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ScienceDirect

Energy Procedia 80 (2015) 193 – 200

Energy Procedia

12th Deep Sea Offshore Wind R&D Conference, EERA DeepWind'2015

Sensitivity of Wave Fatigue Loads on Offshore Wind Turbines under varying Site Conditions

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Abstract

Considerable variations in environmental site conditions can exist within large offshore wind farms leading to divergent fatigue loads on support structures. An efficient frequency-domain method to calculate wave-induced fatigue loads on offshore wind turbine monopile foundations was developed. A verification study with time-domain simulations for a 4MW offshore wind turbine showed result accuracies of more than 90% for equivalent bending moments at mudline and interface level. This accuracy and computation times in the order of seconds make the frequency-domain method ideal for preliminary design and support structure optimization. The model is applied in sensitivity analysis of fatigue loads using Monte-Carlo simulations. Local and global sensitivity studies and a probabilistic assessment give insight into the importance of site parameters like water depth, soil stiffness, wave height, and wave period on fatigue loads. Results show a significant influence of water depth and wave period. This provides a basis for design optimization, load interpolation and uncertainty analysis in large wind farms.

Peer-review under responsibility of SINTEF Energi AS

Keywords: Offshore wind turbines; wave fatigue load; sensitivity analysis; frequency-domain; site variation

1. Introduction

Fatigue loads on offshore wind turbine (OWT) support structures vary in large wind farms due to changing environmental site conditions. Full load calculations, which are commonly done in the time-domain, are computationally demanding and cannot be performed for each turbine within the wind farm [1]. In practice, loads are

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Peer-review under responsibility of SINTEF Energi AS
doi:10.1016/j.egypro.2015.11.422

evaluated for a limited number of design positions within the wind farm. Insight into the sensitivity of loads due to varying site conditions provides a basis for design position optimization during early design phases leading to more cost-effective support structures.

Previous studies investigated the influence of site parameters and foundation configuration on the natural frequency but emphasized the need for further work regarding sensitivity of fatigue damage [2, 3]. Large offshore wind farms are predominantly located in deeper water (25-40m) with monopile support structures. For this setup the design is typically governed by fatigue loads with a significant contribution coming from wave excitation [4].

Therefore, a computational model for efficient assessment of wave induced fatigue damage on monopiles was developed using frequency-domain analysis. For review of implementation and accuracy, a verification study was performed comparing time-domain simulation of a reference case to results obtained with the developed method. Due to its speed and accuracy, the developed method is ideal for sensitivity analysis. This paper aims at better insight into the sensitivity of fatigue loads to varying site conditions like mean sea level (MSL), soil properties, significant wave height (H_S) and wave peak period (T_P).

The remainder of this paper is organized as follows. First, Section 2 outlines the developed frequency-domain method (FDM), followed by a summary of the verification with time-domain simulations in Section 3. Thereafter, sensitivity analyses are addressed in Section 4, while Section 5 provides a discussion of the obtained results. Finally, the paper is ended with conclusions in Section 6.

2. Frequency-Domain Method for Wave Fatigue Loads

In current engineering practice fatigue loads on OWTs are typically assessed by extensive time-domain simulations of various load cases. The time-domain enables non-linear analysis with coupled simulations of wind, wave, and control system. Results of time-domain analysis are considered most accurate and are commonly used for certification. However, for preliminary support structure design less sophisticated models might be sufficient.

FDMs as an alternative have the potential to heavily decrease computational costs. Since frequency-domain analysis is linearized and wind and wave action decoupled, the method is considered less accurate than time-domain approaches. Frequency analysis has been applied to OWTs by several researchers [4, 5, 6, 7]. Kuehn [5] suggested a simplified method for fatigue analysis by superimposing time-domain simulations of aerodynamic loads with frequency-domain results of wave loads on the support structure. Later, van der Tempel [6] applied frequency-domain analysis to integrated support structure design. Both researchers treat wind and wave loads separately but emphasize the importance of dynamic interactions between turbine and support structure caused by coupled wind and wave excitation. The most important dynamic interaction is aerodynamic damping.

