Evaluation of Different Damage Prediction Methods for Support Structures of Offshore Wind Energy Converters

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ABSTRACT

Within this paper calculations in the frequency domain are discussed for the fatigue evaluation of support structures of offshore wind energy converters (OWECs) under wave loads. Different possibilities of modeling the dynamic behavior of support structures of OWECs are discussed and restrictions of simplified conventional methods are shown. Also the different damage prediction methods are compared and an extension of often used methods is introduced to take S-N-curves with varying slopes into account.

KEY WORDS: Offshore Wind Energy; Fatigue; Wave Loading; Frequency Domain; Monopile; Han-Off

INTRODUCTION

An increasing number of wind energy converters has recently been installed in offshore environments. This development leads to the demand of combining design concepts for wind energy converters and offshore structures. Within the research projects with the short titles "GIGAWIND" and "GIGAWIND plus", which are funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety of Germany, the authors are working on different aspects of this question.

Concepts for the fatigue design of offshore structures use deterministic design methods or calculations in the frequency as well as in the time domain. A hybrid time-frequency domain fatigue analysis can be used to significantly reduce the amount of calculation time for the support structure under wave loading.

The calculations in frequency domain as well as the hybrid analysis technique result in a description of the stress distribution for each considered sea state in the frequency domain. It is therefore necessary to predict the damage of structural details from this distribution. Within this paper several approaches from the literature are compared with respect to realistic conditions of the sea environment. In accordance to design guides provided by Germanischer Lloyd (2004) or NORSOK (1998) the calculations should consider S-N-curves with varying slopes. Such varying slopes can not be integrated in all of the existing approaches. Therefore a possible extension to cover such S-N-curves is presented and discussed. Instead of an equivalent stress range parameter this extension uses an equivalent damage value which will be determined by numerical calculations. Comparative calculations will show the influence of the varying slopes on the fatigue damage prediction.

A simplified dynamic modeling can lead to unrealistic estimation of the structural reactions. This problem will be discussed for typical monopile support structures of OWECs. Monopile structures will be used because most of the exsisting OWECs have been built using this structural concept. The simplified modeling method is discussed in comparison to the more complex harmonic response analysis method. The calculations have been carried out using the software tool *Han-Off* which has been developed at the Institute for Steel Construction within the last years.

DESIGN TOOL HAN-OFF

For the calculations presented in this paper the design tool *Han-Off* has been utilized. This tool has been developed within the last years parallel to the work on the research project GIGAWIND and interacts with the commercial FEM package ANSYS©. The tool is capable of predicting wave loads on hydrodynamic transparent structures for regular waves and irregular sea states. An interface to the program WaveLoads exists for the integration of higher order wave theories. WaveLoads has been developed at the Institute for Fluid Mechanics at the University of Hannover, see Zielke et al. (2002), also within the GIGAWIND-project. Comparisons have shown a good agreement of *Han-Off* 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 Kleineidam (2005). It is stated there that for water depths of about 30 m, which are relevant for the presented fatigue calculations, the use of linear wave theory leads to a good estimation of the loads.

Additionally 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 Kleineidam (2005) for more details.

DESIGN CONCEPTS FOR OWECS

For onshore wind energy converters the design of the structures is mainly influenced by wind loads and the loads from the generator which are resulting of the wind forces on the rotor and are depending on the control properties of the generator. These loads are also important for the structural design of OWECs. But with increasing water depth the role of the wave loads increases. For the final design the wind and wave loads have to be combined in a suitable manner. For earlier design stages a separate calculation of the resulting forces with a combination afterwards can be helpful. In this case for fatigue calculations the combination method described by Kühn (2001) could be used. Within this paper concepts for the design of support structures of wind energy converters under wave loads are discussed.

Concepts for the fatigue design of oil and gas platforms vary from deterministic design methods, calculations in the frequency domain to calculations in the time domain. Calculations in the time domain are applied also to the actual generation of multi megawatt onshore wind energy converters. The deterministic design method should be applied only for very stiff structures as has been shown by Kleineidam (2005). The concept of calculations in the time domain is the most comprehensive one of the considered concepts and it would be helpful, at least for early design stages, to have methods with a smaller amount of calculation time. Calculations in the frequency domain are discussed within this paper as a more effective calculation method for monopile support structures of OWECs.

CALCULATIONS IN THE FREQUENCY DOMAIN

Stochastic Concept

A sea state can be characterized by its stochastic properties. If a support structure is exposed to such a stochastic load process, the reaction of the structure will also be a stochastic process as described by Natke (1992). The sea state as underlying physical process can be described by a spectrum of the wave energy $\Phi_{\zeta\zeta}(\omega)$. Also the structural reaction can be described by a spectrum for example by spectra of the stresses $\Phi_{\sigma\sigma}(\omega)$ for the different structural details. To use this method for calculation purposes the correlation between the sea state and the reaction of the structure has to be described also in the frequency domain. Formally this correlation can be described using transfer functions $H_{\sigma\sigma}(\omega)$ for every structural detail, as given in Eq. 1.

$$\Phi_{\sigma\sigma}(\omega) = H_{\sigma\sigma}{}^2(\omega) \cdot \Phi_{\zeta\zeta}(\omega) \qquad (1)$$

Within the offshore oil and gas industry the transfer functions for such calculations are often based on deterministic single waves. This procedure is used within this paper and is described in detail by Vugts and Kirna (1976). Within this procedure it is necessary to choose different wave periods for a corresponding wave height. Vugts and Kinra recommended to choose waves with a constant steepness. Exemplary calculations for typical support structures of OWECs have shown that the influence of waves with a different steepness is quite small for the frequencies discussed in this paper, see Kleineidam (2005). The wave periods have to be taken into account for the calculation of the dynamic structural reaction which will be discussed within the next paragraphs. The procedure is shown schematically in Fig. 1.

