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Assessment of a standard ULS design procedure for offshore wind turbine sub-structures

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Abstract. Sub-structures of offshore wind turbines are designed according to several design load cases (DLCs) that cover various fatigue (FLS) and ultimate limit states (ULS). The required DLCs are given in the current standards, and are supposed, on the one hand, to cover accurately all significant load conditions to guarantee reliability. On the other hand, they should include only necessary conditions to keep computing times manageable. For ULS conditions, the current work addresses the question whether the current design practice is, firstly, sufficient, and secondly, sensible concerning the computing time by only including necessary DLCs. To address this topic, data of five years of normal operation, simulated using a probabilistic approach, is used to extrapolate 20-year ULS loads (comparable to a probabilistic version of DLC 1.1 for sub-structures). These ULS values are compared to several deterministic DLCs required by current standards. Results show that probabilistic, extrapolated ULS values are fairly high and exceed standard DLC loads. Hence, the current design practice might not always be conservative. Especially, the benefit of an additional DLC for wave peak periods close to the eigenfrequency of the sub-structure is indicated.

1. Introduction

Offshore wind energy is an important, growing market to achieve the global targets of reducing greenhouse emissions. However, costs of offshore wind energy are still quite high, and therefore, it is not really competitive [1]. As sub-structures of offshore wind turbines (OWTs) make up about 20 % of the capital costs [2], it is necessary to develop optimised and reliable designs to minimise costs. Hence, design requirements for OWTs, given by current standards [3], should include DLCs for FLS and ULS that, on the one hand, accurately cover all important load conditions to guarantee reliability. On the other hand, insignificant conditions should be excluded to keep computing times moderate and to make optimisations possible. For sub-structures, FLS is design driving in most cases. Nevertheless, as turbines are built in increasingly harsher environmental conditions (ECs) and as weather conditions tend to become more extreme, the consideration of ULS loads is a topic of increasing relevance, and is the focus of this work.

The required DLCs for ULS design can be loosely divided into three categories: extrapolated 50-year values from normal operation (DLC 1.1), ULS loads from extreme ECs with a recurrence period of 50 years (e.g. DLC 6.1), and fault cases and controller actions (e.g. DLC 2.1). The last category highly depends on the controller and the specific design making general conclusions nearly impossible. Typically they are not design driving, or even if they are, special treatment is needed, which is out of the scope of the present work. Furthermore, this category includes

many highly transient manoeuvres involving moderate geometric non-linearities. Accurate simulations of transient manoeuvres are problematic for most state-of-the-art models [4]. Hence, as common in academia [5], these cases are not analysed in detail here. Surely, this is a simplification, and for real design purposes, DLCs of this category have to be investigated separately using the specific control algorithms. For the second category - extreme ECs - there is a lot of ongoing work identifying the most important DLCs for OWTs [6, 7]. Concerning the load extrapolation, for onshore wind turbines, over the last few years, there has been an extensive discussion on different extrapolation methods [8, 9, 10] and improved sampling methods in order to avoid extrapolation [11]. Still, all proposed methods have their shortcomings or risks as recently demonstrated by van Eijk et al. [12]. Furthermore, for OWTs, additionally exposed to wave loads, investigations concerning extrapolated ULS loads are limited. Some rare examples are Agarwal and Manuel [13, 14], while the extrapolation is partly based on limited field data [13]. The shortage of research for OWTs might be a result of a missing DLC for extrapolated ULS loads for sub-structures. Starting from this missing DLC for the sub-structure, the question arises whether the current DLCs [3] are adequate to guarantee efficient and reliable designs of OWTs. Is it possible to reduce the number of DLCs to limit computing time, or should additional DLCs - like the extrapolation one or a DLC for wave resonance - be included? Hence, in this work, a standard ULS design procedure [3] is assessed.

To address this topic, a probabilistic version of DLC 1.1 (ULS extrapolation) for sub-structures is compared to several deterministic DLCs for extreme ECs. Thus, for the NREL 5 MW OWT on a monopile sub-structure, 5 years of normal operation (power production and idling conditions, no fault cases, start-ups, etc.) are simulated using a probabilistic approach and the aero-elastic FASTv8 code. The probabilistic approach takes not only different stochastic realisations for turbulent wind and irregular waves (random seeds) into account. Additionally, ECs like wind direction, turbulence intensity, and wave peak period are varied according to their own correlated statistical distributions. Statistical distributions are derived using real offshore measurement data [15]. This enables a quite realistic representation of several years of operation. Subsequently, the 5-year ULS values are extrapolated to 20 years of OWT lifetime using the maximum values of all simulations (MAX extrapolation). Subsequently, the probabilistic approach is compared to several deterministic DLCs with extreme ECs. For these DLCs, ECs are extrapolated to 50-year values.

