage equivalent load magnitude at a selected target probability of exceedance provides an indicator of the integrity of the structure for the next year. The extrapolated damage equivalent load over a year is validated using measured multi-year damage equivalent loads from a turbine in the Lillgrund wind farm, which is subject to wakes. The simulation of damage equivalent loads using the method of level crossings of a Gaussian process is shown to be able to reconstruct the damage equivalent load for both blade root and tower base moments. The prediction of the tower base fore-aft DEL is demonstrated to be feasible when using the Vanmarcke correction for very-narrow band processes. The combined method of fast damage equivalent load computations and stochastic extrapolation to the next year, allows a quick and accurate forecasting of structural integrity of operational wind turbines.

1 Introduction

The fatigue damage on wind turbine structures is strongly influenced by the stochastic inflow to the turbine, which is mainly composed of wind turbulence and spatial variations such as shear and veer. [Dimitrov et al. (2017)]. For offshore substructures, the irregular ocean waves also results in dynamic loads leading to fatigue damage. The Palmgren-Miners rule [Miner et al. (1945)] is the standard approach followed in the design of wind turbines by which it is ensured that the linear damage sum over an intended lifetime is lower than unity after considering required safety margins. Since the Miner damage variable is not a physically measurable quantity, a substitute for damage is used, which is the Damage Equivalent Load (DEL). This is the load level at a particular number of cycles, which results in the same damage as the original summation of a multitude of different load cycles with different amplitudes. Damage equivalent load provides a measurable quantity from an operating turbine that can be compared with results from simulations made in the design phase, whereas the Miner's damage is an abstract quantity

of ratio of number of cycles, that is difficult to quantify. Therefore verification of fatigue life on wind farms is usually made using DELs and not damage.

The conventional wind turbine fatigue design process considers a set of aeroelastic load simulation results under normal operation, transients and stand-still under normal turbulence conditions, whereby the load cycles determined over a short period of time at each mean wind speed are assumed to repeat continually over its full expected lifetime. However, it is seldom accurate to consider that the load cycle amplitudes and cycle counts seen in simulations of a few hours can be taken to repeat over 25 years, a typical wind farm lifetime. The IEC 61400-1 standard [IEC (2019)] does informally recommend a stochastic extrapolation process to determine the amplitude and cycle count of the largest amplitude loads as part of the fatigue design process. Indeed, when load measurements are processed in wind farms, there can be a wide variation in damage equivalent loads, much more than seen in the conventional design process. The question then needs to be addressed as to whether larger damage equivalent loads seen in measurements as compared to simulated values encountered in the design process using limited load simulations is indicative of reduced structural reliability and decreased lifetime.

To better quantify fatigue life over long time, it is needed to perform stochastic extrapolation of the short-term DELs to determine the probability of the DEL magnitude over the long term and thereby determine the life of the structure. Extrapolation of extreme loads [Natarajan and Verelst (2012)] is mandated by the IEC 61400-1 to determine the 50-year ultimate design load level, but there is no mandatory requirement presently to extrapolate fatigue DEL. The DEL is an aggregated quantity over a period of 10-minutes or higher. Since it is an aggregation, the value of the damage equivalent load is relatively stable and may not change significantly for isolated load excursions within a time series resulting from the randomness of a stationary process. However the real conditions on the wind farm has varying wind turbulence intensities for a given mean wind speed, thus resulting in varying damage equivalent loads. The resulting DEL values from different 10-minute simulations over different wind turbulence at a given mean wind speed can be extrapolated, so that the probability of exceeding a target damage equivalent load level over a long term period can be determined. This is more accurate and realistic method than the conventional process used today of assuming the same load cycles over a limited set of load simulations are prevalent for the entire life of the turbine.

The fatigue damage as expressed in terms of the DEL is strongly dependent on the wakes within wind farms [Gallinos et al. (2016)], due to strong correlation of several load components with the wind turbulence in the wake. This implies that varying atmospheric conditions such as the wind direction, stability can influence the wake turbulence and thereby also change the DELs on the turbine of interest. Therefore the DEL magnitude is conditional on the turbulence in the inflow. However, since the turbulence in wakes is a function of a multitude of variables such as the turbine position, the wind direction, upstream turbine thrust, upstream turbine yaw etc., it is not readily feasible to quantify the cumulative distribution function (CDF) of the wake turbulence. Herein, a novel approach is put forward to determine the return period of the DEL magnitudes conditional on the mean wind speed, wherein the variation in the DEL is considered to directly correlate to the variation in the wake turbulence. It is also common that many wind farms may possess a wind turbine that is instrumented with load sensors and from which the 10-minute load statistics is archived. This usually implies the 10-minute mean, standard deviation, maximum and minimum are available. The damage equivalent load is often not stored as its computation requires rainflow counting or similar procedures to be available on the turbine computer, which is often not the case. In such situations on a number of wind

farms, it is essential that the DEL can be computed from the measured standard deviations of the loads. This is not a prevalent practise, but is straight forward to map the std. deviation of loads to the DEL, if the underlying stochastic process is assumed to be Gaussian or Poisson. In the following sections, the one year DEL at the blade root and tower base of wind turbines in a farm is predicted using both stochastic extrapolation of the measured DEL and through synthesis of the DELs using the measured loads std. deviations over limited intervals. The method of synthesis of DELs using 10-minute statistics also allows the computation of DELs without the need of detailed turbine information present, such as required for an aeroelastic model. This allows the wind farm owner to simulate DELs quickly without access to detailed turbine information that is possessed only by the wind turbine manufacturer.

Some authors refer extrapolation to imply the prediction of DELs for a future time interval based on measured DELs and wind conditions in the past [Hübler et al. (2018b), Hübler et al. (2018a)]. In the present work, extrapolation of DEL is defined as a stochastic methodology to determine the return period of increasing DEL magnitudes outside the domain of present results. Continuous monitoring and assessment of the turbine structural life is crucial since the costs of unplanned downtime and repairs outweigh the cost of monitoring; also, early correction of wind farm operation ensures safety of structures for their intended lifetime and for life extension. Wind farm operational correction can be carried out by derating upstream wind turbines to reduce the wake turbulence generated by those turbines and thus lower loads on the downstream wind turbines [Dimitrov and Natarajan (2021), Munters and Meyers (2018)]. In the next sections, the ability to use measured or simulated ten-minute load statistics to directly quantify DELs and the use of the stochastic extrapolation methodology to forecast the return-period of DELs is explained, which leads to a criteria to determine if the measured DELs on a wind turbine are within design limits.

