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Methodology for estimating offshore wind turbine fatigue life under combined loads of wind, waves and ice at sub-zero temperatures

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Abstract

Due to increasing trend of building offshore wind turbines (OWTs) in seas at high latitudes where seasonal sea ice occurs, novel methods for design of such structures are needed. Specifically, the effect of ice-induced vibrations (IIVs) on fatigue life of the structures is currently poorly understood. Therefore, the goal of this paper is to analyze the current state-of-the-art approach for estimating the ice loads contribution to the fatigue life of OWTs and identify the current knowledge gaps. Moreover, the paper proposes a methodology for developing a combined load spectrum of wind, waves and ice using numerical simulations, with an ultimate goal to develop applicable Gaßner curves characterizing the variable-amplitude nature of the loading pattern. Finally, the use of small-scale fatigue tests under sub-zero temperatures in order to develop the appropriate S-N and Gaßner curves is discussed.

Keywords: Fatigue life of OWT; Fatigue tests; Ice-induced vibrations; Low-temperature fatigue; Variable-amplitude loading

Nomenclature

CAL	Constant-amplitude loading	D	Fatigue damage sum [-]
CFD	Cumulative frequency distribution	D_{real}	Realistic damage sum [-]
FLS	Fatigue limit state	D_{spec}	Damage sum for one sequence [-]
FTT	Fatigue transition temperature	f_{exc}	Exceedance frequency [-]
IIV	Ice-induced vibrations	k	Scaling factor for VAL tests [-]
LC	Load case	L_{s}	Spectrum size [-]
OWT	Offshore wind turbine	n	Number of occurring cycles [-]
SGRE	Siemens Gamesa Renewable Energy	N	Number of cycles to failure [-]
TUHH	Hamburg University of Technology	N_{exp}	Num. of cycles to failure in VAL tests [-]
VAL	Variable-amplitude loading	S	Number of stress range classes [-]
WASH	Wave action standard history	t	Time [s]
		σ	Stress [MPa]
		σ_{a}	Stress amplitude [MPa]
		σ_{max}	Maximal stress amplitude [MPa]
		$\Delta\sigma$	Stress range [MPa]

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1. Introduction

The concept of *sustainable development*, universally accepted amongst the developed countries, constantly increases the global demand for *green energy* coming from renewable sources. Therefore, as the new technologies are invented, also the traditional ones are being improved with their range of applicability extended. One of the oldest known sources of renewable energy is the wind power. From the late 19th century, when the first windmill used for the production of electric power was built, until today's modern wind turbines, the technology of harnessing the power of wind constantly improved, and the amount of installed capacity grew exponentially. In the recent years, the focus of the wind power industry has shifted from onshore to offshore wind farms. This is due to the fact that the offshore winds are stronger and steadier, with offshore installations also having a lesser visual impact on the landscape.

The offshore wind turbines (OWTs) have traditionally been built in seas with little or no seasonal sea ice, and therefore the main structural loads came from the wind and waves. However, as the amount of installed power increases, the offshore wind farms are expanding to the waters with significant amounts of seasonal sea ice, such as the Northern Baltic Sea or Bohai Sea. Therefore, the effect of sea ice needs to be taken into account when designing the structural components of OWTs.

Design of OWTs is mainly governed by IEC61400 standard, which in reference to ISO19906 also defines the ice loading. This mainly focuses on static ice loads due to the nature of Arctic oil and gas structures which are the focus of ISO19906. However, contrary to these, design of OWTs is significantly driven by fatigue strength. When it comes to calculating the fatigue damage (Igwemezie et al., 2019), estimates of site-specific wind and wave loading cycles can be derived based on metocean data. The sea ice contributes to the fatigue damage through ice-induced vibrations (IIVs). The IIVs occur as the ice crushes against the structure (Ye et al., 2019; Zhang et al., 2018; Hendrikse, 2017), which is a typical ice failure mode for vertically sided offshore structures including monopile foundations of OWTs. However, the contribution of IIVs to the fatigue damage is currently poorly understood and modeled using numerous simplifications.

Therefore, the goal of this paper is to analyze the current state-of-the-art approach for estimating the ice loads contribution to the fatigue life of OWTs and identify the current knowledge gaps (Section 2). Furthermore, a methodology for developing a combined load spectrum of wind, waves and ice for OWTs is proposed (Section 3). Moreover, small-scale fatigue tests at sub-zero temperatures based on the presented methodology are discussed (Section 4). Finally, Section 5 concludes the paper.