2. Simulation setup

2.1. Environmental conditions

For both ULS approaches in this work (probabilistic extrapolation and deterministic DLCs), environmental conditions are needed. In case of a probabilistic load extrapolation, statistical distributions of the most relevant parameters are needed, whereas for the DLC-based approach, extreme values of the environmental inputs are necessary. For the FINO3 measurement mast in the North Sea - being operated on behalf of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) - high quality data of several years is available[1]. This data includes, inter alia, precise measurements for wind speed and direction, water level, and wave height, period and direction. Furthermore, turbulence intensities, wind shear exponents, and ocean current speeds can be calculated using the available information. Statistical distribution were derived and are published by Hübler et al. [15]. Therefore, FINO3 data is used in this study. For the probabilistic approach, the distributions of Hübler et al. [15] are applied. For the DLC-based approach, extreme values are derived using the same data. Details of the extreme value calculation are given in Section 3.1. For more information concerning

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[1] Raw data of the FINO3 platform is freely available for research purposes. See `http://www.fino3.de/en/` for details.

the data and the statistical distributions, it is referred Hübler et al. [15].

2.2. Wind turbine model

For all time domain simulations - conducted in this work - the aero-servo-hydro-elastic simulation framework FASTv8 [16] of the "National Renewable Energy Laboratory" (NREL) is used. A soil model that applies soil-structure interaction matrices [17] enhances the FASTv8 code. The required soil matrices are based on non-linear spring models that are linearised at operating conditions [18]. Soil conditions of the OC3 phase II model [19] are assumed.

The NREL 5 MW reference wind turbine with the OC3 monopile as sub-structure [19] is investigated. The simulation length is set to 10 minutes according to current standards [3] and findings in Hübler et al. [15]. The "run-in" time (i.e. the time that has to be removed from each time series to exclude initial transients) is set to 30 seconds. According to Hübler et al. [15], this "run-in" time should be sufficient for ULS simulations (and the present simulation setup), if initial conditions - e.g. for the rotor speed - are used, which is done in this study. The turbulent wind field is calculated using the Kaimal model, and the JONSWAP spectrum is applied to compute irregular waves.

2.3. ULS analysis

For the ULS analysis, maximum stresses are decisive. These stresses are extracted from the time series that are the results of the time domain simulations using FAST. Several limit states are taken into account. For the monopile, Eurocode 3, part 1-6 [20], is used to analyse the plastic limit state, cyclic plasticity limit state, and buckling limit state (LS 1-3). The yield stress is set to 355 MPa. Additionally, ULS proofs for the foundation piles are performed including axial and lateral soil proofs according to GEO2 [21] and a plastic limit state proof (LS 1) for the steel pile below mudline. Especially the last proof can be decisive, as the bending moment frequently reaches its maximum below mudline. For all ULS proofs, for different locations, utilisation factors (UF), being the percentage of the maximum allowed loads, are the outcomes. The highest UF of all locations is considered to be pivotal. Ageing or plastic effects are neglected.

3. ULS calculation

3.1. DLC-based approach

According to current standards, the ULS design is based on several deterministic DLCs. Some of the most important DLCs for sub-structures focus on extreme ECs. In this work, a probabilistic approach, presented in the next section, is compared to five different deterministic DLCs, all based on extreme ECs. These DLCs are summarised in Table 1, and resemble DLCs in current standards [3].