2 Methodology

Given load cycles over 10-minute intervals as obtained through rainflow counting of the output time series of aeroelastic simulations, the annual 10-minute damage equivalent load at a given mean wind speed bin is conventionally computed as

$$L_{eq|v} = \left(6 N_v \frac{\sum_{i=1}^{n}(n_i L_i^m)}{Neq} \right)^{\frac{1}{m}} \tag{1}$$

where N_v is the number of hours in a year at the mean wind speed, v, n_i is the number of load cycles of amplitude L_i and m is exponent of the SN curve of the material. The load time series used to compute n_i and L_i in Eq. (1) are conventionally results from rainflow counting of very limited aeroelastic simulations performed under conditions important for fatigue damage. The duration of the load time series over all mean wind speeds and operational conditions simulated is seldom over a few days and the same load cycles are assumed equivalent prevalent for the lifetime of the wind turbine. In practise, a load measurement campaign will provide a wide scatter in DELs [Barber et al. (2016)], so that it may be difficult to ascertain based on the limited simulations, as to what is the design DEL value that is to be considered for assuring that the magnitude of the measured DELs are within acceptable limits to ensure structural integrity.

While frequency domain DEL computation methods such as the Dirlik's method [Ragan and Manuel (2007)] have been used by some, these methods require the knowledge of the load spectrum and may not always be the best choice for design valida-

tion due to erroneous spectra. On the other hand, level-crossing methods need not always require availability of the process spectrum. If the 10-minute statistics of the standard deviation, maxima and minima of loads are available, then assuming the load amplitude can be expressed as a Gaussian process, the probability of crossing an amplitude level, L_i follows a Rayleigh

95   distribution, that is

$$pdf(L_i) = \frac{L_i}{\sigma_L^2} e^{-\frac{L_i^2}{2\sigma_L^2}} \tag{2}$$

where

$$L_i = g_i \sigma_L \tag{3}$$

where g_i is the number of standard deviations, σ_L away from the mean μ_L The number of load cycles with amplitude greater

100   than L_i (upcrossings) is given by

$$Nc_i = \nu e^{-\frac{L_i^2}{2\sigma_L^2}} \tag{4}$$

where ν is the mean crossing frequency, which here will be assumed to be the first rotational frequency (P) of the rotor for the blade flap loads and the first natural frequency for the tower base in the loading direction of interest. Based on the Rayleigh distribution decay rate, a load amplitude bin can be determined which provides one load cycle in that amplitude bin, that is

105   the number of upcrossings of level L_i minus upcrossings of $L_i + \Delta L_i$ is unity. Equation 3 and 4 assume a Gaussian process with a single mean crossing-frequency of interest. For broadband Gaussian processes or Poisson processes, the methods of Cramer-Leadbetter [Cramer and Leadbetter (1967)] can be used, which have also been proven for extreme value analysis [Madsen et al. (1986)]. However for highly damped structures, the stochastic response is a very narrow-band process and in such cases, equation 4 can overly magnify the rate of level crossings. Vanmarcke [Vanmarcke (1975)] prescribed a correction

110   factor to accurately determine the level crossings of very narrow-band processes, which states that the rate of crossings of such a process is

$$N_{v_i} = \nu_v e^{-\frac{L_i^2}{2\sigma_L^2}} \tag{5}$$

where

$$\nu_v = \frac{1 - e^{-\sqrt{2\pi}(1-\alpha^2)^{0.6} L_i/\sigma_L}}{1 - e^{-\frac{L_i^2}{2\sigma_L^2}}} \tag{6}$$

115   α is the Vanmarcke bandwidth parameter, which for a very narrow band process will approach unity.

For a Gaussian process with a known std, deviation, Eq. (1) can also be written as

$$L_{eq|v} = \left(6 N_v \sigma_L^m \frac{\sum_{i=1}^n (n_i g_i^m)}{Neq}\right)^{\frac{1}{m}} \tag{7}$$

We assume g_i is a standardized random normal variable between [-min,max] recorded loads, that provides a unit cycle for each amplitude level. Equation 7 in combination with Eq. 4-6 allows very fast computation of the damage equivalent load over a

time interval of relevance, without the need for aeroelastic load simulations. The only needed inputs are the 10-minute mean, std. deviation, minimum, maximum load levels and the dynamic frequency of interest. This also implies that the DEL values over several input wind conditions (wind turbulence, mean wind speed) can be determined over long time, without limiting the DEL to only a few 10-minute computations per mean wind speed as is the practise today.

2.1 Extrapolation of Fatigue

The DEL values show a wide scatter based on the varying inflow turbulence due to wake conditions and other contributions at any given mean wind speed. While the knowledge of the 10-minute load statistics will enable the ready reconstruction of the DEL as per the previous section, it is also essential to determine the probability of exceedance of a DEL magnitude, that is, to determine the magnitude of the DEL that can possess a one-year return period or a 10-year return period. The DEL is a stochastic variable that is dependent on wind turbulence, wind direction etc and herein it is assumed that the DEL follows a Weibull distribution with three parameters. Extrapolation of the tail of the Weibull distribution will provide the long-term DEL values and the corresponding return period for those values. The cumulative distribution function (CDF) of the DEL magnitudes over different 10-minute intervals may be determined using their median rank [Hoole et al. (2019)], from which a 3-parameter Weibull distribution can be fit, whereby the probability of a damage equivalent load magnitude d, is given as:

$$F(d) = 1 - e^{(-(d-\gamma)/\alpha))^{\beta}} \tag{8}$$

The fitting of the CDF to the DEL may be implemented using the median rank as computed from DEL values from aeroelastic simulations, field measurements or as obtained with the Gaussian process approach described in the previous subsection. The median rank is fit to measured or simulated DEL using the empirical relationship for Weibull distributions:

$$mR(L_i) = \frac{i}{N+1} \tag{9}$$

where i is the sorted rank of the load L_i and N is the number of DEL values used in the fitting process.