2. Current procedures for estimating the ice loads contribution to the fatigue life of OWTs

The current approach for estimating the ice loads contribution to the fatigue life of OWTs is based on the occurrence of load cycles with a certain magnitude within a fixed time frame, in combination with S-N curves derived at laboratory room temperature. However, from the literature it is well known that fatigue strength changes with temperature. Above the so-called fatigue transition temperature (FTT), which is correlated with the change in fracture behavior to cleavage controlled brittle fracture, fatigue strength is higher than at room temperature. However, below the FTT, fatigue strength is significantly reduced (Walters et al., 2016). For this reason, S-N curves derived at sub-zero temperatures (as in Braun et al., 2019) are required to allow accurate fatigue assessment for sub-zero temperature applications.

In order to assess the fatigue damage due to variable-amplitude loading (VAL) sequences, linear damage accumulation after Palmgren and Miner is the main tool for ships and offshore structures. However, several studies (Jacoby, 1969; Schütz and Zenner, 1973) showed that considerable uncertainties should be expected when linear damage accumulation approach is used without prior validation. The two main aspects in this respect are the sequence and mixture of loads, and the contribution of load cycles below the fatigue limit. Under constant amplitude loading (CAL) the latter will not yield crack propagation. For VAL sequences however, the contribution cannot be neglected, since larger load cycles will result in further crack propagation not only due to static fracture modes and thus load cycles below the fatigue limit will partially contribute to the damage as well. This contribution is considered in the design phase of offshore structures by using S-N design curves with modified slope below the fatigue limit. Non-conservative life predictions can therefore be avoided. The modification used for offshore structures nowadays is hereby only meant for wave loading and thus only validated for loading spectra that ships and offshore structures will experience in regions of the world without sea ice. To this day there are no joint load spectra for combined wind, wave and ice loads, nor studies on how such joint fatigue damage can be assessed apart from simple superposition of the individual damage contributions. Such superposition relies on consequently separate sets of S-N design curves or joint load spectra. Existing case studies of this principle are insofar of theoretical nature and not backed by real load scenarios. Consequently, experiments are required to obtain reliable S-N curves to validate the design approach.

When the long-term stress range distribution for the whole service life is expressed by a stress spectrum, it is possible to calculate the fatigue damage by splitting the stress spectrum into a number of representative blocks of equivalent stress range. This allows calculating the damage contribution of each block individually. The fatigue life is consequently defined by the sum of damage accumulated in each block independently. However, blocks with high mean stress effects can lead to changes in fatigue crack growth (Ehlers et al., 2015 and Führing, 1977) and therefore the hypothesis of linear damage accumulation loses its validity. In other words, sequences with high ice loads occurring for example in the first winter, which will cause such stress effects, invalidate the assumptions of independent damage accumulation. Furthermore, such high loads occurring early in the design life adversely influence the lifetime compared to the occurrence of the highest loads at the end of the design life. Current standards for fatigue design introduce design fatigue factors to reduce the acceptable fatigue damage. Alternatively, a load history with its variation in amplitude accounting for the ice-structure interaction besides the open water loads can be used. Consequently, the fatigue damage can be accumulated over this variable amplitude loading to assess the design life. Defining such VAL is however challenging, because the fatigue critical loading histories accounting for the correct sequence of high ice loads and low open water loads must be known for the specific design scenario.

3. Development of the combined load spectrum of wind, waves and ice

Towards addressing the issues mentioned above, a methodology for the development of the combined load spectrum of wind, waves and ice for OWT is presented. Numerical simulations are used to calculate the time series of the combined loads for each load case (LC), which are then used to derive the combined load spectrum. For this purpose, several steps are projected, as given in Fig. 1.

