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Sensitivity Analysis of Material and Load Parameters to Fatigue Stresses of an Offshore Wind Turbine Monopile Substructure

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Abstract

Steel monopiles are support structures mostly applied for offshore wind turbines. Their installation is straightforward, in particular, in shallow and medium waters. While the wind turbine tower is primarily affected by wind, the wave loads are dominant for the monopile, as it is submerged to a large extent. This study deals with the influence of uncertainties in material and load parameters on the behaviour of those structures. It is investigated how the scattering of material properties (namely Young's modulus of elasticity) affect the structural response. In addition, loads with different characteristics are applied, and it is examined how the changes in loads influence the structural response. The analysed output data of interest are the extreme stresses leading to the accumulation of fatigue damage. In order for a realistic modelling, wave loads are considered with irregular sea states with different wave characteristics (significant wave heights and wave peak periods). The final aim of the analysis is to classify the effects of specific wave characteristics on the stresses by means of a sensitivity analysis. The analysis shows that variations in the wave peak period have the strongest influence on stress outputs. This effect results from the strong sensitivity of the structural dynamical response to the decrease of the difference between the values of the wave peak frequency and the natural frequencies of the structure.

Keywords: Offshore wind energy, Monopile substructure, Sensitivity analysis, Uncertainties, Wave load

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1. Introduction

As offshore wind turbines (OWTs) are exposed to aerodynamic, hydrodynamic and mechanical loading, they are especially prone to fatigue damage. While the tower and blades are mostly affected by aerodynamic loads, the substructure is primarily influenced by wave-induced loads. Both loads are stochastic in nature, which must be taken into account in the design of OWT support structures to model realistically the loads that influence the structural responses, e.g., the stresses used to predict the fatigue damage. These random inputs cause significant uncertainties in the structural response, and are traditionally treated in the verification process through a semi-probabilistic approach by means of partial safety factors. To improve the understanding of the effect of the uncertainties, in this work it is investigated how changes in material properties and load parameters affect the response of the OWT support structure by employing a fully probabilistic approach. Global sensitivity analyses are performed in order to examine the effect of changes of all parameters varying simultaneously and to retrieve the influence level of each uncertain parameter globally. Insight into the importance of different input variances is obtained by computing the Sobol′ indices [11, 12].

2. Methods

2.1. Numerical FE model of monopile structure

Several different support structures can be employed for OWTs. A monopile support is considered here, as it currently represents the most common substructure application for OWTs, due to its simple design and installation compared to the alternatives. The monopile structure is made of a cylindrical steel tube with changing cross sectional diameters and wall thicknesses. The example structure in this study has a cylindrical hollow cross section of 8 m diameter at its bottom. The lower 35 m of the structure are below the seabed. The soil is modelled with sets of two-directional non-linear springs by means of load/deflection method [14]. The monopile is designed for a water depth of 40m. The submerged section has a truncated cone shape, in which the cross sectional diameter reduces from 8 m to 6 m. Finally, it continues above the still water level for 18 m, where it is supposed to be connected with the wind turbine tower through a transition piece [10]. The whole structure is constructed in steel, characterized by the following nominal material properties: Poisson ratio 0.3, density of the material 7850 kg/m^3, shear modulus 78 GPa, and the Young´s modulus of elasticity 215.12 GPa. In the subsequent parts of this work, the Young's modulus will be one of the parameters affected by uncertainty. The structure has been modeled using the finite element analysis code "Poseidon", developed in-house at the Institute for Steel Construction of the Leibniz Universität Hannover [3, 13]. The numerical 3D and beam model of the monopile structure with mudline and still water level are shown in Fig. 1.