Modeling of Dynamic Effects

Dynamic excitation of a certain frequency leads to a dynamic structural reaction in the same frequency. The amplitude of the reaction, expressed for example in terms of stresses, depends on the dynamic properties of the structure as well as on the distribution and the magnitude of the exciting forces. Different methods could be used to take the dynamic behavior of the structure into account. In the following the usage of dynamic amplification factors is discussed in combination with a reduction of the dynamic behavior to a one-mass-spring system. Compared to that, the results of a more complex dynamic modeling will be discussed using a harmonic response analysis under consideration of the distribution of stiffness and mass of the underlying structure.

Simplified Dynamic Modeling. For support structures of OWECs beside the stiffness of the structure the top mass consisting of rotor and nacelle has a significant influence on the dynamic behavior. As a simplified model a one-mass-spring system is discussed here. For this

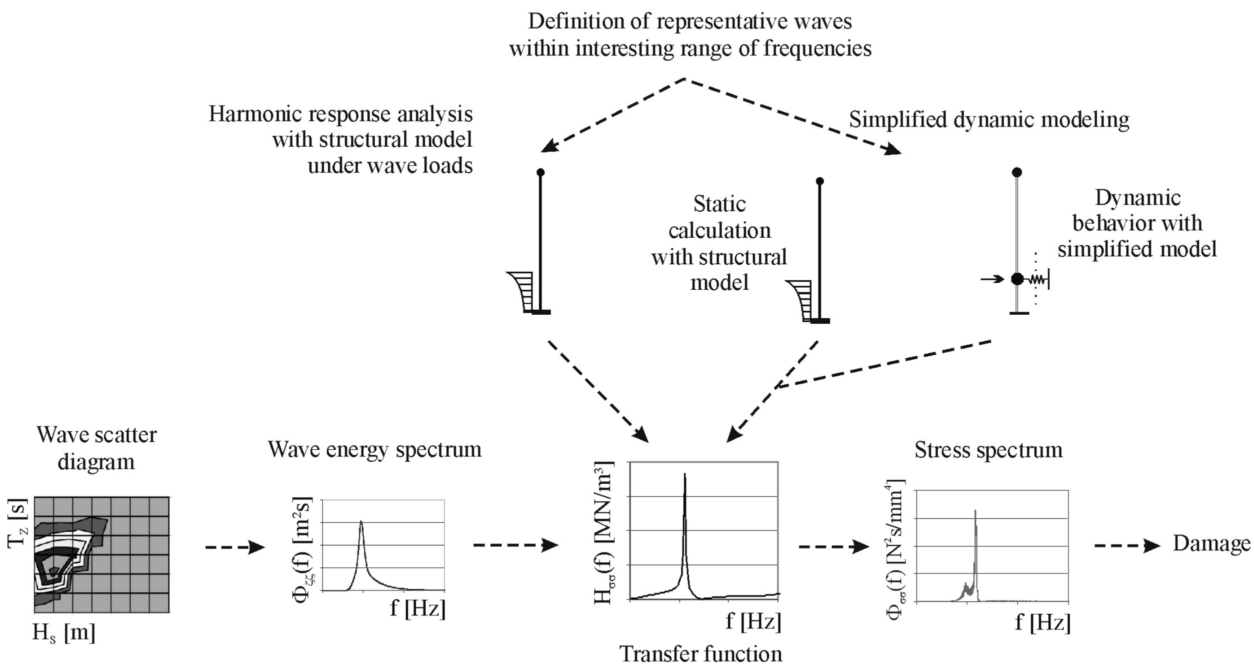


Fig. 1. Scheme of calculations in the frequency domain, based on Kleineidam (2005)

kind of system dynamic amplification factors DAF can be calculated analytically as given in Eq. 2.

$$\text{DAF} = \frac{1}{\sqrt{\left(1-\left(\frac{\Omega}{\omega}\right)^2\right)^2 + \left(2\cdot\zeta\cdot\frac{\Omega}{\omega}\right)^2}} \tag{2}$$

with
Ω rotational frequency of the excitation
ω natural frequency of the one-mass-spring system
ζ viscous damping factor

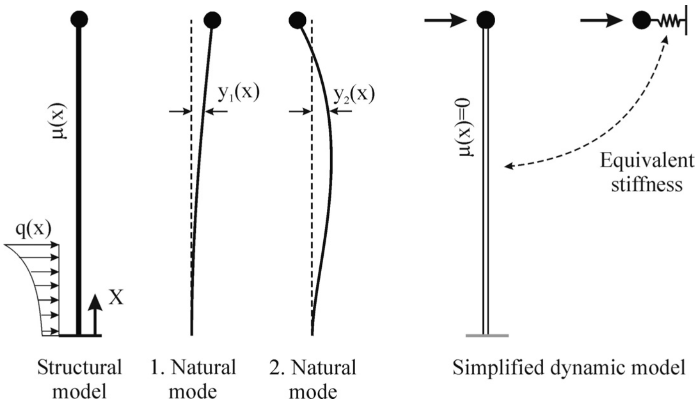


Fig. 2. Structural model and simplified dynamic model for determination of DAF, based on Kleineidam (2005)

These DAF are used to represent the dynamic reactions of the whole structure. The difference between the static structural model and the dynamic model which is used to integrate the dynamic influences is displayed in Fig. 2.