Extrapolation of the fitted CDF is made to a minimum of a one year return period, whereby the DEL magnitude with a one-year return period is identified. This provides a readily implementable technique to compute the DEL for a long duration of at least one year without requiring to simulate the full period. It also provides a robust DEL value over long time, rather than applying the conventional methodology used in practise (IEC 61400-1 2019) of simulating loads for a minimal duration and assuming the same load cycles are applicable for the full lifetime.

The results from stochastic extrapolation of simulated blade root flap damage equivalent moment, obtained from limited aeroelastic simulations is shown in Fig. 1. The extrapolation in Fig. 1 uses Eq. (8) and (9) at a mean wind speed of 10 m/s using simulated blade root moments under normal turbulence inflow. Figure 1 shows that the extrapolation is stable even for very low probabilities of exceedance and can therefore be used to extrapolate DELs across different mean wind speeds and wind turbulence levels.
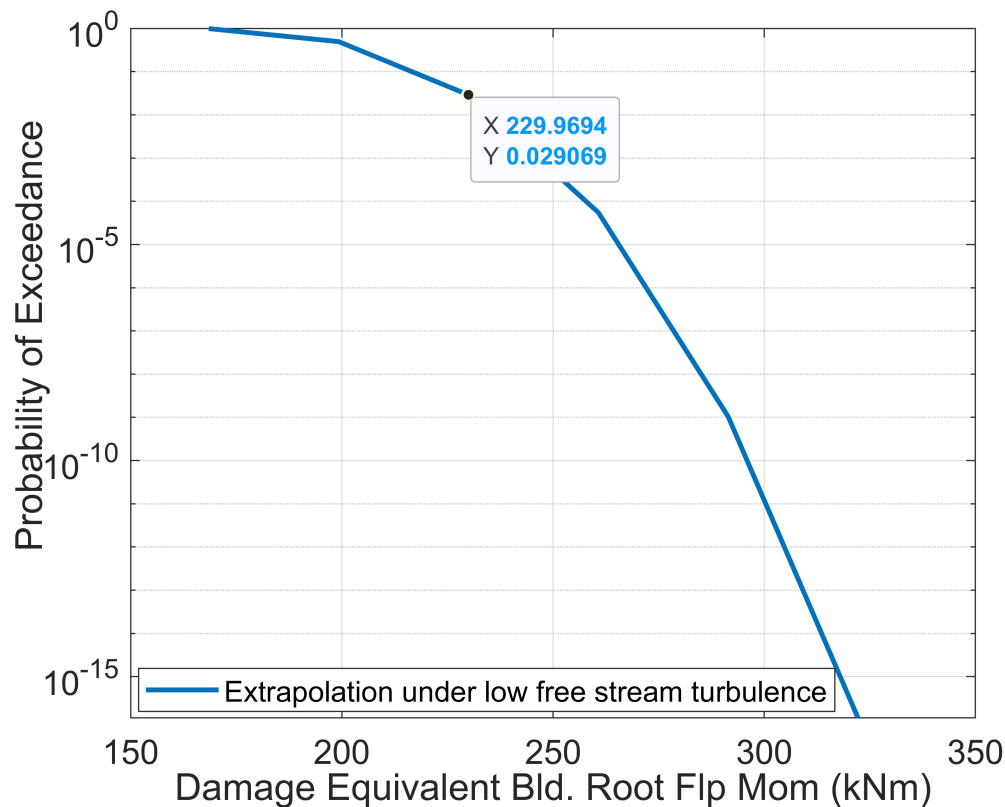
Figure 1. Blade root flap damage equivalent moment extrapolation at 10 m/s for low wind turbulence

2.2 Measurement Data

Loads and SCADA measurements from the Lillgrund offshore wind farm [Dimitrov and Natarajan (2021)] are used in the validation of the methodology described in the above subsections. The blade root and tower base loads on a fully instrumented turbine (C-08) that is the middle turbine in the bottom row shown in Fig. 2 are used in this process. Depending on the wind direction, varying inflow turbulence is experienced by this turbine due to the wake effects. This results in a wide scatter in damage equivalent moments at any given mean wind speed can be seen, an example of which is shown in Fig. 3.

Simulated DEL using the conventional methods does not provide such a variation as seen in Fig. 3 due to limited 10-minute samples and therefore the stochastic models in Eqs. (4)-(6) are used to replicate this variation in DEL. Extrapolation to a one year probability of exceedance is made using both a small subset of the measured DELs and using stochastic simulation set. The one year extrapolated DEL value for both the tower base and blade root are validated with the measured DEL over a year.
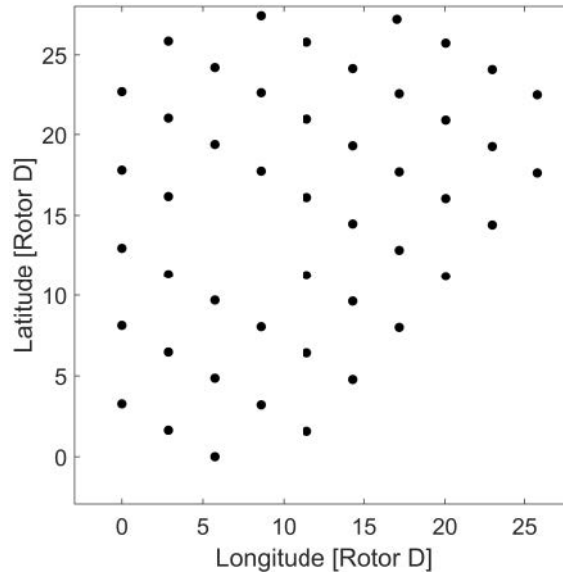
Figure 2. Layout of the Lillgrund wind farm

3 Fatigue from Gaussian Process Analysis

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The blade root flap moment and the tower base fore-aft moment are the main focus points, as these two moments are strongly driven by wind turbulence and wake effects. The life consumption of the blade and support structure within a wind farm is highly dependent on these load components. For the blade root flap moment, the primary frequency of interest for fatigue damage is the rotor rotational speed or the 'p' frequency. While the blade flap moments also contain multiples of p, such as 2p, 3p etc., these are of much lower energy content and the primary energy content is the p frequency. For the support structure, the primary excitation frequency is usually the first natural frequency of the structure. It is assumed that the turbines designs have been made as to not result in resonant excitation. While the tower fore-aft moment spectra has a peak at its natural frequency, it is assumed that this is not caused by excitation from rotor harmonics, such as 3P.

