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Efficient Fatigue Design for Tripod Structures in North and Baltic Seas

Prof. Dr.-Ing. Peter Schaumann, Dipl.-Ing. Patric Kleineidam
Institut für Stahlbau; Universität Hannover; Germany

Summary

For support structures of offshore wind energy converters (OWECs) in moderate water depth gravity based foundations and monopile foundations have been used. For greater water depths as discussed for German offshore wind parks in North Sea and Baltic Sea other types of structures like tripod foundations are suitable. Until now, such structures can hardly be analysed with existing design tools for offshore wind energy converters within an integrated design. For this reason the design calculations have to be divided into the calculations for wind loads and those for wave loads. To gather for example the calculated damage values for constructional details the results have to be superposed afterwards.
Established design methods for platforms of the oil and gas industry should not be used without validation of their applicability for support structures for OWECs. For this validation the characteristics of the dynamic behaviour has to be taken into account. For an efficient prediction of the dynamic structural reactions for irregular sea states a so called hybrid analysis can be adapted for support structures of OWECs. The application of this method is discussed in this paper and the results of exemplary calculations for tripod structures in North and Baltic Sea environments are presented. The required calculations have been carried out with the design tool Han-Off which has been developed at the Institute for Steel Construction within the last years.

Keywords: Offshore Wind Energy, Fatigue, Wave Loading, Hybrid Analysis

1. Introduction

Support structures of Offshore Wind Energy Converters (OWECs) are exposed to combined loading from wind and waves. Therefore, to gain adequate design methods for OWECs the established design concepts for offshore platforms and onshore wind energy support structures have to be improved. Traditional concepts for fatigue design vary from deterministic design methods, which can be used in special conditions for oil and gas platforms, to calculations in the time domain, which are applied to the actual generation of multi megawatt onshore wind energy converters.
For support structures of offshore wind turbines in moderate water depth gravity based foundations and monopile foundations have been used. For greater water depths as discussed for German offshore wind parks in North Sea and Baltic Sea other types of structures like tripod foundations are suitable. Until now, such structures can hardly be analysed with existing design tools for offshore wind energy converters within an integrated design. For this reason the design calculations have to be divided into the calculations for wind loads and those for wave loads. To gather for example the calculated damage values for certain details the results have to be superposed afterwards.
To take the dynamic behaviour of support structures for OWECs properly into account not all design methods for platforms of the oil and gas industry are applicable. In this paper the so called hybrid analysis which has been developed for deepwater platforms will be used as an efficient method. Firstly the design tool *Han-Off* will be presented, then, after a presentation of the hybrid analysis, its application will be shown with exemplary calculations for tripod structures in North and Baltic Sea environment.

2. Design Tool *Han-Off*

For the calculations presented in this paper the design tool *Han-Off* has been utilised. This tool has been developed within the last years by the co-author parallel to the work on the research project GIGAWIND. The tool is capable of predicting wave loads on hydrodynamic transparent structures for regular waves and irregular sea states. An interface exists to the program WaveLoads for the integration of higher order wave theories. WaveLoads as well as *Han-Off* has been developed within the GIGAWIND-project, WaveLoads at the Institute for Fluid Mechanics at the University of Hannover, see [12]. Comparisons for *Han-Off* have shown a good agreement with other programs. For nonlinear waves with properties near to the wave braking limit the chosen wave theory can have a remarkable influence on the wave loads, see [9]. It is stated there that for water depths of about 30 m, which are relevant for the presented calculations, and with respect to fatigue the use of linear wave theory leads to a good estimation of the expected loads.
In addition measured time series at the research platform FINO1 have been compared to simulated time series of irregular sea states for certain environmental conditions. The rainflow spectra of the measured normal forces show a very good accordance with the results of the simulations, see [9] for more details.

3. Design of OWECS under Wave Loading

Concepts for the fatigue design of oil and gas platforms vary from deterministic design methods, which can be used for special conditions [1], to calculations in the time domain. These are applied also to the actual generation of multi megawatt onshore wind energy converters. The calculation in the time domain is the most comprehensive one of the considered analysis methods.