Harmonic Response Analysis. Using the simplified method described above influences resulting from the location and the distribution of the exciting forces as well as influences resulting from the distribution of the stiffness and the mass cannot be taken into account. To overcome this restriction alternatively a numerical harmonic response analysis can be carried out. With a harmonic response analysis the dynamic response of a system can be determined for harmonic excitations. The exciting wave loads are calculated for every frequency using the linear wave theory. The harmonic response analysis is described by the authors in more detail in Schaumann and Kleineidam (2002). It should be borne in mind that in this case the dynamic model is identical to the structural model.

FATIGUE 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. Possible techniques are discussed in the following sections.

Basic Assumptions

It is common use to base the damage evaluations for constructional details of steel structures on Miners damage accumulation method, given in Eq. 3.

$$D = \sum_i \frac{n_i}{N_i} \tag{3}$$

For different classes of stress ranges $\Delta\sigma_i$ the corresponding number of allowable stress cycles N_i has to be calculated. This corresponds to the S-N-curve relevant for the detail.

For stresses described in the frequency domain as discussed here the probability of different stress ranges has to be determined. Assuming a constant slope of the S-N-curve often equivalent stress ranges $\Delta\sigma_{equ}$ are calculated for every stress spectrum. The stress ranges are referred to the slope of the S-N-curve and are calculated as given in Eq. 4, see e.g. Chaudhury and Dover (1985) for more details.

$$\Delta\sigma_{equ}{}^m = \int_0^\infty \left(\Delta\sigma^m \cdot p(\Delta\sigma)\right) d\Delta\sigma \tag{4}$$

The allowable number of stress cycles N for a certain stress range $\Delta\sigma$ can be calculated from the S-N-curve according to Eq. 5. In this equation a denotes the constant value of the S-N-curve while m denotes the slope of the S-N-curve. The variables are used in accordance with Eurocode 3.

$$N = \frac{a}{\Delta\sigma^m} \tag{5}$$

The number of stress cycles n which are expected to occur during a certain time period T can be calculated based on the assumption of a narrow band stress spectrum using Eq. 6. This equation is based on the calculation of the expected number of peaks E[P] of the process.

$$n = E[P]\cdot T = \sqrt{\frac{m_4}{m_2}}\cdot T \tag{6}$$

In this equation m_i denotes the i-th moment of the spectrum S_{ZZ} which are calculated using Eq. 7.

$$m_n = \int_{-\infty}^{\infty} \omega^n \cdot S_{ZZ}(\omega)d\omega \tag{7}$$

Using these equations a value for the expected damage E[D] can be calculated as it is given in Eq. 8. It has to be considered that in this equation the equivalent stress range is used.

$$E[D] = \frac{n}{N} = \sqrt{\frac{m_4}{m_2}}\cdot T \cdot \frac{\Delta\sigma_{equ}{}^m}{a} \tag{8}$$

For practical cases the equivalent stress range has to be calculated. In the literature some formulas can be found which are based on an analytical solution of Eq. 4. These solutions are also based on the assumption of a constant slope of the S-N-curves. The effect of this assumption in comparison to S-N-curves as they are required by the guidelines for support structures of OWECs will be discussed in the next sections. Some of the analytical solutions for the equivalent stress ranges are given in equations 9 ~ 11. Eq. 9 is based on the assumption of a narrow band spectrum while in Eq. 10 and 11 different adaptations taking into account more realistic properties of the spectra are given which have been introduced by different authors.

- Narrow band spectrum, see Chaudhury and Dover (1985)

$$\Delta\sigma_{equ}{}^m = \left(2\cdot\sqrt{2\cdot m_0}\right)^m \cdot \left[0.75\cdot\Gamma\left(\frac{m+2}{2}\right)\right] \tag{9}$$

- Hancock and Gall (1985)

$$\Delta\sigma_{equ}{}^m = \left(2\cdot\sqrt{2\cdot m_0}\right)^m \cdot \left[\alpha\cdot\Gamma\left(\frac{m+2}{2}\right)\right] \tag{10}$$

- Chaudhury and Dover (1985)

$$\Delta\sigma_{equ}{}^m = \left(2\cdot\sqrt{2\cdot m_0}\right)^m \cdot \left[\frac{\varepsilon^{m+2}}{2\cdot\sqrt{\pi}}\cdot\Gamma\left(\frac{m+1}{2}\right) + \left(1+\text{erf}(x)\right)\cdot\frac{\alpha}{2}\cdot\Gamma\left(\frac{m+2}{2}\right)\right] \tag{11}$$

The error function erf(x) in Eq. 11 can be estimated as described by Bishop (1994). This approximation is given in Eq. 12.