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Under the above conditions of turbine operation, the blade root flap damage equivalent moment is narrow band Gaussian and the tower base fore-aft damage equivalent moment is very narrow-band Gaussian. The reason for the very-narrow band assumption the tower base fore-aft DEL is due to the strong aerodynamic damping of the support structure during turbine operation. This implies that Eq.(4) can be used to compute the DEL cycles for the blade root flap moment and Eq. (5) and (6) may be used to compute DEL cycles for the tower fore-aft moment. Finally Eq. (7) is used to compute the DELs. To validate the above assumptions, the computed DELs are compared for each 10-minute period for a variety of wind/wake conditions over a year with the respective measured DELs.

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Further time-domain aeroelastic simulations using the HAWC2 software [Larsen and Hansen (2012)] are also made to compute the blade root and tower base damage equivalent moments. The DELs obtained from all three methods, that is,

Gaussian process analysis, aeroelastic simulations and field measurements are extrapolated to determine the one-year DEL
value. Based on this extrapolation, a criteria is established in the following sections that allows lifetime assessment of blades
180   and towers.

(a) Blade Root   (b) Tower Base

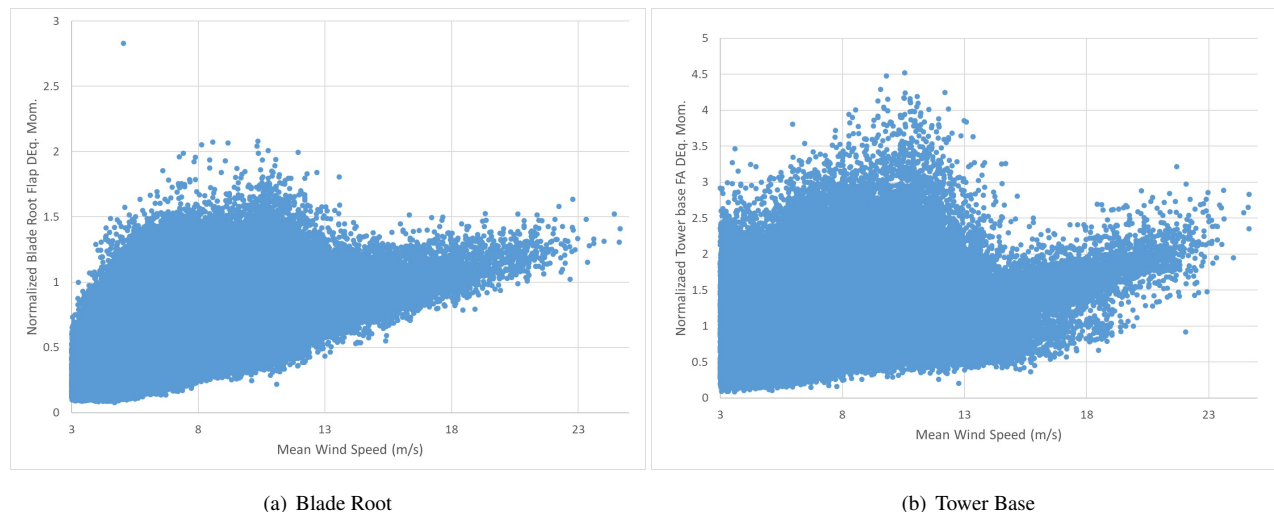



Figure 3. Measured 10-minute blade root flap and tower base fore-aft damage equivalent moments on the C-08 turbine.

4   Results

4.1   Extrapolation with Measured Loads and comparisons with Aeroelastic Simulation Results

Figure 3 describes the measured blade root flap damage equivalent moments and tower base fore-aft damage equivalent mo-
ments over a one-year period normalized by a characteristic value and as a function of mean wind speed for turbine C-08. The
185   large spread in the measured DELs is due to the varying turbulence from the wake as a function of wind direction. Figure 4
depicts the normalized Blade root flap and tower base fore-aft DELs using the results from limited number of aeroelastic load
simulations over all IEC 61400-1 turbulence classes and with different random seeds of wind turbulence at each mean wind
speed. The results in Fig. 4 show a typical number of simulation based results as made in the final turbine design and type
certification.
190   Due to the limited number of load simulations at each mean wind speed, the spread seen in the DELs in Fig. 4 is much
lower than in Fig. 3 and the magnitude variation of the DELs is lower in Fig. 4. However the loads simulations included wind
inflow with the highest IEC turbulence class 'A' and therefore is supposed to represent a safe upper load level. The question
arises as to whether the measured DEL magnitudes on the actual turbine imply that the structures on the turbine are close to
their intended fatigue lifetime or if their reliability is sufficiently intact to enable continued operation for further years. This