For simple structures like monopiles analytical solutions for calculations in the frequency domain can be found in [7]. As a combination of both, the calculations in time and frequency domain, the so called "hybrid time-frequency domain fatigue analysis" which has been developed for very deep water platforms of the oil and gas industry, see [8], is suggested and discussed for the fatigue design of support structures of offshore wind energy converters. With this method the advantages of the calculations in the time domain with its possibilities of taking nonlinear effects into account are combined with the high numerical efficiency of the calculations in the frequency domain.

3.1 Hybrid Analysis

As the description of sea state is done by the wave spectra in frequency domain it would be promising to get the structural response also in frequency domain. In that case two problems of great interest arise. Firstly it must be clarified how the structural response can be derived and secondly, a damage evaluation has to be carried out for stress spectra in the frequency domain.

Assuming that the structure is the connection between the stochastic wave process and the stochastic stress process in the structure as a consequence of wave loading, every detail of the structure can be represented by a transfer function in frequency domain. The concept contains the simulation of representative time series of wave loadings and furthermore the calculation of the structural response in time domain under consideration of nonlinear effects. For this representative time series of the stresses the according transfer function can be calculated using equation 1. To do this the time series of the stresses must be transferred into the frequency domain using e.g. the fast fourier transformation.

$$H_{\sigma\sigma}(f) = \sqrt{\frac{\Phi_{\sigma\sigma}(f)}{\Phi_{\zeta\zeta}(f)}} \qquad (1)$$

Once the transfer function is determined the stress spectrum for every sea state can be calculated by combining the transfer function with spectra of sea states, according to equation 2.

$$\Phi_{\sigma\sigma}(f) = \left|H_{\sigma\sigma}(f)\right|^2 \cdot \Phi_{\zeta\zeta}(f) \qquad (2)$$

The use of simulated time series results in stochastic scatter for the realisations. This can have an influence on the damage prediction with this method. Therefore, a sufficient number of short realisations or a longer realisation with a sufficient length has to be used.

3.2 Damage Evaluation in Frequency Domain

While it is state-of-the-art to evaluate time series of stresses using the rainflow counting method, for the evaluation of stress spectra other techniques must be applied. Bishop has compared different possibilities in [2]. His conclusion is that the formula of Dirlik, see [3], leads to the best results. This method is used for the damage evaluation of stress spectra described in this paper.

For practical cases the use of S-N-curves with changing slopes is required by certain design codes like Eurocode 3 [5] or GL [6] and must therefore be taken into account for support structures of OWECs. An equivalent number of allowable stress cycles is introduced in [10] instead of an equivalent stress range to integrate such S-N-curves in this concept. In equation 3 the reciprocal of this value is given.

$$\frac{1}{N_{equi}} = \int_0^\infty \left(\frac{\Delta\sigma^{m(\Delta\sigma)}}{a(\Delta\sigma)} \cdot p(\Delta\sigma) \right) d\Delta\sigma \qquad (3)$$

In this equation $m(\Delta\sigma)$ and $a(\Delta\sigma)$ denote the characteristics of the S-N-curve and $p(\Delta\sigma)$ denotes the probability of the stress ranges which is calculated in the frequency domain based on Dirliks formula.

4. Exemplary Calculations in North and Baltic Seas

4.1 Tripod T-3 3.6 MW

Within this paper the tripod structure T-3 shown in Fig. 1 is used for comparative calculations. The detailed descriptions of the dimensions are published in [9].

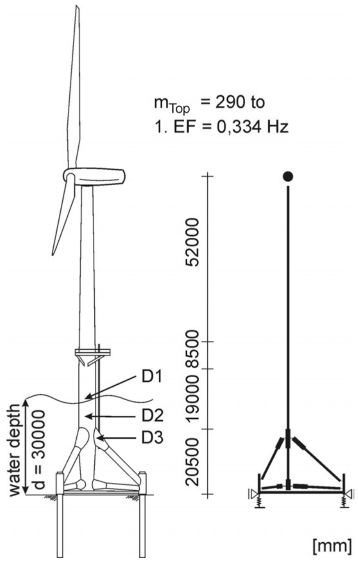

Figure 1: Tripod structure T-3 and numerical model

It has to be stated that this is not an optimised structure for a certain location but has been used in [9] for studies on different design methods. The dimensions are based on preliminary loads for the GE 3.6 MW machine.[1]

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[1] The preliminary loads have been provided to the authors by courtesy of GE WindEnergy, Salzbergen Germany.