$$\begin{aligned}\text{erf}(x) = {} & 0.3012\cdot\alpha + 0.4916\cdot\alpha^2 + 0.9181\cdot\alpha^3 \\ & -2.3534\cdot\alpha^4 - 3.3307\cdot\alpha^5 + 15.6524\cdot\alpha^6 - 10.7846\cdot\alpha^6\end{aligned} \tag{12}$$

Within these equations α and ε describe the properties of the underlying stress spectra. The irregularity factor α and the band width parameter ε can be defined as given in the following equations, see for example Chaudhury and Dover (1985):

$$E[0] = \sqrt{\frac{m_2}{m_0}} \tag{13}$$

$$\alpha = \frac{E[0]}{E[P]} \tag{14}$$

$$\varepsilon = \sqrt{1-\alpha^2} \tag{15}$$

As described above equations 9 ~ 11 are based on the assumptions of a constant slope of the S-N-curve. The implications of this simplification will be discussed in the following paragraphs with respect to realistic S-N-curves.

S-N-Curves with Varying Slopes

For practical cases the use of S-N-curves with changing slopes is required by certain design codes like Eurocode 3 (2002), NORSOK (1998) or GL (2004) and must therefore be taken into account for support structures of OWECs. Typical S-N-curves for the same structural detail are shown in Fig. 3. It can be seen that there are differences between the codes. Especially within offshore and wind energy codes no cut-off limit $\Delta\sigma_L$ is used. Within the design concept of the Eurocode the cut-off limit defines a limit below which stress ranges of the design spectrum do not contribute to the calculated cumulated damage.

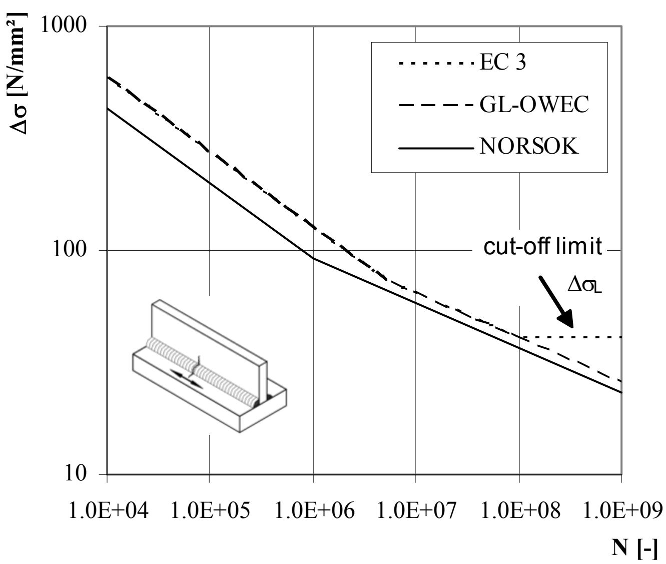


Fig. 3. S-N-curves for a repaired automatic or manual fillet or butt weld as an exemplary detail category according to different guidelines

Equivalent Number of Allowable Stress Cycles N_{Equ}

An equivalent number of allowable stress cycles has been introduced by the author in Kleineidam (2005). This concept can be used to take into account S-N-curves with different slopes. It is based on the following principles:

For every stress range the number of allowable stress cycles can be calculated from the S-N-curve. If also the probability density function of the stress ranges of the underlying stress spectrum is known a number of allowable stress cycles for this stress spectrum can be calculated by a numerical integration. This concept can be seen as an extension to Eq. 4 and is given in Eq. 16.

$$N_{equ} = \frac{1}{\int_0^\infty \left(\frac{\Delta\sigma^{m(\Delta\sigma)}}{a(\Delta\sigma)} \cdot p(\Delta\sigma) \right) d\Delta\sigma} \tag{16}$$

The concept will be shown for an example. Assuming for a certain detail that 80% of the stress cycles occur with $\Delta\sigma$ = 50 N/mm² and 20% of the stress cycles with $\Delta\sigma$ = 100 N/mm² the equivalent number of allowable stress cycles can be calculated according to Eq. 17, see Tab. 1 for interim values. For this example a detail category 100 according to Eurocode 3 has been used.

$$N_{equ} = \frac{1}{\sum p_i / N_i} = \frac{1}{1.23 \cdot 10^{-7}} = 8.13 \cdot 10^6 \tag{17}$$

Table 1. Example for application of equivalent number of allowable stress cycles, values for detail category 100 according to Eurocode 3

i	$\Delta\sigma_i$	p_i	m	log a	N_i	p_i/N_i
[-]	[N/mm²]	[-]	[-]	[-]	[-]	[-]
1	50	0.8	5	16.036	3.5E+07	2.30E-08
2	100	0.2	3	12.301	2.0E+06	1.00E-07
	sum	1.0				1.2302E-07

If a number of 4.00 E6 stress cycles is expected to occur the damage value can be determined as given in Eq. 18.

$$D = \frac{n}{N_{equ}} = \frac{4.00 \cdot 10^6}{8.13 \cdot 10^6} = 0.492 \tag{18}$$

Alternatively the same damage value can be calculated by determining the sum of the parts of the damage as given in Eq. 19.

$$D = \sum \frac{n_i}{N_i} = \frac{0.8 \cdot 4.00 \cdot 10^6}{3.5 \cdot 10^7} + \frac{0.2 \cdot 4.00 \cdot 10^6}{2.0 \cdot 10^6} = 0.092 + 0.400 = 0.492 \tag{19}$$