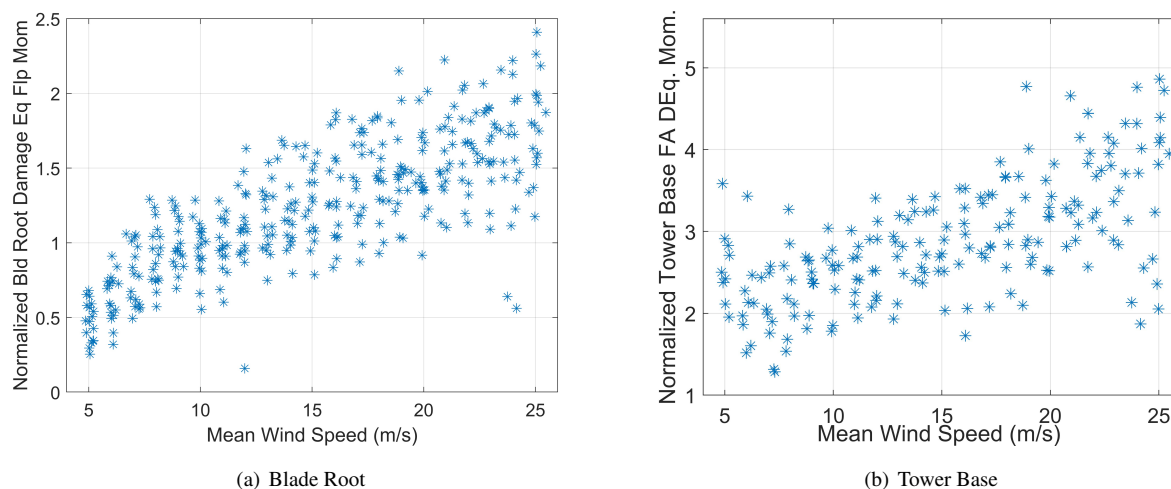
(a) Blade Root

(b) Tower Base

Figure 4. Simulated 10-minute Blade root flap damage equivalent moment and Tower base fore-aft damage equivalent moment over different mean wind speeds and turbulence

195 question can be answered only if the probability of exceedance of the DEL magnitudes are assessed, for which the process of extrapolation is used, whereby the one-year DEL magnitudes between simulated values and measured values can be compared.

The stochastic extrapolation of the DELs using the 3-parameter Weibull distribution is validated using the measured blade root flap moment. A small sample of 10-minute measured blade root flap DELs over all turbulence levels is used to fit the Weibull distribution parameters that quantify the probability of exceedance of the DEL magnitudes. This stochastic fit is then

200 extrapolated to a one-year probability of exceedance and compared with the median rank of the one-year measured DELs to validate the approach. The results are shown in Fig. 5 for two different mean wind speeds, wherein it can be seen that the tail of the extrapolated fitted distribution corresponding to the one-year exceedance probability matches the median rank of the measured DELs very well. This process can therefore be replicated at all mean wind speeds and over all turbulence to determine DEL magnitudes with multi-year return periods. The resulting DEL magnitude probability can be weighted with the

205 probability of mean wind speed to determine the DEL over all mean wind speeds.

Figure 6 displays the long-term extrapolated values for the blade root flap damage equivalent moment and tower base damage equivalent moment, from which the DEL magnitude corresponding to the one-year exceedance probability can be determined. A 3-parameter Weibull distribution is fitted to the probability of exceedance of the DEL magnitude using a few sample measurement values and the resulting stochastic distribution is extrapolated and compared with the median rank of

210 the measured DELs in Fig. 6. It can be seen that extrapolation using the 3-parameter Weibull distribution provides a good representation of the measured 1-year DEL for both the blade root and tower base over various mean wind speeds.

The same extrapolation can also be performed using only the simulated DEL values for the same two load sensors and the results are shown in Fig. 7. The simulated DELs cover all IEC turbulence classes and these are representative of the turbulence levels experienced by the actual turbine. However the simulated results use the 90% quantile of turbulence, whereas

(a) 7 m/s   (b) 10 m/s

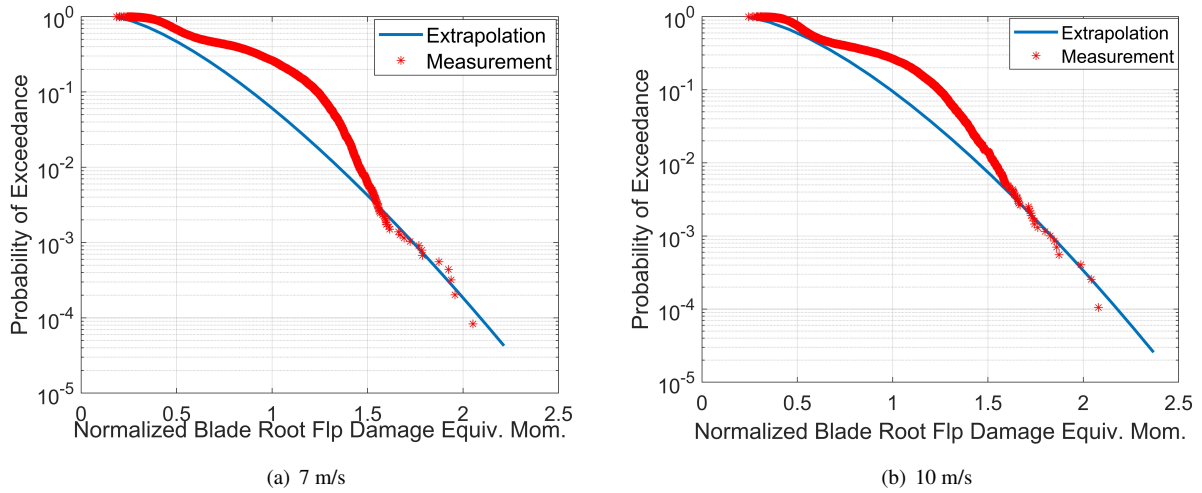



Figure 5. Validation of the stochastic extrapolation method with the measured one-year median rank of the DEL

(a) Blade Root   (b) Tower Base

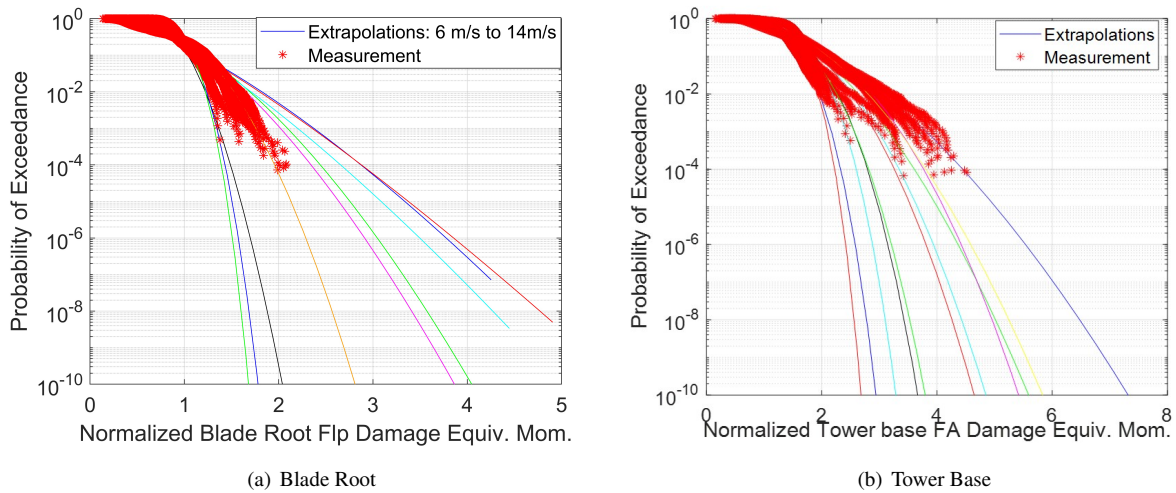



Figure 6. Comparison of the 10-minute extrapolated blade root flap bending damage equivalent moments and the extrapolated tower base fore-aft damage equivalent moment using measurements.