For each DLC, raw data is used to derive the necessary conditions summarised in Table 1. These conditions can be extreme values (i.e. 50-year extremes (x_{50})), dependent "extreme" values ($x_{50|y}$), mean values ($\bar{x}$), or dependent mean values $\bar{x}_{|y}$. The general procedure consists of three steps:

1) Select raw data (extreme values or dependent values)
2) Fit a distribution to the data if necessary
3) Calculate the required values (mean value, 1-year extreme, 50-year extreme)

Table 1. Deterministic DLCs (Wind speed (v_s), turbulence intensity (TI), wind shear exponent (α), wave height and period (H_s, T_p), wind-wave misalignment ($\Delta\theta$), yaw error (Ψ), near and sub-surface current velocity (v_{ns}, v_{ss}), sea level above mean sea level (Δ_{sl}))

Event	DLC	v_s $\mathrm{m\,s^{-1}}$	TI -	α -	H_s m	T_p s	$\Delta\theta$ °	Ψ °	v_{ns} $\mathrm{m\,s^{-1}}$	v_{ss} $\mathrm{m\,s^{-1}}$	Δ_{sl} m
50-year storm	6.1	v_{s50} 40.2	$\mathrm{TI}_{50\|v_s}$ 0.128	$\bar{\alpha}_{\|v_s}$ 0.127	$H_{s50\|v_s}$ 11.3	$T_{p50\|v_s}$ 14.1	- 0	- 8	v_{ns50} 4.10	v_{ss50} 3.40	Δ_{sl50} 2.90
1-year storm	6.3	v_{s1} 28	$\mathrm{TI}_{1\|v_s}$ 0.0939	$\bar{\alpha}_{\|v_s}$ 0.127	$H_{s1\|v_s}$ 5.95	$T_{p1\|v_s}$ 11.2	- 0	- 20	v_{ns1} 2.44	v_{ss1} 1.95	Δ_{sl1} 1.50
Extreme turbulence	1.3	$\bar{v}_s$ 3-25	TI_{50} $f(v_s)$	$\bar{\alpha}$ $f(v_s)$	$\bar{H}_s$ $f(v_s)$	$\bar{T}_p$ $f(v_s)$	$\overline{\Delta\theta}$ $f(v_s)$	- 8	$\bar{v}_{ns}$ 0.441	$\bar{v}_{ss}$ 0.285	$\bar{\Delta}_{sl}$ 0
Extreme wind shear	1.5	$\bar{v}_s$ 3-25	$\overline{\mathrm{TI}}$ $f(v_s)$	α_{50} $f(v_s)$	$\bar{H}_s$ $f(v_s)$	$\bar{T}_p$ $f(v_s)$	$\overline{\Delta\theta}$ $f(v_s)$	- 8	$\bar{v}_{ns}$ 0.441	$\bar{v}_{ss}$ 0.285	$\bar{\Delta}_{sl}$ 0
Extreme sea state	1.6	$\bar{v}_s$ 3-25	$\overline{\mathrm{TI}}$ $f(v_s)$	$\bar{\alpha}$ $f(v_s)$	H_{s50} $f(v_s)$	$T_{p50\|H_s}$ $f(v_s)$	$\overline{\Delta\theta}$ $f(v_s)$	- 8	$\bar{v}_{ns}$ 0.441	$\bar{v}_{ss}$ 0.285	Δ_{sl1} 1.50

The 50-year storm (DLC 6.1) and three ECs (wind speed, turbulence intensity, and wind shear exponent) are used as an example to explain the procedure in detail:

Starting with the independent variable, a wind speed with a recurrence period of 50 years has to be determined (v_{s50}). In step 1), extreme value data is required. In this work, all extreme values are based on 4-week maxima that are directly extracted from the data (see Figure 1). 4-week maxima are chosen according to Schmidt et al. [22]. As discussed by Schmidt et al. [22], this period could be chosen differently. However, too long periods (e.g. one year) lead to too few data points to accurately fit distributions. Too short periods (e.g. one day) include many non-extreme values and cannot guarantee independent maxima. For the chosen 4-week maxima, a minimum time lag of 3.5 days between two maxima is used to guarantee independent peaks, while a maximum storm duration of 7 days is assumed. In step 2), different statistical distributions are fitted to the 4-week maxima using a maximum likelihood estimation. Theoretically, for an infinite number of extracted maxima, the maxima should follow a generalised extreme value (GEV) distribution. However, it has been shown before that GEV distributions can be conservative and other distributions - without theoretical justification - enable more accurate fits of extreme values [23]. That is why visual inspections and Kolmogorov-Smirnov tests (KS tests) are utilised to select the best fitting distributions (e.g. extreme value distribution for wind speeds, but Normal distribution for turbulence intensities). Having determined a statistical distribution, in step 3), values corresponding to a recurrence period of 50 years can be determined (see Figure 2):

$$x_{50} = P^{-1}\left(1 - \frac{4}{52 \times 50}\right) = P^{-1}\left(1 - 1.54 \times 10^{-3}\right), \tag{1}$$

where P^{-1} is the inverse cumulative distribution function.