To use the concept of the equivalent number of allowable stress cycles for calculations in the frequency domain the probability density function of the stress ranges has to be known. One possible definition of this function has been described by Lin (1976) with its mathematical background. He defines the probability density function of the stress peaks as it is given in Eq. 20.

$$p(\sigma) = \frac{\varepsilon}{\sqrt{2\cdot\pi\cdot m_0}} \cdot \exp\left(-\left(\frac{x}{\alpha}\right)^2\right) + \frac{x\cdot\varepsilon}{\sqrt{2\cdot\pi\cdot m_0}} \cdot \left(1+\mathrm{erf}(x)\right) \cdot \exp\left(-\left(\frac{\varepsilon\cdot x}{\alpha}\right)^2\right)$$

with $$x = \frac{\sigma\cdot\alpha}{\sqrt{2\cdot m_0}\cdot\varepsilon} \tag{20}$$

For this equation the error function as defined in Eq. 10 can be used. Assuming that the stress spectrum represents a process with a zero mean value, the stress ranges can be derived which are necessary for the damage evaluation.

Based on extensive numerical investigations Dirlik (1985) has developed a description of the probability density function of the stress ranges which is nowadays favoured by Kühn (2001) or Bishop (1994). It represents an empirical correlation between the probability density function and the moments of the underlying stress spectrum and it is given in Eq. 21.

$$p(\Delta\sigma) = \frac{\frac{D_1}{Q} \cdot e^{\frac{-Z}{Q}} + \frac{D_2 \cdot Z}{R^2} \cdot e^{\frac{-Z^2}{2 \cdot R^2}} + D_3 \cdot Z \cdot e^{\frac{-Z^2}{2}}}{2 \cdot (m_0)^{0,5}} \tag{21}$$

with $Z = \frac{\Delta\sigma}{2 \cdot (m_0)^{0,5}}$ $\quad x_m = \frac{m_1}{m_0} \cdot \left[\frac{m_2}{m_4}\right]^{0,5}$

$R = \frac{\alpha - x_m - D_1^2}{1 - \alpha - D_1 + D_1^2}$ $\quad D_1 = \frac{2 \cdot (x_m - \alpha^2)}{1 + \alpha^2}$

$D_2 = \frac{1 - \alpha - D_1 + D_1^2}{1 - R}$ $\quad D_3 = 1 - D_1 - D_2$

$Q = \frac{1.25 \cdot (\alpha - D_3 - (D_2 \cdot R))}{D_1}$

The author also has carried out comparative investigations of the damage evaluation in frequency and time domain using the design tool *Han-Off*. The damage evaluation of the time series has been executed with the rainflow counting method as it is described by Clormann and Seeger (1986). For the damage evaluation in the frequency domain the presented formulation of Dirlik has been utilized after shifting the time series into the frequency domain by a fast fourier transformation. The agreement of the results is very good. The differences between the different methods are small (about only 10%) as it has been presented in Schaumann and Kleineidam (2004). For a good agreement of the results it is important that exactly the same sector of the time series is used for both types of evaluation.

Comparative Damage Evaluations in Frequency Domain

To evaluate the influence of both, the evaluation methods in frequency domain and the influence of the S-N-curves with different slopes, comparative calculations have been carried out. The comparisons are based on stress spectra which are calculated using an analytical formula. This formula has been proposed by Wirsching and Light (1980) and is given in Eq. 22. Chaudhury and Dover (1985) have also used this formula. With Eq. 22 realistic stress spectra can be derived for different sea states. The characteristics of these stress spectra are determined which are necessary for the damage evaluation as described above.

$$\Phi_{\sigma\sigma}(f) = A \cdot H_S{}^Q \cdot \frac{\exp\left(-\frac{1050}{(2 \cdot \pi \cdot T_D \cdot f)^4}\right)}{T_D{}^4 \cdot (2 \cdot \pi \cdot f)^5 \cdot \left(\left(1 - \left(\frac{f}{f_0}\right)^2\right)^2 + \left(\frac{2 \cdot \xi \cdot f}{f_0}\right)^2\right)} \tag{22}$$

with
- $A = 5580$ — scale factor
- H_S — significant wave height [m]
- T_D — peak period of sea spectrum [s]
- $f_0 = 0.286$ — 1st eigenfrequency of the system [Hz]
- $Q = 3.25$ — exponent for nonlinear influence of the wave height [-]
- $\xi = 0.02$ — damping parameter

With these values the analytical expression has also been used by Wirsching and Light (1980).

Table 2. Sea data

Sea state [-]	H_S [m]	T_D [s]	Fraction of time [-]	Irregularity factor α [-]
1	16.01	17.3	0.0000368	0.507
2	14.48	16.5	0.0000932	0.535
3	12.96	15.8	0.00037	0.560
4	11.43	14.7	0.0022	0.604
5	9.9	13.6	0.0073	0.652
6	8.38	12.7	0.0135	0.694
7	6.86	11.6	0.0265	0.747
8	5.33	10.3	0.060	0.811
9	3.81	9.1	0.21	0.865
10	2.28	7.7	0.49	0.919
11	0.76	4.4	0.19	0.987