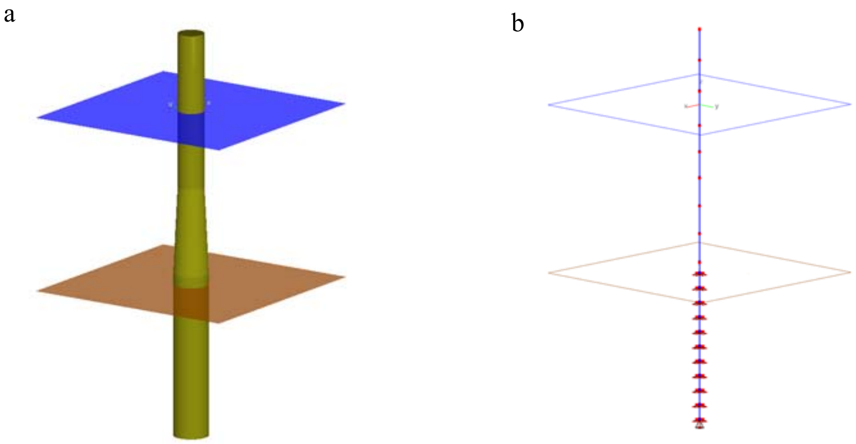

Fig. 1.Numerical model of monopile structure (a) 3D model; (b) beam model.

2.2. Load modelling

Ocean waves are irregular and random in shape, height, length and speed of propagation. A real sea state is best described by a random wave model. In literature, many methods are proposed to describe and model the wave conditions for structural design purposes [1, 2, 3]. For a quasi-static analysis, it is sufficient to use deterministic regular waves characterized by wave length and corresponding wave period and wave height. However, slender structures with significant dynamic response, such as OWTs, require a stochastic modelling of the sea surface and its kinematics by means of time series analysis. In applications, the sea state is usually assumed as a random process that is stationary over a certain period of time. Depending on the conditions and purpose of the analysis, the period of sea state stationarity can range from 30 minutes to 10 hours.

The characteristics of a stationary sea state can be modelled by means of wave energy spectra. Wave spectra can be given in table form, as measured spectra, or by a parameterized analytical formula. The specific wave spectrum depends on the geographical area with local bathymetry and the severity of the sea state. Models of wave spectra formulations depending on characterizing parameters of a sea state, the significant wave height and the zero-up-crossing period, are used. These parameters are explained according to [2]:

Significant wave height (H_s)

H_s is defined as the mean value of the 1/3 biggest wave heights recorded in the observed time series. This value is usually shown in scatter diagrams obtained from site measurements.

Mean zero-up-crossing period (T_z)

T_z is the mean period of all successive up-crossings of the zero-water level of the water surface within the time series. Wave energy spectra is usually defined by the wave peak period T_p, which is the period that is associated with the highest amount of wave energy, and this value is most commonly given in scatter diagrams obtained from site measurements. The relation of T_z and T_p depends on the shape of the spectrum and can only be established in an approximate manner. In IEC 61400-3 [1] the following relation is recommended:

$$T_p = T_z \sqrt{\frac{11+\gamma}{5+\gamma}} \tag{1}$$

where γ is spectrum shape parameter that depends on the chosen energy spectrum. The most frequently applied spectra for describing the wind-excited seas are Pierson-Moskowitz (PM-) spectrum and JONSWAP spectrum. The PM-spectrum was originally proposed for a fully developed sea. The JONSWAP spectrum, which extends PM to include fetch limited seas, is used for modelling of the sea state in this paper. It is based on the PM-spectrum, extended by the shape parameter γ:

$$S_{JS}(\omega) = nf\ S_{PM}(\omega)\ \gamma^{exp\left(-\frac{1}{2}\left(\frac{\omega-\omega_p}{\sigma*\omega_p}\right)^2\right)} \tag{2}$$

In this equation, $S_{PM}(\omega)$ is the PM-spectrum defined by:

$$S_{PM}(\omega) = \frac{5}{16} H_S^2 \omega_p^4 \omega^{-5} \exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right) \tag{3}$$

Here *nf* stands for normalizing function given by:

$$nf = 1 - 0.287\ln(\gamma) \tag{4}$$

σ is bandwidth parameter, whose value is set in accordance to DNV-RP-205 [2].
γ is shape parameter. For $\gamma = 1$, the JONSWAP spectrum is equal to PM-spectrum. Here, the value of γ is set to 3.3, which is the value recommended for the location North Sea [2].
The JONSWAP spectrum is accurate and applicable in:

$$3.6 < \frac{T_p}{\sqrt{H_s}} < 5 \tag{5}$$

where T_p is in seconds and H_s in meters, and should be used with caution outside this interval.
Finally, for calculating the wave loads the Morison's equation, as following, is used:

$$f = f_d + f_m = 0.5 * C_d * \rho_{water} * D * u_\perp * |u_\perp| + C_m * \rho_{water} * A * \dot{u_\perp} \tag{6}$$

where: f is force per unit length of the member, f_d is drag term of the wave force, f_m is inertia term of the wave force, C_d is hydrodynamic drag coefficient, C_m is hydrodynamic inertia coefficient, ρ_{water} is water density, D is diameter of the member in the respected section, A is cross section area of the member, $u_\perp$ is velocity of the flow normal to the member surface and $\dot{u_\perp}$is acceleration of the flow normal to the member surface [1, 2, 3]. Hydrodynamic coefficients are adopted according to [4].