The damage evaluation presented in this paper has been carried out for the details D1 to D3 marked in figure *1*. For detail D3 at the tripod joint the calculation of structural stresses is required for the fatigue assessment. The structural stresses are determined using the parametric formulas of Efthymiou and his concept of influence functions to take into account the spatial effects of the loading in the non planar braces, see [4]. The structural stresses used within this paper are determined for the chord-saddle location of the joint. A numerical evaluation of the stress concentration factors for this detail is not in the focus of this paper although some effects cannot be taken into account using the parametric equations and need further investigations for final design tasks.

4.2 Transfer Functions for Relevant Details

For the presented structure calculations in time domain have been carried out with the specific properties described in Table 1. The viscous damping factor is denoted with ζ within this paper. The JONSWAP spectrum has been modified to yield certain minimum values in the spectrum. This leads to more numerical stability for the determination of the transfer functions, see [9] for more details.

Simulation time	1200 s
Type of spectrum	JONSWAP_mod
ζ	0.03
Sea state for TF1	H_S=1.5 m; T_Z=5.5 s
Sea state for TF2	H_S=2.5 m; T_Z=6.5 s

Table 1: Parameters for the representative calculations

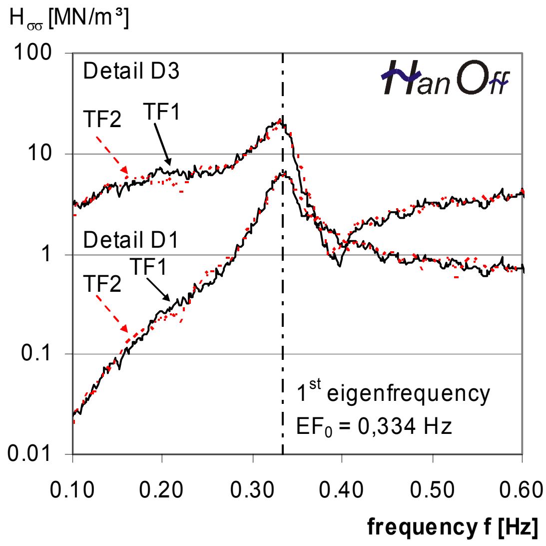

Figure 2: Numerically determined transfer functions for details D1 and D3, based on different sea states TF1 and TF2

The transfer functions for the different details in Figure 2 show a good agreement between the realisations TF1 and TF2. Additionally some aspects of the typical behaviour of support structures for OWECs can be seen. The static fraction of the structural answer is quite small for detail D1 that means that the dynamic behaviour plays a significant role for the fatigue assessment. This is caused by the fact that the static loads are quite small in this part of the structure in comparison to the inertia forces of the top mass caused by the dynamic structural reaction. For detail D3 the static fraction of the reaction is significantly higher.

This can be seen as an example that simplified dynamic models which do not take into account this specific behaviour can lead to misinterpretation of the calculated damage values. Therefore deterministic methods which use only one dynamic amplification factor for the whole structure cannot describe the typical dynamic behaviour of support structures of OWECs, see [9] for a detailed discussion.

	Rainflow count time series TF1	Hybrid with TF1	Hybrid with TF2
D1	2.20E-07	2.23E-07	1.92E-07
D2	5.27E-07	5.46E-07	4.75E-07
D3	4.85E-03	5.00E-03	4.53E-03

Table 2: Damage values rainflow count versus hybrid analysis for sea state H_S = 1,5 m; T_Z = 5,5 s; reference period: 20 years

The fatigue evaluation has been done assuming S-N-curves as defined in the GL-guidelines. It can be seen in table *2* that the fatigue assessment in the time domain using rainflow counting and in the frequency domain using Dirliks formula lead to a very good agreement. The agreement has the same quality for different locations. Even for detail D1 which is located at the still water line the differences in the predicted damage values are smaller than 10% for both transfer functions compared to the rainflow count. This is a remarkable result because calculations in the frequency domain with transfer functions based on simplified methods have been recently found not to predict the damage very well for support structures of wind energy converters at still water line, see for example [11]. With the presented hybrid method this disadvantage can be overcome.