2.1. Approach

The developed FDM consists of three parts. Firstly, wave loading is obtained from a linearized Morison equation using wave kinematics power spectral densities (PSD) based on JONSWAP wave spectra. Secondly, structural transfer functions to determine the internal load response spectra are derived from a finite element (FE) model. After performing a modal analysis on this FE model, the transfer functions are synthesized using the modes in the frequency range of interest at the desired input and output degrees of freedom. In this synthesis, aerodynamic damping as a function of wind speed and wind-wave misalignment is taken into account. Finally, equivalent load ranges are obtained from the response spectra by use of Dirlik's method that provides information equivalent to rainflow-counting in the time-domain [8]. Output of the program are equivalent fatigue loads (EFL) for a specified number of cycles. The achieved computation time for one simulation case is approximately 10s.

2.2. Assumptions

To create a fast method, several assumptions are implemented simplifying full load calculations.

Assumptions for environmental data: Soil is modeled with distributed linear springs according to the Winkler model [9, 10]. Further effects like currents and sea ice are neglected, since the effects on the load level are expected to be minor. Sea ice can have a major impact on loads but is assumed to not occur for the considered sites e.g. North Sea. It is assumed that scour protection is installed so that erosion and scour effects are not considered.

Assumptions for structural model: Foundation and tower are described with a linear FE model of Timoshenko beam elements. It is based on a realistic reference design, where outer diameter, wall thickness and elastic properties change over height of the support structure. The first ten modes of the structure are taken into account according to ten eigenfrequencies. The rotor-nacelle-assembly (RNA) is modeled as an equivalent concentrated mass on top of the tower. Damping consists of a contribution from combined structural, hydrodynamic and soil damping (damping ratio ca. 1%) and a contribution from aerodynamic damping (damping ratio ca. 1.5 - 8%). The latter is a function of wind speed, rotor speed, and mode shape and is superimposed to structural damping. It is determined turbine-specific with modal analysis from a non-linear aero-elastic model. Aerodynamic damping for the first mode (fore-aft) is increased for aligned wind and waves, while it is decreased for higher structure modes as well as for wind-wave misalignment. The term interface refers to the node at tower bottom.

Assumptions for calculation method: The absolute formulation of Morison's equation is used, since structural velocity is low compared to wave velocity. The drag term is linearized with a method developed by Borgman [11]. Constant stretching is used to stretch wave kinematics from mean sea level to wave crest [12]. Diffraction is accounted for by use of the empirical MacCamy-Fuchs diffraction correction [13]. Instead of using distributed transfer functions of the FE model along the monopile wave-action zone, only transfer functions for equivalent wave loads at mean sea level are generated in order to minimize the computational effort.

3. Verification

The frequency-domain approach is verified with time-domain simulations for a reference case using a non-linear aero-elastic tool, Bonus Energy Horizontal axis wind turbine Code (BHawC), for global dynamic analysis of wind turbines. The reference case consists of a 4MW OWT in several fatigue relevant sea states. The turbine is located in a water depth of approximately 35m. For each sea state wind and wave directionalities are simplified into fully aligned or misaligned. Fully aligned describes identical wind and wave directions while fully misaligned waves arrive with 90° offset to wind. Structural models for the support structures are identical in terms of structural dimensions, damping, and modal properties. Simulations are run wave-only, i.e., with aerodynamics turned off. The parameters for the time-domain simulation are summarized in Table 1a. Each simulation has a length of 600s with 0.04s time step. The use of 5 random realizations (seeds) minimizes statistical errors in the simulation.

Table 1a. Simulation parameters verification study.

Parameter	Value
Length of time series	600s
Time step	0.04s
Number of seeds	5

Table 1b. Parameter Welch's method.

Parameter	Value
Window type	Hamming
Number of sections	10
Overlap	50%

Simulation results are compared qualitatively in terms of response moment PSDs and quantitatively with EFLs. PSDs are generated from the load time series by applying Welch's method for which the choices are specified in Table 1b. The time series were multiplied with a Hamming window and divided into 10 sections with 50% overlap. Welch's method uses periodogram spectrum estimates to reduce noise in the estimated spectrum due to limited length of the time series. Rainflow-counting is applied to the load time series to obtain the number of cycles N_i per load range L_i from which the equivalent lifetime fatigue load *EFL* for a specified number of cycles N_k is computed with Equation 1 [14]. The material parameter $m=4$ is chosen for welded steel. T_{sim} is the simulation time and n equals the number of load ranges. Results of the verification study are presented in section 5.