215   the measured turbulence covers a range of quantiles. Consequently, it can be compared if the extrapolation using the simulated DELs in Fig. 7 has a higher one-year DEL magnitude at the one-year probability of exceedance than the measured one-year DEL magnitudes over different mean wind speeds. The weighted probability of the DEL with the annual probability of mean wind speeds can be quantified to enable a definite conclusion on a target annual DEL magnitude, above which the turbine structure can be said to possess a diminished annual reliability level.

|(a) Blade Root|(b) Tower Base|

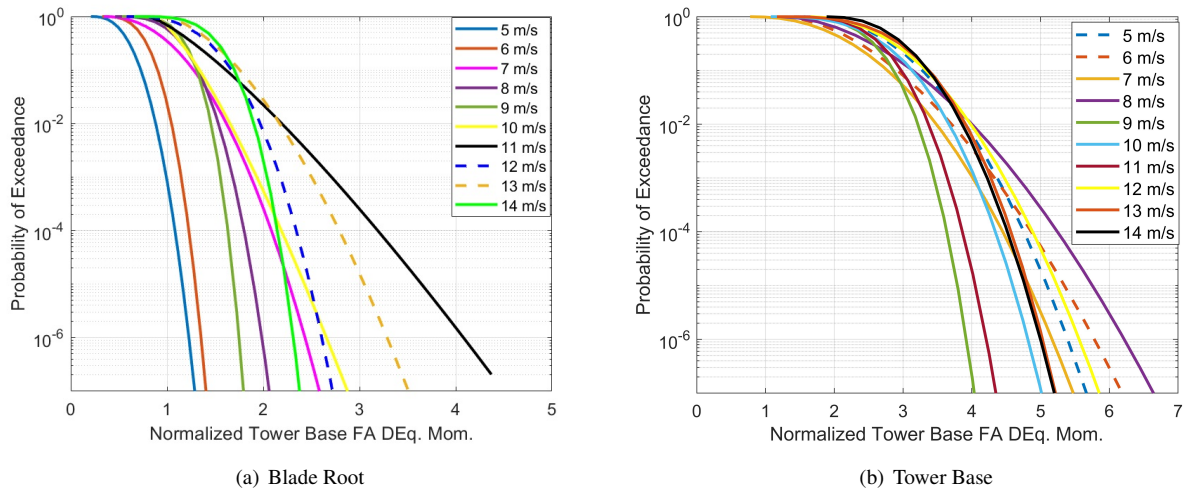



Figure 7. Comparison of the 10-minute extrapolated blade root flap bending damage equivalent moments and the extrapolated tower base fore-aft damage equivalent moment using simulations.

220   It should be noted 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.

4.2   Extrapolation with Gaussian Process Analysis (GPA)

Since aeroelastic simulation is time consuming and therefore provides limited DEL results, the methods for narrow-band and
225   very narrow band processes as explained in previous sections are used to directly simulate one-year of DELs for the C-08 wind turbine blade root and tower base. The 10-minute measured load mean and standard deviations are used to determine the DEL values. A one-year DEL simulation using Eq. (4-7) requires only a few seconds on a standard laptop computer. Many load measurement statistics often do not possess DEL magnitudes and under such conditions the DEL magnitudes can be re-created using Eq. (4-7). If measured 10-minute load statistics is unavailable, then the aeroelastic simulations can be used to determine
230   a range of mean and std. deviations relevant for the 10-minute load magnitudes as a function of mean wind speed and wind turbulence.

   Figure 8 compares the resulting blade root flap damage equivalent moment from the GPA with the measured DELs at two different mean wind speeds. The results in Fig. 8 show that for all the different wind turbulence variations with various wake angles, the simple Gaussian process analysis provides a similar quantification of the true DEL as seen in measurements.
235   For these blade root flap DELs, Eq.(4) is used directly without the Vanmarcke correction to obtain the number of crossings of different levels. However if the same method is used (i.e. without the Vanmarcke correction), for the tower base fore-aft

(a) 7 m/s wind speed (b) 10 m/s wind speed

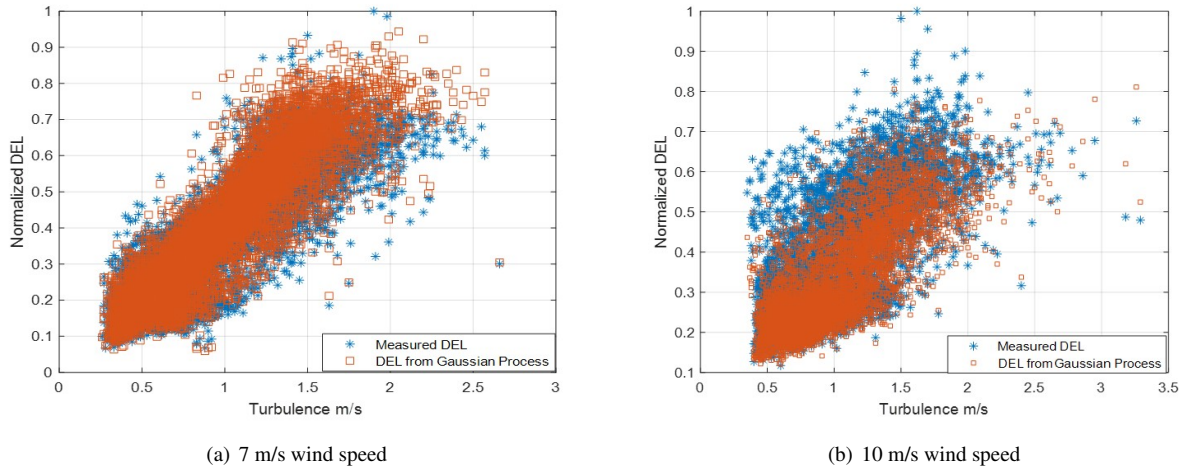



Figure 8. Comparison of the 10-minute blade root flap bending damage equivalent moments between the Gaussian process method and measurement data on the C-08 turbine.