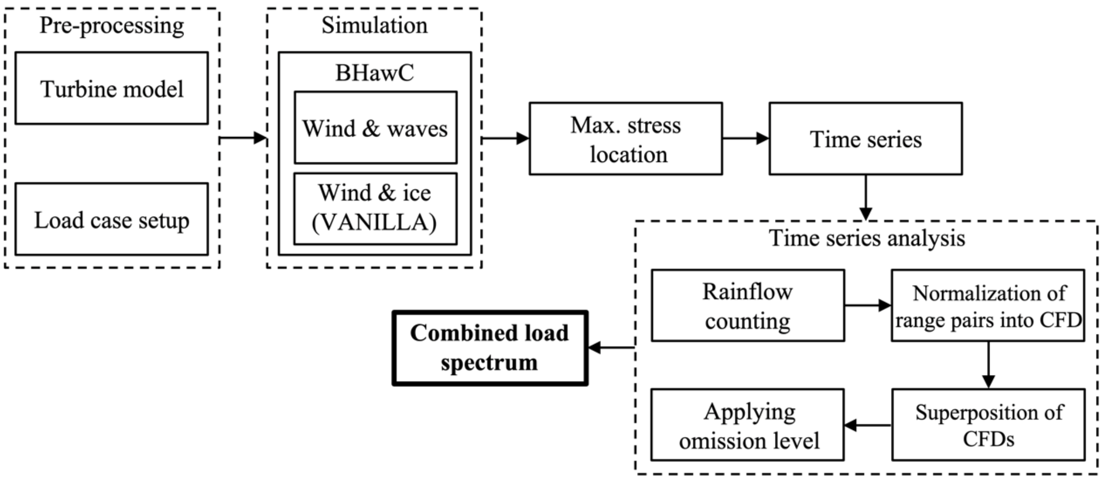

Fig. 1. Procedure for obtaining combined load spectrum of wind, waves and ice using numerical simulations.

3.1. Pre-processing

In this step, a model of an OWT is selected. Furthermore, critical LCs for the fatigue limit state (FLS) analysis are selected, according to the IEC61400 standard. These include different variations of wind, waves and ice conditions, in combination with the operating modes of the turbine (in production or idling).

3.2. Simulation

In this step, numerical simulations are run in order to estimate the structural response of OWT under the influence of environmental loads. At SGRE, this is achieved using BHawC, which is a structural finite element and aeroelastic model of OWT with integrated simulation environments for: (1) Estimating the combined effect of wind and waves; (2) Estimating the combined effect of wind and ice. For the latter, simulation model called VANILLA is used, which is an implementation of the model developed by Hendrikse and Nord (2019). The model simulates interaction between a drifting ice floe and a vertically sided offshore structure in order to estimate the IIVs. Note that the two simulation environments (1) and (2) are mutually exclusive, as during the ice-structure interaction, wave loads are negligible.

3.3. Max. stress location

In this step, the vertical coordinate along the height of OWT where the maximal stress occurs is determined for each of the simulated load cases. This is derived from the bending moment distribution, which in combination with the structural geometry gives the stress distribution. The bending moment distribution usually reaches its maximal value near the mudline. However, as the support structure is produced from the plates of high thickness, usually the point of maximal stress occurs elsewhere in the structure where the plate thickness is smaller.

3.4. Time series

In this step, based on the considerations discussed above, a time series of stress at the max. stress location for each LC is extracted from the simulation results. These time series contain the information about the stress profile that the critical point in the structure experiences during a certain period.

3.5. Time series analysis to obtain combined load spectrum

The standard procedure for estimating the cumulative frequency distribution (CFD) of stress time series is the so-called rainflow counting method (Matsuishi and Endo, 1968). Compared to other methods, this method agrees with the local elastic-plastic behavior of the material. Between reversal points, hysteresis loops are formed. However, as for all cycle counting methods only information of the mean, magnitude, and cycle counts are stored. Information of frequency, duration, and sequence of loads are lost. From a fatigue testing perspective, information of frequency and duration of loads are insignificant in the range of typical structural applications (Jacoby, 1969). The reason for this is that the fatigue strength is largely independent of frequency as long as the test specimen temperature is constant. Moreover, below the yield limit where no creep conditions occur, duration of loads does not affect fatigue damage. It is therefore believed that it is not necessary to use the exact time series for testing as long as the load CFD is a statistically adequate sample of operational or simulated time series (Heuler and Klätschke, 2005). However, as initially mentioned, this basic assumption of VAL-based fatigue assessment may not hold for high loads and partially low temperatures, affecting the general fatigue strength of structural materials and welded components. For this purpose, a spectrum of wind, waves, and ice loads is generated representing one year of service. This approach, which is already used for offshore load spectra like the wave action standard history (WASH) (Pook and Dover, 1989), allows a representation of loads reflecting the seasonal change of loads. Combining the times series of more than one year might result in VAL sequences with adjacent load peaks (see Li et al., 2016 regarding sequence effects caused by storms). Moreover, a one-year spectrum or VAL sequence can be combined with a seasonal temperature sequence. Consequently, schematic process of obtaining such one-year combined load spectrum for wind, waves and ice is presented in Fig. 2.