2.3. Uncertainties within the modelling process

Uncertainties in the loads and in the structure are captured by stochastic variables in the analysis to explore their effects on the structural response in order to eventually improve the design of OWT support structures. It is investigated which uncertain input parameters contribute most to the uncertainties in the output, namely extreme stresses that cause accumulated fatigue damage. In this manner a better insight into the importance of varying parameters to the variance of the output is obtained. The influence of varying stochastic parameters to final stresses in structure are investigated by means of global sensitivity analysis, namely through computing Sobol' sensitivity indices [11, 12].

The investigated varying material and load parameters are:

- Young´s modulus of elasticity
- Significant wave height, H_s and
- Wave peak period, T_p.

H_s and T_p are load parameters whose variation is given through scatter diagrams obtained by measurements on offshore sites. For the North Sea, parameter variations are taken from "EU UpWind" project (SES6 No 019945 UPWIND) named "UpWind Design Basis" [5]. For the purposes of this study, wave parameters from scatter diagrams for K13 Deep Water Site and for the most frequent wind speed of 9-11m/s are used. Young's modulus values are sampled from a lognormal distribution with mean value of 215.12 GPa and coefficient of variation of 0.06, as given in [6].

2.4. Sampling of varying parameters

In a full probabilistic analysis, it is necessary to perform a large number of numerical simulations with varying parameters. For this purpose, the finite element code is linked to an advanced software for stochastic analysis, namely OpenCOSSAN, which allows more sophisticated uncertainty quantification and management [7, 8].

First, a qualitative analysis of the effect of the uncertainties is performed by using Latin Hypercube sampling to generate sample inputs in the predefined range. Then, the Sobol' indices are computed; these global sensitivity indices are based on the decomposition of the variance of the output into its individual input contributions. In this case, the correlation between the variation of significant wave height and wave peak period, shown by the available data history (Fig. 2.), is taken into account. However, given the complex dependency shown in the data, it was necessary to use a multivariate mixed distribution model [9], where a correlated bivariate Gaussian distribution is centred around each data bin mid-point of the bi-dimensional histogram, with a weight proportional to the height of the bin. Additionally, the mixed distribution is constrained for the upper and lower boundaries of the parameter values. Figure 2 shows the comparison between the discrete data scatter diagram and 1000 sets of H_s and T_p sampled in OpenCOSSAN. The figure shows a good agreement of the real data with the empirical distribution with respect to the density of sampling. The deviations from the real data scatter, due to the mixture model, are acceptable.

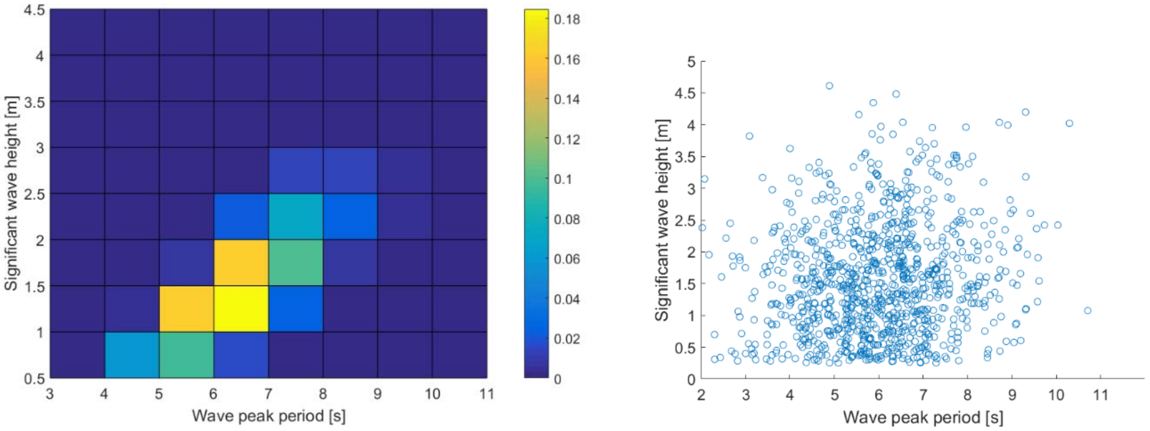

Fig. 2. Samples from Gaussian Mixture distribution model (right) compared to real data histogram (left)