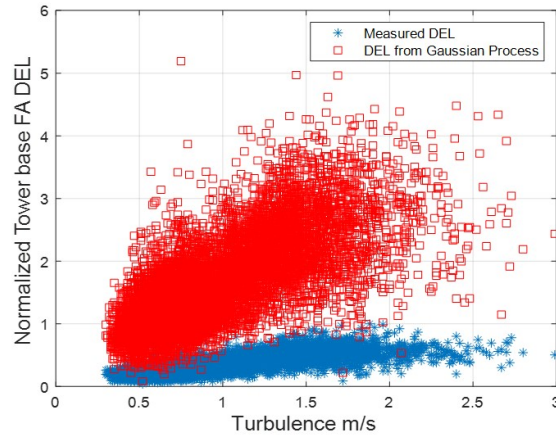



Figure 9. Comparison of the 10-minute Tower base fore-aft damage equivalent moment with measurements at 7 m/s using the Gaussian process method without Vanmarcke correction

damage equivalent moment, then as seen in Fig. 9, the tower base fore-aft DELs are greatly amplified in comparison to the measured DELs. This is due to the significant aerodynamic damping, that is not considered in Eq. (4).

The Vanmarcke correction in the limit that $\alpha - > 1$ provides the bandwidth for a highly damped system. Figure 10 provides
240   the same comparison for the tower base fore-aft damage equivalent moment, with the Vanmarcke correction and now a very good match between the DELs computed with this methodology and the measured DELs is seen.

(a) 7 m/s wind speed   (b) 10 m/s wind speed

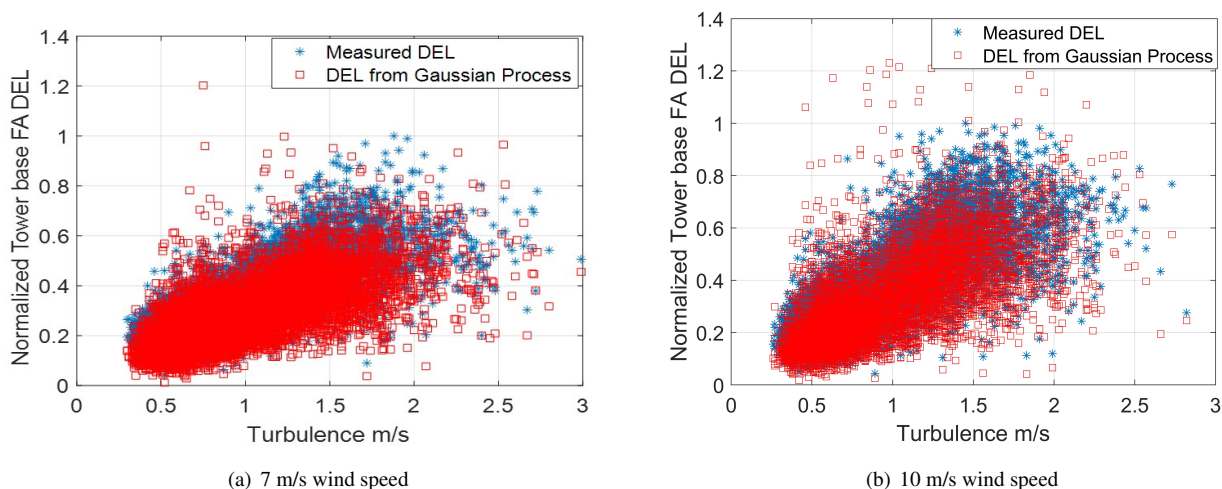



Figure 10. Comparison of the 10-minute tower base fore-aft bending damage equivalent moments between the Gaussian process method and measurement data on the C-08 turbine.

The matching comparisons in Figs. 8 and 10 imply that the results from the GPA can be sampled to also perform a stochastic extrapolation of the DEL magnitudes to obtain a one-year DEL value or even to higher return periods. Considering the computation speed of the Gaussian process analysis, it is also possible to directly simulate multi-year damage equivalent moments.

245   Figure 11 displays the extrapolated one year DEL values for the blade root and tower base with the GPA as compared to measurements using a few samples used to fit the 3-parameter Weibull CDF. Since under normal measurements, the results of GPA tally well with measured DELs for the blade and tower, this method can also be used to detect anomalous wind turbine operation, wherein DEL values that are significantly away from the predictions by GPA are measured. This can happen, for example if there is tower resonance with the rotor rotational speed or if there is shut-down of the turbine under high turbulence

250   or other uncommon events.

Based on this method, the extrapolated simulated DEL magnitudes (also using simulated std. deviations) should display higher DEL values for the same probability of exceedance as compared to the extrapolated measured DEL values, in which case the structural integrity of the turbine structure is not compromised. This allows a direct quantification of the life consumption of the turbine structures in a farm if the certification design loads of the turbines in question are available, so that the relative

255   difference in the DEL magnitudes with the actual inflow conditions is obtained. Without such an extrapolation, the probability of obtaining DEL magnitudes higher than the design DEL magnitudes is not known and therefore the extrapolation of DEL is a necessary procedure.