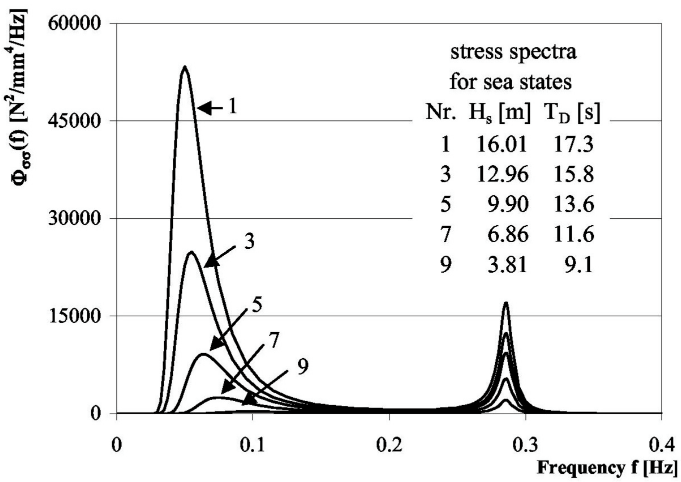


Fig. 4. Stress spectra for different sea states of table 2, based on Kleineidam (2005)

For the comparisons presented here stress spectra according to Eq. 22 have been used for the sea states shown in Tab. 2. The irregularity factor for each sea state can be seen in the last column of Tab. 2. The different stress spectra show a wide range of statistical properties. For some of the sea states the stress spectra are illustrated in Fig. 4.

Assuming that the fatigue life should be determined in agreement with the rules of Eurocode 3, for every stress spectrum a damage equivalent S-N-curve can be derived with a constant slope. To do this it is necessary to calculate the damage value firstly under consideration of the S-N-curve with different slopes and to fit then a S-N-curve with a constant slope to derive the same damage value. This damage equivalent S-N-curve can hardly be transferred to other sea states. For the example presented here the fatigue life is calculated with the different methods described above.

For the two methods which can take S-N-curves with different slopes into account a detail category of 100 is assumed. The S-N-curve is used without cut-off limit as it is required in the wind energy and offshore guidelines. It would be no problem to integrate a cut-off limit in the concept of fatigue life estimation presented here.

For the other methods a constant slope of the S-N-curve of m = 4 is used. The corresponding value for the determination of the S-N-curve log a = 14.2949 has been derived in that way that for the formula of Dirlik the same damage value is calculated for the sea state Nr. 6 with both S-N-curves.

Table 3. Damage values for sea states of Tab. 2 calculated with different methods for damage evaluation in frequency domain, reference period: 20 years

Sea state Nr.	S-N-curve, constant slope m = 4; log a = 14,2949				S-N curve, GL category 100	
	Narrow band	Hancock	Chaudhury Dover	Dirlik	Chaudhury Dover	Dirlik
1	0.01434	0.00969	0.00779	0.00727	0.00397	0.00354
2	0.02064	0.01469	0.01169	0.01106	0.00682	0.00619
3	0.04354	0.03248	0.02570	0.02454	0.01733	0.01598
4	0.13521	0.10876	0.08620	0.08288	0.06679	0.06265
5	0.21760	0.18891	0.15235	0.14591	0.13534	0.12788
6	0.16870	0.15585	0.12912	0.12222	0.12986	0.12222
7	0.12514	0.12446	0.10802	0.10007	0.11434	0.10528
8	0.09134	0.09851	0.09114	0.08236	0.08688	0.07732
9	0.06698	0.07712	0.07502	0.06731	0.05028	0.04422
10	0.01441	0.01763	0.01765	0.01620	0.00651	0.00587
11	0.00014	0.00018	0.00017	0.00018	0.00003	0.00003
Sum	0.898	0.828	0.705	0.660	0.618	0.571
Difference Dirlik S-N	57%	45%	23%	16%	8%	-

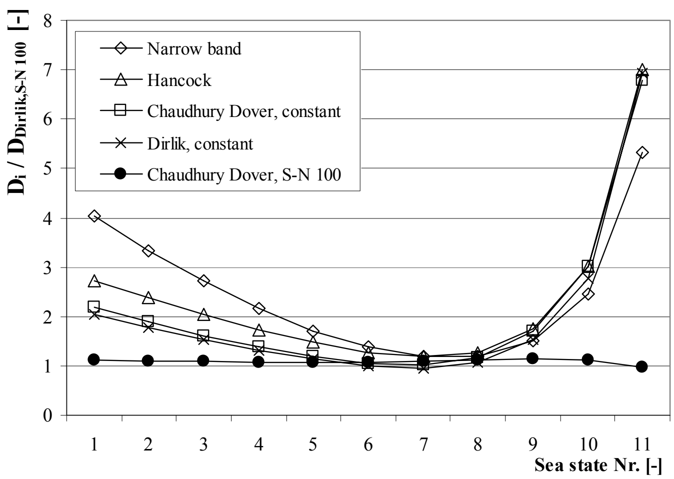


Fig. 5. Comparison of the related damage values of the different methods for the different sea states