3. Results

1000 numerical simulations with random combinations of material and load parameters are performed. Each simulation generates irregular sea states with a duration of 1800 s and a time step of 0.1 s. For each cycle, the extreme stresses in the monopile's cross section at mudline level are determined. Therefore, for each simulation there are two single outputs, namely the minimum and maximum stress, that are of interest in the fatigue analysis. Figures 3 and 4 show sensitivity measures of stress results to the three varying parameters. The sensitivities are normalized with respect to relative changes of each parameter to offer the insight into the influence of parameters to load sensitivity.

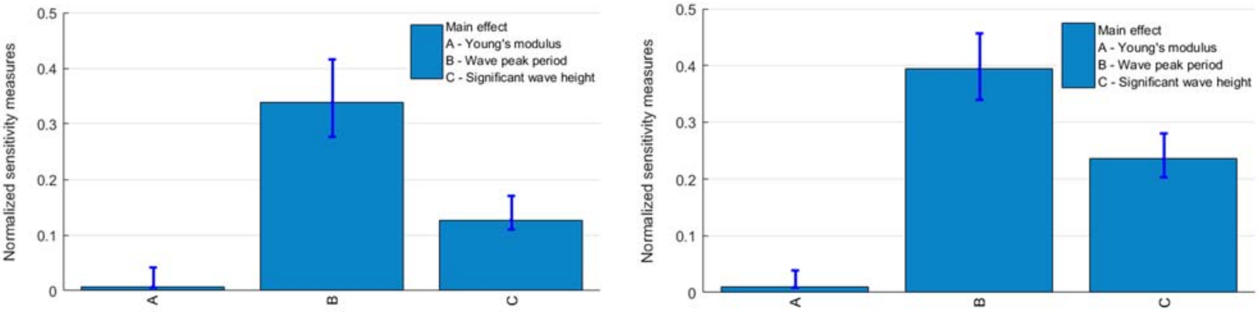

Fig. 4. Sensitivity indices for minimal (left) and maximal (right) stresses with confidence intervals 5% - 95%

It can be seen that the variation of the material parameter has very low effect on the output variance despite changing the structural system characteristics. The reason is that a range of possible oscillations of this parameter is very narrow [6]. In contrast to this, the variation of the load parameters influences the stress results greatly, as they directly affect the wave loads and have a wider range of variation. The highest variance in output is attributed to the variability of the wave peak period. In fact, if the difference between the values of wave peak frequency and the natural frequency of the system is decreasing, it leads to stronger dynamic amplifications and increased stresses. This especially relates to decreasing the wave peak period, as it can lead to exciting the structure in one of its lower natural frequencies.

4. Conclusions

The traditional semi-probabilistic approach within the design of support structures of offshore wind turbines uses partial safety factors in order to cover unknown uncertainties within the design process. The gap in this approach is the absence of ability to determine the sources of the uncertainties and their contribution to the final result of interest. This research is conducted in order to better perceive importance of single parameters, whose values are scattering due to the stochastic nature of the sea state processes and uncertainties in material properties.

Results have shown that the extreme stresses are to the highest extent influenced by wave load parameters, especially wave peak period. Sensitivity indices show that the examined material parameters affect the stresses to a lower extent. The reason may be the narrow range of possible scattering, or simply the lower contribution of its scattering to the stresses.

Sensitivity results are strongly influenced by the selection of the reference case (wind speed) as well as the selected parameter ranges. Therefore, in order to generalize the results, other cases, conditions and starting assumptions must be considered. Investigation of extreme stresses makes a good indicator for the further research with the complete fatigue damage of time series as an output.

5. Acknowledgements

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