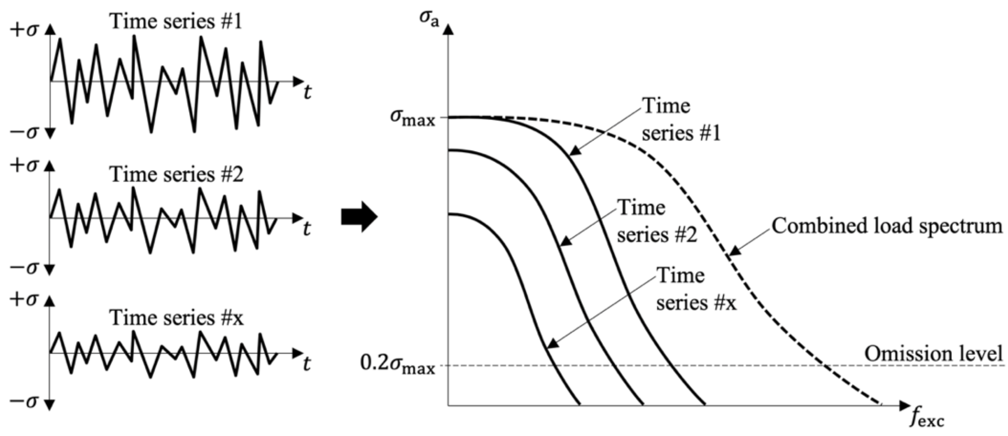

Fig. 2. Schematic presentation of combined load spectrum of wind, waves and ice.

Long-term recordings have revealed that wave-induced loading is usually Gaussian or Rayleigh random process (Pook and Dover, 1989). The long-term distribution of the load spectra for various sea states is achieved by superposition as illustrated in Fig. 2. The resulting cumulative load spectrum can be standardized and often described by a Weibull distribution. For ships and offshore structures, the main damage contribution usually comes from low-frequency wave loads. In case of pure wave-induced Gaussian distributed loading, the shape of the combined load spectrum has a straight-line shape in a half logarithmic diagram (Fricke and von Lilienfeld-Toal, 2008). The reason is that stresses caused by wave and wind loading are usually proportional to loads. However, effects such as IIVs may cause a type of synchronization resulting in large amplitude vibrations of offshore structures, causing high stress response with high number of cycles and a CFD more similar to the one illustrated in Fig. 2. The annual probability of such events has therefore to be taken into account in a combined load spectrum accounting for wave, wind, and ice loading. This can still be achieved by superposition, but requires estimates of the site-specific probability of such events. For this purpose, large numbers of structural simulations are required combining the three load contributions. For each time series, rainflow counting is performed to count the range and number of load cycles within one simulation to define a short-term distribution of the loads. By normalizing the simulated short-term scenario with the annual probability of occurrence, a one-year CFD for the particular event is calculated.

In order to reduce testing time, the long-term distribution is often truncated in the range of small load cycles well below the fatigue limit of the material. In test on notched and unnotched steel and aluminum specimens Heuler and Seeger (1986) found a stress of 50% of the fatigue limit to be a suitable omission level. Alternatively, Schütz et al. (1990) suggested a fixed range suppression of 10 μm/m and a further omission of the two lowest sea states for the load sequence WASH1 derived for tubular offshore structures. Moreover, they estimated that for a typical wave spectrum a reduction of cycles by one order of magnitude means an average omission level of 15% based on the maximum stress amplitude, which is much less than the 50% suggested by Heuler and Seeger (1986). Here an omission level of 20% of the maximum stress amplitude is applied, which was found to be suitable for VAL testing. This corresponds to roughly 1.5 decades of reduced cycles for a straight-line spectrum and is the upper limit before the omission seems to influence fatigue life significantly (Sonsino, 2005).

4. Small-scale fatigue tests

In order to verify a design procedure for offshore structures subject to the wind, waves and ice load contributions, sub-zero temperature S-N curves and a verification of the damage accumulation hypothesis for the generated VAL sequence are required. For this purpose, and to account for the effect of sub-zero temperatures on the fatigue strength, a climate chamber is used, which can be seen in Fig. 3. Cooling is performed by vaporized nitrogen, which is controlled by a temperature gauges in the chamber and on the specimen. The temperature can be kept constant within ±1 °C, see Braun et al. (2019). CAL fatigue testing is carried out under axial loading, with a temperature range of -180 °C and +280 °C on a Schenck horizontal resonance testing machine with maximum load capacity of 200 kN at a frequency around 33 Hz. For VAL fatigue testing the generated load spectrum is transferred into a turning point sequence, which is used as an input for a hydraulic testing machine.

Fig. 3. Fatigue testing climate chamber at TUHH.