$$EFL = \left(\sum_{i=1}^{n} \frac{N_i}{N_k} \cdot \frac{T_{life}}{T_{sim}} \cdot L_i^m \right)^{1/m} \tag{1}$$

4. Sensitivity Analysis

In the sensitivity analysis the verified FDM is used to study effects of the site variations of the parameters MSL, soil, H_S and T_P on EFLs. The structural properties are unchanged in the analyses, except for the length of the monopile, which is adjusted to keep hub height constant in terms of the absolute value to MSL. Tower properties are not modified, thus the distance between MSL and interface is constant in the analysis. Soil variations are represented by scaling of the soil stiffness which is obtained from nominal p-y curves with a factor that is constant over the full depth. Load sensitivity is analysed locally, globally, and in a probabilistic assessment. In every analysis all parameters are assumed to be independent. H_S and T_P are actually dependent but can be regarded independent for short-term consideration and small parameter variations. The local and global analyses consider variations in one variable at a time with the other three parameters remain unchanged, while the probabilistic assessment varies all four parameters simultaneously.

4.1. Local and global sensitivity

In the local approach the parameters are varied deterministically with a deviation of 1% around their nominal value. The relation of EFL to parameter is by definition linear in local sensitivity analysis. The local sensitivity *S* is defined as the relative change of *EFL* due to a change of the parameter *X* around its nominal value according to Equation 2.

$$S = \frac{\Delta EFL}{\Delta X} \tag{2}$$

In the global approach the parameter changes cover the full range of variability that can be expected within a wind farm. For each parameter 1000 deterministic simulations were run, stepping through the parameters with uniformly spaced increments. Table 2 states the chosen nominal values as well as global ranges of the parameters.

Table 2. Parameter variations.

Analysis	**Parameter**	**MSL [m]**	**Soil factor [-]**	**H_S [m]**	**T_P [s]**
Local sensitivity	Nominal value	35	1	2	7
Global sensitivity	Global range	20-40	0.1-1.9	0-6	2-12
Probabilistic assessment	Mean	31	1	2	7
	Standard deviation	3.5	0.2	0.25	1

4.2. Probabilistic assessment

The probabilistic assessment uses Monte Carlo sampling (MCS), where a normal probability distribution of the parameters is assumed based on their mean value and standard deviation (cf. Table 2). Random combinations of the four parameters are picked in 10000 MCS leading to an accuracy of ±0.4% for the estimate of normalized EFL. Parameter ranges were chosen to represent realistic variations within an exemplary wind farm site. In this frame the design is still valid concerning the natural frequency constraint. The choice is made based on wind farm data, existing publications of sensitivity studies [3, 15], and expert opinion. The standard deviations of MSL and soil over the wind farm are expected to be larger, while the wave properties vary less. The MSL mean value differs from the nominal value in the local sensitivity analysis since it is chosen as the average of an exemplary wind farm site, while the nominal MSL represents the design position with highest deterministic loads. Soil properties typically contain high uncertainties due to difficult measurement while the water depth is known with high accuracy.

5. Results and Discussion

5.1. Verification results

Results of the verification study are exemplarily presented for a sea state of $H_S=2.2m$ and $T_P=7.0s$. Figure 1a presents the time series of the response moment at mudline generated with BHawC. The comparison of normalized PSDs in Figure 1b shows that the developed method gives a very good estimate. A response at wave peak frequency $f_P=0.14Hz$ and the first eigenfrequency $f_1=0.29Hz$ due to dynamic amplification are predicted appropriately. The response of the FDM at eigenfrequency is slightly shifted to a higher frequency compared to the BHawC result which is due to the modelling of added mass in the FE model. The FDM represents accurately that no response is visible in the frequency range around the second bending eigenmode of the structure $f_2=0.85Hz$ for this example case.