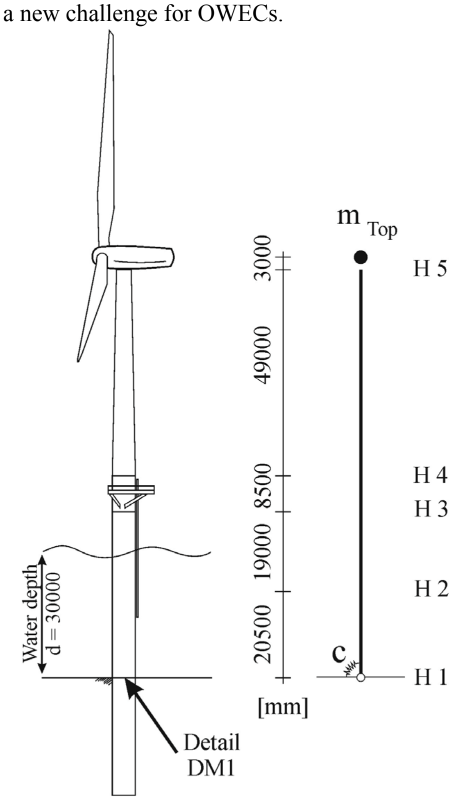
The results of the comparisons are given in Tab. 3. The calculated damage values are presented for the discussed example for a life time of 20 years and the fractions of time of the single sea states as given in Tab. 2. The results which have been derived with the formula of Dirlik for the S-N-curve with different slopes are used as reference values. This has be done because Buoyssy (1993) has shown in an extensive comparison that the formula of Dirlik leads to a very good estimate of damage values compared to a rainflow counting of corresponding time series. The sum of the damage values for all other methods discussed here is higher than for these reference values.

Discussion of the Different Methods

On first sight the usage of a S-N-curve with a constant slope seems to lead to acceptable results. But as Fig. 5 illustrates this is mainly depending on the chosen reference sea state for the determination of the corresponding S-N-curve with a constant slope. In Fig. 5 the damage values are displayed relative to the reference value for every sea state. For the sea states beside sea state Nr. 6 the agreement is quite good while for extreme sea states the differences are increasing up to factors of about 7. The relevance of the extreme sea states is quite small for the sum of the calculated damage because they possess either small probabilities of occurrence or small contents of wave energy. The methods based on the formula of Chaudhury/Dover or Dirlik show a very good agreement.
Stress spectra with higher numbers can be described very well as narrow band spectra. The assumption of a narrow band spectrum leads then to damage values which are comparable to other methods using a constant slope for the S-N-curve. For the stress spectra for sea states with lower numbers are getting broader the assumption of a narrow band spectrum leads to higher damage values.
For the damage evaluation of calculations in the frequency domain it is concluded that the presented enlargement of the methods to take S-N-curves with different slopes into account leads to more accuracy with only a small additional amount of calculation time.

EXEMPLARY CALCULATIONS FOR A MONOPILE STRUCTURE

To discuss the influence of the dynamic modeling on the calculated damage values comparative calculations in the frequency domain have been carried out. For these calculations a typical monopile structure has been used as displayed in Fig. 6. Especially the water depth of about 30 m, as it can be expected for wind parks in the German Bight, represents a new challenge for OWECs.



H	D [mm]	t [mm]
1	5800	80
2	5800	70
3	5800	40
4	5000	34
5	3450	20

Fig. 6. Exemplary monopile structure and static system with dimensions (diameter D and wall thickness t) for different heights, based on Kleineidam (2005)

For the calculations a top mass of 290 tons has been used to represent OWECs of 3~4 MW. As a representation of the dynamical properties of the system the rotational stiffness c at the mud line has been varied. The fatigue evaluations presented here have been carried out for the detail DM 1 at the mud line as marked in Fig. 6. The S-N-curve has been used as described in the GL guidelines assuming a detail category of 100, see Fig. 3. The partial safety factor for the material has been taken into account with a value of 1.25. For the fatigue evaluation Dirliks method has been used as described above.

Influence of the Dynamic Modeling

For this structure transfer functions are calculated using the simplified dynamic modeling as well as the harmonic response analysis. This is described in more detail by Kleineidam (2005). There it has been proved that the usage of the simplified dynamic modeling can not be used to predict the damage caused by the wave loads for typical structures of OWECs near to the still water line. Here results of calculations in the frequency domain are given for the mud line.
Within a parameter study the influence of the eigenfrequency and the damping properties on the calculated damage values has been investigated. Also the chosen dynamic model will be discussed. Different wave scatter diagrams as shown by Kleineidam (2005) are used for typical sea conditions in the North Sea and the Baltic Sea.

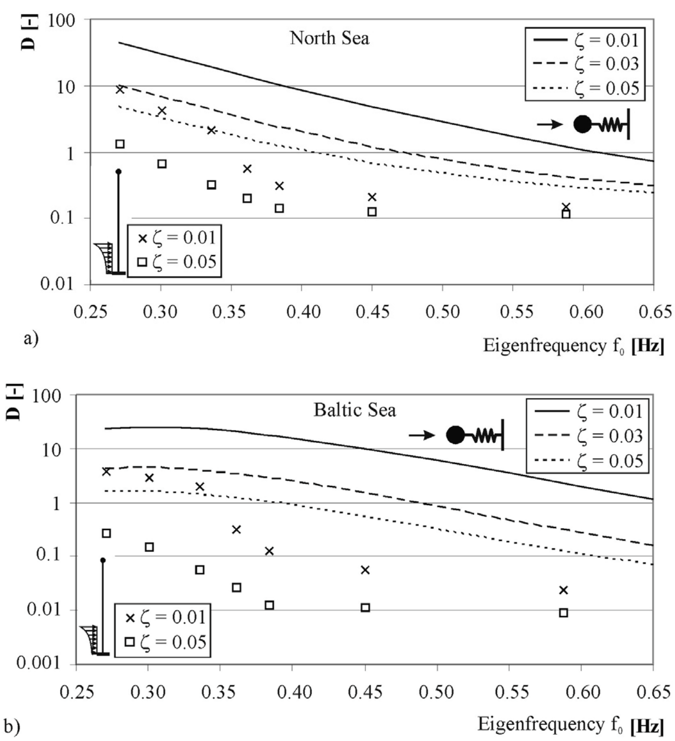


Fig. 7. Calculated damage values depending on eigenfrequency and viscous damping factor ζ for a) North Sea and b) Baltic Sea conditions, based on Kleineidam (2005)