| | (a) Blade Root | | (b) Tower base |

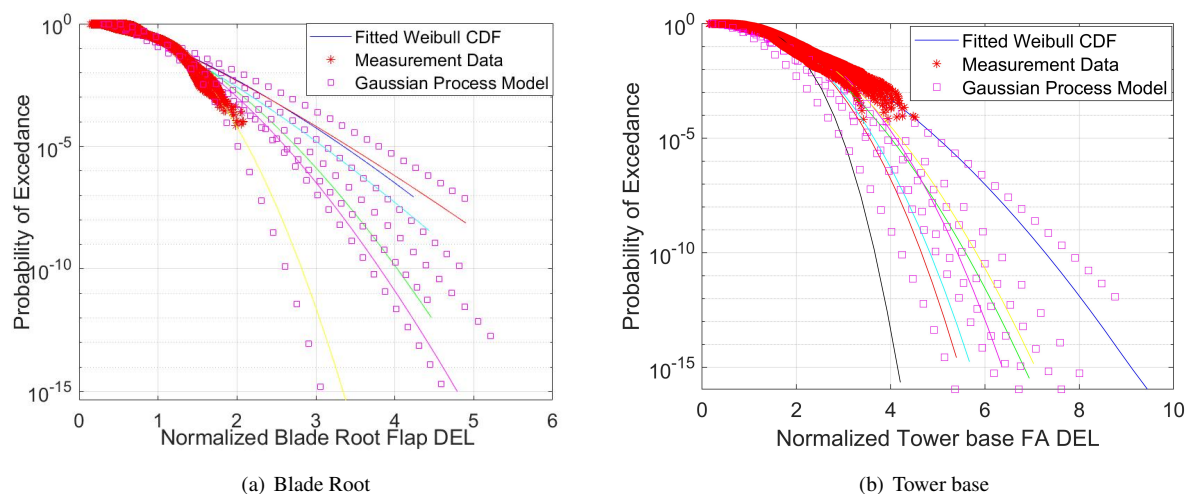



Figure 11. Comparison of the 10-minute extrapolated blade root flap damage equivalent moment and tower base fore-aft damage equivalent moment using the Gaussian process method and measurement data on the C-08 turbine.

5   Conclusions

Methodologies for computing DELs over multiple years and determining the probability of exceedance of DEL magntiudes
were developed and validated using measurements from the Lillgrund wind farm. The synthesis of DELs using available
mean and standard deviation of the loads was presented and validated for the blade root flap moment and tower base fore-
aft moment. This provides a fast methodology to simulate the DELs for long duration without loss of accuracy. Different
approaches for narrow-band processes (blade flap) and very narrow-band processes (tower base fore-aft) were delineated and
shown to also be useable as data sets for stochastic extrapolation to determine probabilities of exceedance. A suitable indicator
to verify structural integrity of the turbine structure was proposed as the magnitude of the DEL at the one-year probability of
exceedance, based on past measurements and compared to the corresponding DEL magnitude in the design basis. The process
of structural integrity verification was shown and quantified through the comparison of extrapolated DELs from measurements
obtained from a single turbine with the corresponding extrapolated DEL magnitudes using simulation results. The capability to
synthesize DELs from 10-minute load statistics also allows ease of storage of multi-year data, without the need for time-series
analysis. The combined methods of synthesis of DELs and stochastic extrapolation allow forecasting damage into the future
and can be used as a decision making tool to implement wind farm control methods that either reduce loads or increase power
production, based on the need.

Author contributions.

Conceptualization, Development of methodology, implementation, validation, writing-review and editing.

275 *Competing interests.*

The author declares that there are no conflicts of interest in this article.

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References

280   Barber, S., Mechler, S., and Nitschke, M.: The effect of wakes on the fatigue damage of wind turbine components over their entire lifetime using short-term load measurements, Journal of Physics: Conference Series, 753, 2016.

Cramer, H. and Leadbetter, M.: Stationary and Related Stochastic Processes, John Wiley Sons Inc, New York, 1967.

Dimitrov, N. and Natarajan, A.: Wind farm set point optimization with surrogate models for load and power output targets, Journal of Physics: Conference Series, 2021.

285   Dimitrov, N. K., Natarajan, A., and Mann, J.: Effects of normal and extreme turbulence spectral parameters on wind turbine loads, Renewable Energy, 101, 1180–1193, https://doi.org/10.1016/j.renene.2016.10.001, 2017.

Gallinos, C., Dimitrov, N., Larsen, T., Natarajan, A., and Hansen, K.: Mapping Wind Farm Loads and Power Production – A Case Study on Horns Rev 1, Journal of Physics: Conference Series, 753, 2016.

Hoole, J., Sartor, P., Booker, J., Cooper, J., V, X., Gogouvitis, and Schmidt, R. K.: Systematic statistical characterisation of stress-life datasets
290   using 3-Parameter distributions, International Journal of Fatigue, 129, 2019.

Hübler, C., Gebhardt, C. G., and Rolfes, R.: Methodologies for fatigue assessment of offshore wind turbines considering scattering environmental conditions and the uncertainty due to finite sampling, Wind Energy, 21, 1092–1105, 2018a.

Hübler, C., Weijtjens, W., Rolfes, R., and Devriendt, C.: Reliability analysis of fatigue damage extrapolations of wind turbines using offshore strain measurements, Journal of Physics: Conference Series, 1037, 2018b.

295   IEC: International Standard IEC61400-1: Wind Turbines - Part 1: Design Guidelines, 2019.

Larsen, T. J. and Hansen, A. M.: How to HAWC2, the user's manual, Tech. Rep. R-1597, Technical University of Denmark, Department of Wind Energy, 2012.

Madsen, H., Krenk, S., and Lind, N.: Stationary and Related Stochastic Processes, Prentice Hall, Englewood Cliffs, NJ, 1986.

Miner, M. A. et al.: Cumulative damage in fatigue, Journal of applied mechanics, 12, 159–164, 1945.

300   Munters, W. and Meyers, J.: Dynamic Strategies for Yaw and Induction Control of Wind Farms Based on Large-Eddy Simulation and Optimization, Energies, 11, 177–190, 2018.

Natarajan, A. and Verelst, D. R.: Outlier robustness for wind turbine extrapolated extreme loads, Wind Energy, 15, 679–697, 2012.

Ragan, P. and Manuel, L.: Comparing Estimates of Wind Turbine Fatigue Loads using Time-Domain and Spectral Methods, Wind Engineering, 31, 2007.

305   Vanmarcke, E.: On the distribution of the first-passage time for normal stationary random processes., Journal of Applied Mechanics, 42, 215–220, 1975.