For dependent "extreme" values (e.g. turbulence intensity), the procedure is slightly different. The explanation is that for a 50-year storm, the turbulence intensity will not be its 50-year extreme (TI_{50}), as this extreme value will occur at lower wind speeds. Hence, an "extreme" turbulence intensity given a 50-year wind speed ($\mathrm{TI}_{50\|v_s}$) has to be used. This means that for step 1), no 4-week maxima are selected, but values that occur simultaneously to the 4-week wind speed maxima (see Figure 1). This yields turbulence intensities that occur for high wind speeds, but not extreme turbulence intensities occurring at lower wind speeds. Having the raw data, step 2) and 3) are the same as before. Hence, various distributions are fitted to the data
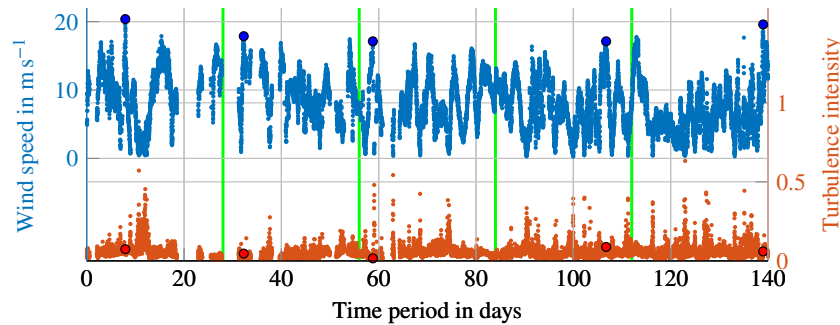
Figure 1. Wind speed and turbulence data of 24 weeks. 4-week periods are marked with vertical lines. Selected peaks for the wind speed and the simultaneously occurring values of the turbulence are highlighted.
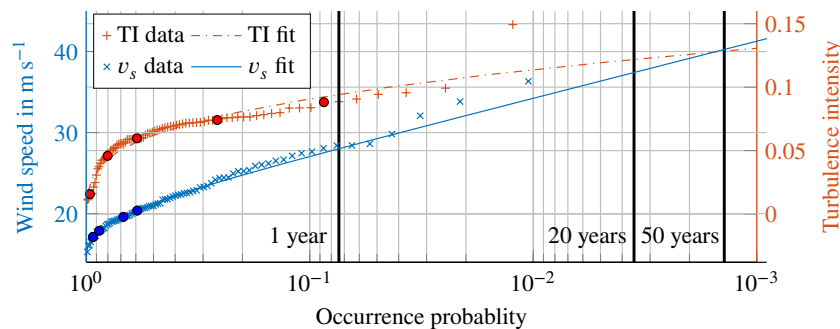

Figure 2. Extrapolation of 50-year wind speeds and the depending turbulence values. Highlighted data points of Figure 1 are marked again. An extreme value fit for the wind speed and a normal fit for the turbulence intensity is applied.

and a 50-year value is extrapolated. The usage of extrapolated dependent "extreme" values or dependent mean values is discussed later on.

Lastly, for dependent mean values (e.g. wind shear exponent), in step 1), the simultaneously occurring values are used again. Step 2) is not needed, as in step 3), the mean value of all selected values is calculated.

The decision whether ECs are dependent "extreme" values or mean values is quite challenging and cannot answered with certainty in all cases. In this context, it is useful to investigate whether the dependent values follow a clear trend (i.e. are correlated with the independent values). On the one hand, for turbulence intensities occurring simultaneously to 4-week wind speed maxima, increasing turbulence intensities for higher wind speed maxima can be found. On the other hand, for wind shear exponents, such a correlation does not exist being the reason for using the dependent mean value.