The typical approach to account for VAL in fatigue design of ships and offshore structures is the linear damage accumulation hypothesis after Palmgren and Miner. The damage sum is given by

$$D = \sum_{\mathrm{i}=1}^{S} \frac{n_{\mathrm{i}}}{N_{\mathrm{i}}} \tag{1}$$

where S is the number of stress range classes and N is a number of cycles to failure for a given stress range $\Delta\sigma$ with the occurrence of n cycles. Here fatigue failure is assumed to occur when a damage sum reaches $D = 1$. This assumption has been widely applied for simple components and complex welded structures. However, different damage sums have already been found for structural materials and welded joints at room temperature, see Sonsino (2007). Sonsino et al. (2004) found that 90% of analysed test data yield fatigue sums between 0.3 and 3. According to Möller at al. (2015), a damage sum of $D = 0.5$ seems to be conservative for welded joints.

At low temperatures the fatigue strength of both structural materials and welded joints is increased, thus affecting the number of cycles to failure for a given stress range. Moreover, as earlier mentioned, the basic assumption of linear damage accumulation might be violated by effects such as high ice loads occurring for example in the first winter. It is consequently necessary to validate the approach for VAL at sub-zero temperatures. For this purpose, and based on the combined load spectrum discussed in Section 3, VAL sequences can be obtained by randomly sampling from the spectrum, thus creating a realistic time-history of the load, which can be used to preform small-scale fatigue tests. In principal, VAL tests are performed like CAL tests, by repeating the load sequence until specimen failure. Moreover, the load sequence is usually scaled for tests with different maximum load i.e. stress amplitude through scaling factor k. Curve fitting yields a curve similar to the S-N curve for VAL termed Gaßner curve. However, in order to achieve a sufficient load mixing, a VAL sequence has to be repeated at least 5-10 times (Sonsino, 2007). The procedure for determining Gaßner curve based on the combined load spectrum is schematically presented in Fig. 4.

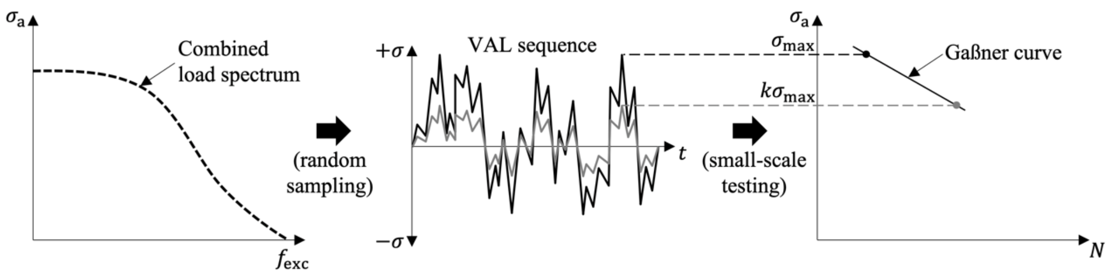

Fig. 4. Determination of VAL sequences and Gaßner curve based on the combined load spectrum.

Based on the above considerations, Eq. (1) is extended by dividing the combined load spectrum into a number of blocks with constant stress range, thus allowing the calculation of the real damage sum D_{real} which yields the same fatigue life N_{exp} as achieved in VAL tests with the spectrum size L_{s}. Here, D_{spec} denotes the fatigue damage calculated for one sequence of the load spectrum using a suitable S-N curve. The relation is given by

$$D_{\mathrm{real}} = \frac{D_{\mathrm{spec}}}{L_{\mathrm{s}}} N_{\mathrm{exp}} \tag{2}$$

which based on a number of tested samples sufficient for reliable statistical inference allows the calculation of damage sum of the OWT structures under sub-zero temperatures.

5. Conclusions

The current standards for the design of OWTs in ice-covered waters do not adequately take into account the effect of ice loads and sub-zero temperatures on the fatigue strength of the structure. Therefore, this paper presents an analysis of the current state-of-the-art approach for estimating the ice loads contribution to the fatigue life of OWTs and identifies the current knowledge gaps. It concludes that the currently existing approaches fail to adequately take into account the following effects: (1) The effect of sub-zero temperatures on the fatigue strength of the structure - the FTT is not adequately accounted for and thus the reliable S-N curves are currently missing; (2) The variable-amplitude nature of the loading pattern – ice action against the structure produces a loading pattern with possible high local load amplitudes which are not adequately accounted for with the currently used linear damage accumulation approaches. With respect to point (1), use of small-scale fatigue tests under sub-zero temperatures in order to develop the appropriate S-N (for CAL) and Gaßner (for VAL) curves is discussed, while with respect to point (2), a methodology is proposed for developing a combined load spectrum of wind, waves and ice using numerical simulations with an ultimate goal to develop applicable Gaßner curves characterizing the variable-amplitude nature of the loading pattern. Based on the above, the findings of this paper are considered to present a framework for the development of a novel design approach for building safer and more reliable OWTs in ice-covered seas.

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