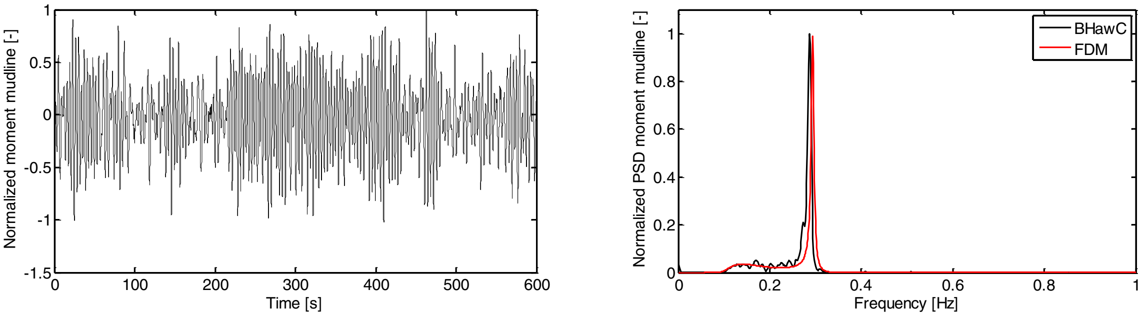

Fig. 1. (a) Time series response moment at mudline. (b) Comparison of normalized PSDs of response moment at mudline.

Figure 2 presents the results of rainflow-counting compared to PDFs obtained by Dirlik's method for the bending moment at mudline. From a qualitative perspective, the results of rainflow-counting are well-described by the PDF. This is likewise the case for response at interface level. Dirlik's formula combines and weights an exponential and two Rayleigh distributions. The closer the rainflow-count can be approximated by a weighted combination of these three distributions, the better will the results obtained by Dirlik's method match it.

The resulting EFL from rainflow-counting and Dirlik's method are given in Table 3. EFLs are normalized with the results of the time-domain simulations. Regarding the response moment estimation, the FDM leads to the closest results for sea states with lower wave heights where an accuracy of more than 95% is achieved. For higher fatigue relevant wave heights, the calculated equivalent fatigue moments differ less than 10% from the time-domain result.

From both qualitative and quantitative analysis, it appears that the developed FDM delivers results close to time-domain simulations for internal moments. However, the developed method is not suitable for detailed design and certification due to its accuracy. The influence of wind induced loads on the total fatigue loads should also be accounted for in relevant locations for design position optimizing and clustering. The developed model is mainly useful for deeper water locations (25-40m) where wave loads are dominating. Potential applications of the method are design position optimization, clustering of turbines, interpolation of wave fatigue loads between design positions, sensitivity and uncertainty analysis and also use in the actual design process e.g. preliminary design.

Table 3. Normalized EFL of time-domain simulations (BHawC) and frequency-domain method (FDM).

Sea State		BHawC Mudline [-]	FDM Mudline [-]	BHawC Interface [-]	FDM Interface [-]
H_S=0.78m	T_P=4.02s	1.0	0.97	1.0	0.99
H_S=2.40m	T_P=7.23s	1.0	0.96	1.0	0.96
H_S=4.34m	T_P=9.64s	1.0	1.08	1.0	0.94

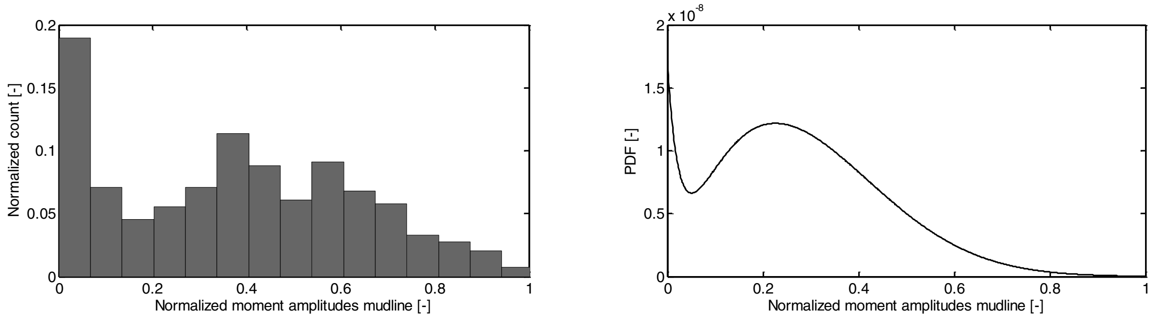

Fig. 2. (a) Histogram of rainflow-counts and (b) Dirlik's PDF. The number of load bins in (a) are reduced for visualization purpose.

5.2. Local and global sensitivity results

The sensitivities obtained from the local analysis are normalized with respect to relative changes of each parameter and offer insight into the influence of parameters on the load sensitivity (cf. Table 4).

Table 4. Normalized local sensitivities for EFL at mudline and interface level.