Having this explanation in mind, the determination of dependent "extreme" values is slightly conservative. If there is a complete correlation between independent and dependent variables (i.e. correlation coefficient of one or minus one), the applied extrapolation for dependent "extreme" values is completely correct. In all other cases, it is more or less unlikely that the 50-year wind speed (independent variable; x_{50}) occurs together with the 50-year value of the dependent turbulence intensities ($x_{50|y}$). However, the usage of the mean value of the dependent turbulence intensities ($\bar{x}_{|y}$) is only correct for completely uncorrelated parameters (i.e. correlation coefficient of zero). In all other cases it is more or less non-conservative.

For all extracted peaks of the independent variable, in this work, only the results of an ordinary maximum extrapolation based on 4-week maxima are shown. Other extrapolation techniques, like a peak-over-threshold (POT) extrapolation, lead to slightly different results (not shown) which might be more accurate. However, in most cases, the maximum method is the most conservative one. Hence, if the probabilistic ULS values exceed the present DLC-based loads (being relatively conservative, as they are determined using the maximum method), the probabilistic ULS values will be higher for all extrapolation methods.

Finally, it has to be mentioned that for the first two events (50 and 1-year storm), an idling turbine is simulated. For the latter three cases, operating turbines are used. Furthermore, the 50-year values for these three parameters are a function of the wind speed, and it is not obvious which wind speed leads to the highest loads. Therefore, for these three DLCs, various 50-year values for wind speeds between 3 and $25\,\mathrm{m\,s^{-1}}$ are simulated ($f(v_s)$ in Table 1). For example, in DLC 1.3, for $3\,\mathrm{m\,s^{-1}} \le v_s < 5\,\mathrm{m\,s^{-1}}$, $\mathrm{TI}_{50} = 0.66$, while for $9\,\mathrm{m\,s^{-1}} \le v_s < 11\,\mathrm{m\,s^{-1}}$, $\mathrm{TI}_{50} = 0.36$. For each DLC, 100 simulations are conducted to cover the stochastic nature of turbulent wind and irregular waves. As the present DLCs are already extreme values (e.g. 50-year storm), the mean value of the 100 simulations is used.

3.2. Probabilistic approach

A possible alternative to the deterministic DLC-based approach that takes scattering conditions into account is a probabilistic or sampling based simulation approach. The necessary steps for this probabilistic approach are the following:

1) For each sample, the wind speed is determined according to the corresponding Weibull distribution (c.f. Hübler et al. [15]).

2) If the wind speed is below cut-in or above cut-off, idling conditions are assumed. Otherwise, an operating turbine is simulated.

3) Wind direction, turbulence intensity, wind shear exponent, and significant wave height are determined using their statistical distributions, while the distributions themselves depend on the selected wind speed.

4) Wave peak period and wave direction are calculated, while their distributions depend on the previously determined wave heights and wind directions.

Hence, this probabilistic simulation procedure makes use of ECs being computed according to their occurrence probability. It resembles the "probability sorting method" of Stewart [24] (sampling according to the probability of occurrence), but does not rely on previously defined bins, and includes some random effects.

Ideally, the full 20-year lifetime would be simulated. However, this is computationally really demanding (nearly six months on 64 cores: 8x Intel Haswell Xeon E5-2630 v3 (8-cores, 2.40GHz, 20MB Cache, 85W)). Therefore, in this work, the probabilistic approach is used to simulate five years of realistic lifetime (computing time of about 1.5 months). This means: About 250,000 samples are generated according to their statistical distributions, and subsequently, for all samples, time domain simulations are conducted. The maximum UF of each simulation is taken. This enables an realistic approximation of 5-year ULS loads (see Figure 3). However, as discussed before, only power production and idling conditions are simulated. Fault cases, start-up, etc. are not taken into account.

Finally, an extrapolation of the 5-year value to 20 years of operation is possible by fitting statistical distributions to the extracted peaks (maximum UFs of each simulation). This fit is achieved by applying a maximum likelihood estimation and only considering the highest - second half of the data in logarithmic scale - UFs (tail fitting). The distribution of the determined maxima of all samples, and the load extrapolation is visualised in Figure 3. Other extrapolation techniques, like POT or ACER [25], are possible and might lead to better approximations.
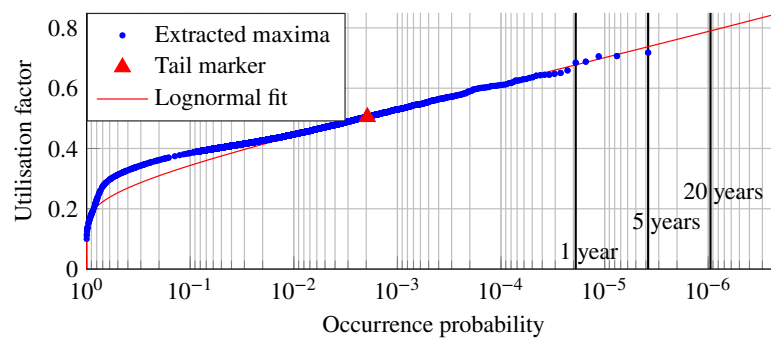
Figure 3. Maximum UFs of all simulations (5 years): lognormal tail fit and 20-year extrapolation.