4.3 Fatigue Damage in North and Baltic Seas

Using the hybrid analysis method the fatigue damage caused by wave loading can be calculated for different locations using the transfer functions shown above. The results for transfer function TF1 are presented in table *3* for one location in northern North Sea (Hogben), one in southern North Sea (FINO1), and one in Baltic Sea.[2]

In table 3 the predicted damage values for the details D1 to D3 are shown for a reference period of 20 years. For detail D3 with a comparatively high static fraction in the structural reaction as explained earlier the highest damage values occur for the northern North Sea environment with its significantly higher waves. Contrary to this for the details D1 and D2 the

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[2] The corresponding wave scatter diagrams are presented in [9]. Partly they are based on literature (Hogben). Partly they have been provided to the authors by courtesy of the Institute of Fluid Mechanics at the University of Hannover (FINO1 ISEB) and OTP GmbH, Rostock (Baltic Sea).

highest damage values occur for Baltic Sea conditions. For these details the dynamic reaction plays a significant role and additionally for Baltic Sea conditions the sea states with high energy fractions are shifted to smaller zero crossing periods. Therefore for the natural period of the exemplary structure resonance effects have to be expected for a significant fraction of the sea states.

Detail	North Sea (Hogben)	Baltic Sea	FINO 1 ISEB
D1	8.88E-06	5.99E-05	5.13E-07
D2	2.08E-05	1.09E-04	1.22E-06
D3	1.83E-01	8.08E-02	1.66E-02

Table 3: Predicted damage values for different locations based on transfer function TF1, reference period: 20 years

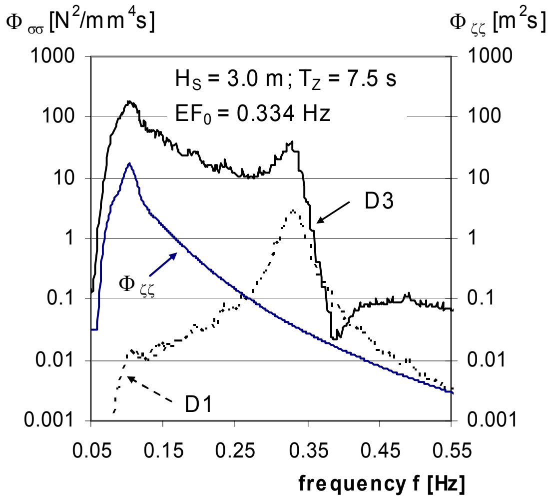

Figure 3: Stress spectra for details D1 and D3; sea state H_S = 3.0 m; T_Z = 7.5 s

The typical behaviour of the different details is illustrated in figure 3. For an exemplary sea state with a comparatively high value for the zero-crossing-period of $T_Z = 7.5$ s the corresponding stress spectra for details D1 and D3 are displayed. For detail D3 a significant fraction of the structural reaction can be found for frequencies between 0.1 and 0.2 Hz where the wave spectrum contains its main fraction of energy. In contrary for detail D1 the peak in the stress spectrum can be found between 0.3 and 0.4 Hz where the resonance of the structure has to be expected (1st natural period EF_0 = 0,334 Hz). For such details the formulation of the wave spectra for high frequencies can have a significant influence on the predicted damage values. This behaviour strongly depends on the dynamic behaviour and therefore on the damping characteristics. For the calculations presented here a damping value of $\zeta = 0.03$ has been used. For higher damping values the dynamic influence mitigates and consequently for environments with higher dynamic effects like the Baltic Sea the predicted damage values will decrease comparatively more than for North Sea conditions.

5. Conclusion

In this paper the application of the hybrid time-frequency domain fatigue analysis which has been developed for deepwater offshore platforms is discussed for OWECs. It has been demonstrated that with this method recently discussed disadvantages of the calculation in frequency domain can be overcome and an efficient damage prediction for support structures under wave loading becomes possible. A comparison between damage values calculated for different locations has been presented which shows that for details near to the still water line which are highly dynamically sensitive higher damage values can occur for Baltic Sea conditions than for North Sea conditions. The design tool *Han-Off* has been used for the presented calculations which has been developed within the last years by the co-author.

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