Location	**Soil**	**MSL**	**H_S**	**T_P**
Mudline [-]	-0.149	1.807	0.991	-1.297
Interface [-]	-0.203	1.533	0.991	-1.707

MSL and T_P influence EFLs most while scaling of soil stiffness only causes small variations of the load level locally around the nominal value. The strong dependency of loads with respect to MSL can be attributed to the combined effect of wave loads increasing with deeper water while the natural frequency of the structure decreases. The decreasing influence of MSL for the results from mudline to interface is due to the fact that the interface level is kept constant with respect to MSL. An increase in MSL thus extends the moment arm to mudline while not altering it to interface level. Soil and T_P sensitivity are higher for interface EFLs, since the relative deflections in the first mode shape are larger there which amplifies the impact of changing natural frequency. The wave height sensitivity is identical at interface and mudline, since all other parameters are kept constant while only the magnitude of the wave load scales linearly.

Soil properties and MSL are expected to have much higher variations within a wind farm compared to H_S and T_P. Since the uncertainty in soil is high [15], it is still a critical parameter in foundation design despite its low local sensitivity. The high sensitivity of loads to water depth makes optimization of design positions and clustering in large offshore wind farms crucial for cost-effective design.

In global analysis EFLs show a linear trend for H_S while T_P, soil, and MSL cause a higher order trend (cf. Figure 3a). The proportionality of EFLs to H_S is explained by the use of Airy wave theory.

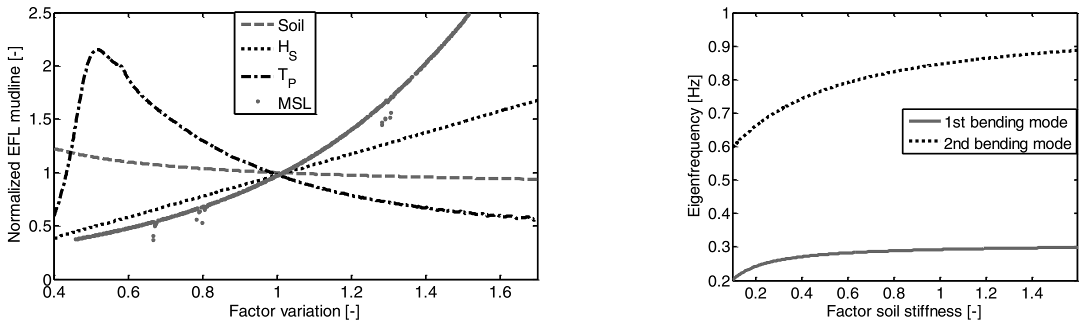

Fig. 3. (a) Normalized EFL (bending moment) at mudline as a function of parameter variation. (b) Change of eigenfrequency with soil stiffness.

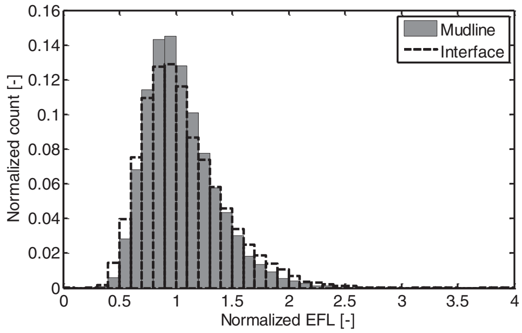

Table 5. Statistical properties of distribution of normalized EFL.

Property	**Mudline [-]**	**Interface [-]**
Mean	1.05	1.07
STD	0.38	0.38
Skewness	6.20	1.65
Kurtosis	114.55	13.57

Fig. 4. Histogram of EFL for probability assessment. EFLs are normalized to the result for all parameters at their mean value.

The analysed parameters either influence wave loads and/or the characteristics of the system, especially eigenfrequency and mode shape. Wave related parameters H_S and T_P change the wave load, soil changes the system characteristics, while MSL influences both. If the distance between natural frequency of the structure and wave peak frequency is decreased, higher dynamic amplification raises fatigue loads. This phenomenon is dominant for decreasing T_P, as for $T_P=3.4s$ the structure with an eigenfrequency of $f_1=0.29Hz$ is excited exactly in its first eigenmode (cf. Fig. 3a).

Decreasing soil stiffness causes lower eigenfrequencies with a square-root dependency as shown in Figure 3b. The second bending mode is affected more strongly, which is caused by larger deflections for the second mode shape at mudline. Decreasing soil stiffness shifts the natural frequency of the structure closer to load excitation frequencies which explains the increase of EFLs.