However, as discussed in the next section, the main findings are independent of the extrapolation approach. Hence, a ordinary MAX extrapolation is sufficient.

4. Results

Resulting ULS loads, computed using the two approaches presented in Section 3, are now shown and discussed. At first, the DLC-based results are regarded in some more detail. As discussed before, for DLC 1.3 to 1.6, it is not obvious which wind speed leads to the highest UF. Therefore, in Figure 4, the mean UFs - of 100 simulations - for all wind speeds and DLC 1.3 are shown as an example. The maxima of the 100 simulations are indicated as well. For increasing wind speeds, the extrapolated 50-year turbulence values reduce. Therefore, the highest loads are not expected for wind speeds close to cut-off, but for wind speeds above rated at about $18\,\mathrm{m\,s^{-1}}$. This is in accordance with previous results for onshore tower bending moments [26].

In Figure 5, the DLC-based approach is compared to the probabilistic one. For DLC 1.3 to 1.6, only the highest values are shown. For the probabilistic approach, 1-year, 5-year, and 20-year values are displayed. The 5-year value is the maximum UF of all simulations (maximum of $6 \times 24 \times 365.25 \times 5 = 262,980$ ten-minute simulations). The 1-year value is the result of 10,000 bootstrap iterations using all UFs. This means that $6 \times 24 \times 365.25 = 52,596$ UFs are dawn (with replacement) out of the 262,980 available samples. This procedure is repeated 10,000 times and yields a statistical distribution of 1-year values. Hence, bootstrapping allows an estimation of the uncertainty of the 1-year value. The standard deviation of the 1-year value distribution (determined using bootstrapping) is marked as well. The 20-year value is the result of the load extrapolation (see Figure 3). Again, 10,000 bootstrap iterations are used, i.e. the extrapolation is repeated 10,000 times. Each extrapolation is based on 262,980 samples (5 years) that are drawn with replacement. This leads to a distribution of extrapolated 20-year values. The standard deviation of the 20-year value distribution is marked as well.

It becomes apparent that the probabilistic approach leads to the highest ULS loads. As these loads already exceed the ULS values of the DLC-based approach for the 5-year value, this fact is independent of the applied extrapolation technique. Hence, a probabilistic assessment of ULS loads during power production is valuable.

Nevertheless, the question arises: What are the physical reasons for the high ULS loads of the probabilistic approach? To answer this question, a closer look at the highest UFs is helpful. Most of the extreme UFs occur at wave peak periods of around 4 s (see Figure 6). This wave period is close to the resonance frequency of the sub-structure (0.25 Hz). From reliability theory, it is well-known that it is challenging to correctly handle load combinations. This fact is especially pronounced, if the highest loads do not occur for combinations of extreme ECs (being the case for wave periods). Consequently, the probabilistic approach reveals the fact that
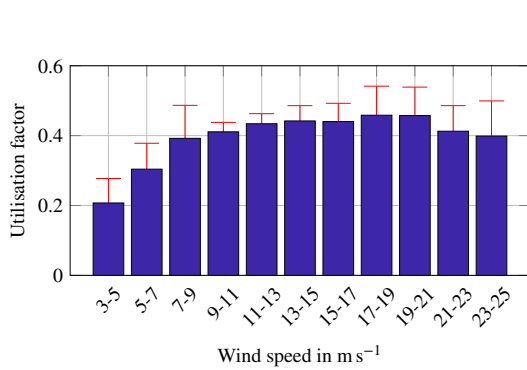
Figure 4. Mean UFs for different wind speeds and DLC 1.3 (extreme turbulence). Error bars indicate maximum values.
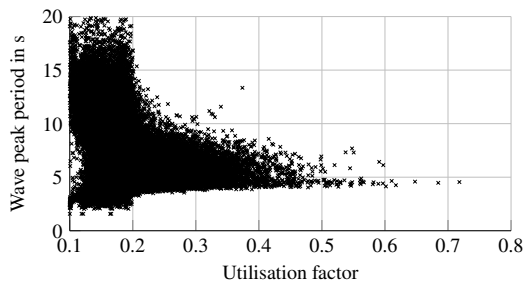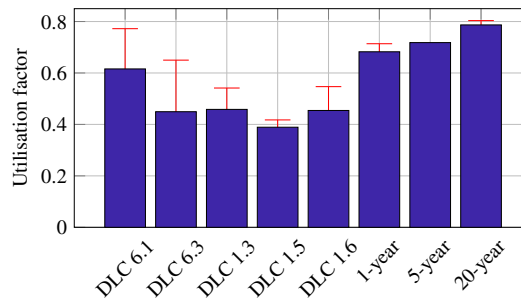