In Fig. 7 calculated damage values are illustrated for the detail DM 1 depending on the eigenfrequency and the viscous damping factor for typical sea conditions in the North Sea and the Baltic Sea. The results are shown for the simplified dynamic modeling and the harmonic response analysis. For both sea conditions a significant influence of the damping on the results of the damage evaluation can be found. For smaller eigenfrequencies the damage values are increasing. This is caused by the fact that the distance between the eigenfrequency of the structures and the frequencies with significant contents of wave energy is getting smaller. For the Baltic Sea conditions frequencies with high wave energies are lying within the range of the investigated eigenfrequencies. This leads to comparatively high damage values even if the absolute damage values are still higher for the North Sea conditions than for Baltic Sea conditions using the harmonic response analysis. For nearly all eigenfrequencies the simplified dynamic modeling leads for Baltic Sea conditions to higher damage values than for North Sea conditions.
The dynamic parts of the structural reaction are significantly higher for the simplified dynamic modeling for detail DM 1 in all cases which have been part of the parameter study. This is caused by the typical distribution of the stiffness and the mass for OWECs and is described by Kleineidam (2005) in more detail. Because of the smaller dynamic influence for the harmonic response analysis the differences between the calculations with different damping values are getting smaller very fast for increasing eigenfrequencies. This effect can be found for the calculations using the simplified modeling too but only for significantly higher eigenfrequencies.
The differences in the dynamic modeling are illustrated in Fig. 8. There stress spectra for an exemplary sea state are illustrated for both types of dynamic modeling. Because of the quadratic influence of the transfer function for the calculation of the stress spectrum, see Eq. 1, the difference between the stress spectra is significant. This underlines the differences in the calculated damage values which have been pointed out.

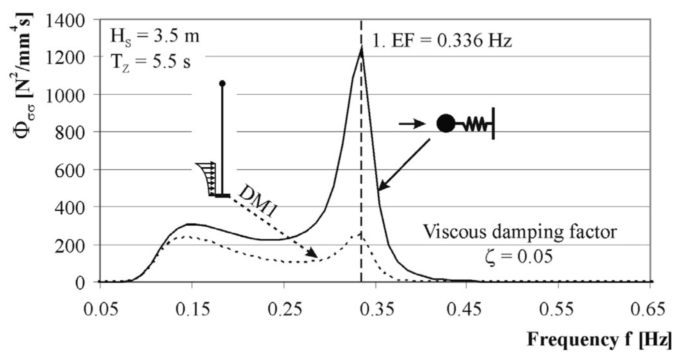


Fig. 8. Comparison of stress spectra for monopile structure at detail DM 1 for different dynamic modeling, based on Kleineidam (2005)

Discussion of the Results

Calculations in the frequency domain are a numerically very efficient method to evaluate the expected damage, if a transfer function is known for a fatigue detail. But the idealizations for the dynamic modeling have a significant influence on the results. It has been shown that for monopile structures of OWECs at the mud line under wave loads significantly higher damage values are determined when the simplified dynamic modeling is used. Additionally it has been pointed out based on Kleineidam (2005) that for details near to the still water line no realistic damage values can be calculated using the simplified dynamic modeling. For these reasons the simplified dynamic modeling should not be used for the calculation of support structures of OWECs even not for parametric studies in very early design stages. At least the distribution of the stiffness, the mass and the loads should be taken into account realistically. This can be done for example by using the harmonic response analysis. This method can be used very well for monopile structures as described in this paper. For complex support structures like for example tripod structures the numerical effort increases. In these cases 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 Kan and Petrauskas (1981), has been suggested and discussed for support structures of OWECs by Kleineidam (2005).

CONCLUSIONS

Within this paper calculations in the frequency domain are discussed for the fatigue evaluation of support structures of wind energy converters (OWECs) under wave loads. To deal with this question the paper is divided into two parts. Within the first part the calculation of fatigue values in the frequency domain is discussed with respect to typical S-N-curves which are required by the certification bodies for OWECs. The use of an equivalent number of allowable stress cycles has been introduced. This concept can take S-N-curves with varying slopes into account and uses the widely accepted formula of Dirlik for the description of the stress ranges of stress spectra in the frequency domain.

Within the second part of the paper the influence of the dynamic modeling is discussed for monopile support structures of OWECs. For calculations in the frequency domain it has been shown that a simplified dynamic modeling can hardly describe the dynamic behavior of support structures of OWECs. This is a result of the typical distribution of the masses and the stiffness. At least these distributions should be taken into account for example by using a harmonic response analysis.

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