A sensitivity study of RNA mass variation proved a trend of EFLs that follow the change of natural frequency closely (not shown). The sensitivity of EFLs to RNA mass can be assumed to arise mainly from the effect of eigenfrequency change. This is in agreement with previous research which treats the natural frequencies of first and second bending mode as main indicator for dynamic response [3].

5.3. Probabilistic assessment results

The histogram of the computed EFLs in the probabilistic assessment with 10000 MC samples is shown in Figure 4 with the corresponding statistical properties stated in Table 5. All input parameters are Gaussian distributed leading to an EFL distribution that is positively skewed to higher loads (cf. Table 5). This is due to the high influence of T_P and MSL on the EFLs, as shown in the scatter plots in Figure 5. Hence, the skewness can be traced back to load sensitivity being of higher order regarding T_P for the considered variation. The stronger positive tail is also represented in the scatter plots where outliers to higher loads are more frequent.

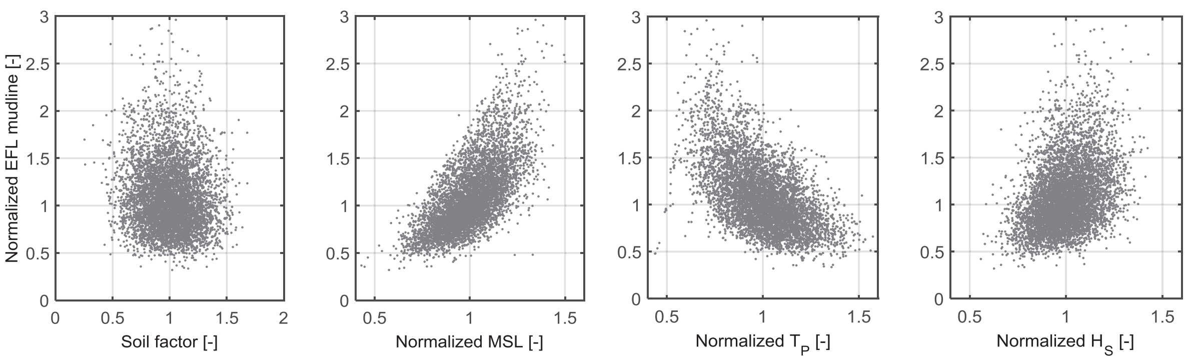

Fig. 5. Scatter plots of normalized EFL for all parameters at mudline for probabilistic assessment.

The scatter plots show the same trends as observed for the global sensitivity study. For this reference case soil has no significant influence on the mean EFL. This is consistent with the expectation based on the local sensitivity analysis. Sensitivity results are strongly influenced by the chosen parameter ranges of the reference case. Therefore, care must be taken for generalization of the results regarding assumptions and conditions in other cases.

6. Conclusion and Outlook

Increased insight into sensitivity of fatigue loads is needed in order to optimize support structures in large offshore wind farms, where considerable variations in environmental site conditions might occur. This paper uses frequency-domain load calculations to analyze the sensitivity of wave-induced fatigue loads to varying site conditions for OWT monopile foundations in deeper water locations. A FDM was created which calculates EFLs based on JONSWAP wave spectra, Morison equation, transfer functions from a FE model of the support structure, and Dirlik's method. This approach results in a computation time of approximately 10s for one simulation case.

Verification of the FDM using time-domain simulations from an aero-elastic code indicates an accuracy of more than 90% for fatigue bending moments at mudline and interface level. Additionally, a qualitative analysis of power spectral densities showed good agreement regarding responses at T_P and first eigenfrequency of the structure. The FDM is used in sensitivity analysis with MC sampling. Local and global analysis reveal high fatigue load sensitivity to changes in MSL and T_P. Normal distributed parameters in a probabilistic assessment yield a positively skewed probability distribution of EFLs.

Due to its accuracy and efficiency, the FDM is ideal for applications where fast simulations are needed, e.g. in design position optimization, clustering of turbines, interpolation of wave fatigue loads and in preliminary design. Further study is required to extend the developed method to include wind loads. Due to the identified importance of wave peak frequency and MSL on the results, further work should reveal the effect of uncertainty in wave loads on fatigue loads.

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