Figure 5. Comparison of UFs for the DLC-based approach and the probabilistic concept. Bars indicate mean values; error bars maximum values for the DLC-based approach, and a single standard deviation for the 1 and 20-year values.
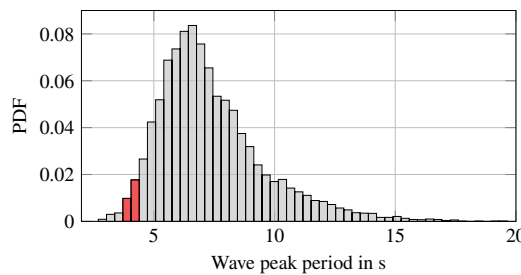

Figure 6. Investigation of high UFs for the probabilistic approach: T_p correlation. Each cross symbolises a 10-minute simulation.

Figure 7. PDF of wave peak periods for $11\,\mathrm{m\,s^{-1}} < v_s < 13\,\mathrm{m\,s^{-1}}$. Region of potential wave resonance is marked.

wave resonance in combination with wave heights significantly greater than zero might be an important load combination for monopiles with medium to large diameters. This wave resonance load combination is not covered sufficiently by the DLC-based approach, as deterministic wave periods are assumed that are normally far of the eigenperiod. Hence, the rare but important load combination of wave periods close to the resonance frequency (see Figure 7) combined with higher waves is neglected.

5. Conclusion and outlook

The current work compares deterministic standard DLCs for the ULS calculation to a probabilistic simulation approach that resembles a realistic turbine lifetime. The results show that - independent of the load extrapolation method - probabilistic (extrapolated) ULS values are fairly high mainly due to wave resonance effects. These loads exceed the deterministic 50-year ULS loads of the standard DLCs. Therefore, it can be assumed that for sub-structures the current DLCs (excluding fault cases, etc.) are not always conservative. The extrapolation of loads in power production - not required by standards for sub-structures - can lead to higher loads, if a probabilistic approach is applied. This results from many unfavourable load combinations like wave peak periods close to the eigenperiod of the structure that are covered by this approach, but are not sufficiently considered by the standard DLCs. However, it has to

be mentioned that the utilised FASTv8 model, though it is a state-of-the-art model, is simplified and partly linearised (e.g. linear beam theory), which might lead to inaccurate simulation results for example for transient manoeuvres or occurring plasticity. That is why some results might be influenced by existing model errors.

The practical implication is that a reconsideration of DLCs might be valuable, in the long term. On the one hand, some load cases can perhaps be removed, as they are unnecessary. Others, like a DLC for wave resonance problems, might be missing. Especially for low eigenfrequencies (new, bigger monopiles for 10 MW turbines or floating OWTs), wave resonance might become more relevant. For these types of structures, the use of a standard DLC-based approach might lead to major damages of the sub-structure, since current safety margins can possibly not cover the neglected load cases. On the other hand, here, only loads of the sub-structure are considered. Some of the "unnecessary" DLCs are important for other turbine components. Furthermore, only numerical results including model errors for one structure and no fault cases, etc. are investigated. Hence, an exclusion of DLCs would be premature. Nevertheless, a detailed analysis of ULS loads due to wave resonance and during (probabilistic) power production should be conducted in order to investigate the relevance of these effects and to guarantee safe design without major failures.

Acknowledgments

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