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Development and Evaluation of Different Fatigue Design Methods for OWECs under Wave Loading

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ABSTRACT: In this paper two different approaches for the evaluation of the fatigue damage of the foundation structures of offshore wind energy conversion systems under wave loading are compared to each other. Software tools for the realisation of the different approaches have been developed and are used for the comparison of the methods. The time domain approach needs a huge amount of calculation time while it is postulated to give a more precise answer of the dynamic behaviour of the structure. The deterministic approach leads to comparable results and can be done in a short time and be therefore useful in early design stages, but it is quite sensitive to some assumptions like the relationship between wave height and period.

KEYWORDS: Offshore Wind Energy Converters, Wave Loading, Fatigue, Time Domain, Deterministic Method

1. INTRODUCTION

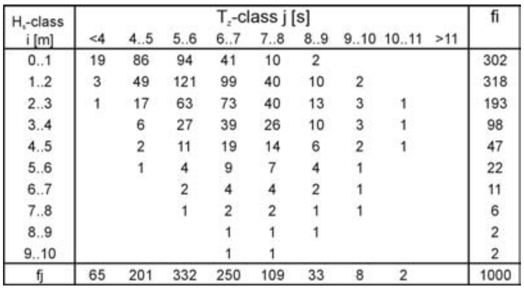
For the fatigue analysis of offshore-structures the corresponding guidelines require the anticipation of the stochastic properties of the long term distribution of the sea states which should be analysed in frequency domain. For Offshore Wind Energy Converters (OWECs), it is state of the art to perform load calculations for wind loading in the time domain. In order to provide an optimal compatibility between wind and wave loading it would be useful to perform time domain analyses for the wave loading as well. Besides the frequency domain, the time domain approach is assumed to deliver the most realistical results. Since calculations in time domain need vast amounts of calculation time, in this paper the use of a deterministic method is evaluated in comparison with time domain calculations. Because of the very short calculation times, the deterministic method seems to be very useful during predesign. For a direct comparison of the methods results are given for an example with the same characteristics in both cases. The work in this paper is concentrated only on the effects of wave loading, because in case of water depth of 30 m and more in North Sea environments it is expected that wave loading will be more significant compared to the influence of the fatigue damage of the wind. The studies presented here have been carried out within the research project GIGAWIND which is funded by the German Ministry of Economics, see http://www.gigawind.de for further details.

2. DETERMINISTIC APPROACH

The deterministic method used in this work is based on the descriptions of Hapel [3]. It is furthermore applied in commercial engineering program systems for offshore structures like for example STAAD.Pro with the Offshore Loading Modul, see [8] and [9]. The method consists of three essential parts which are described in the following section.

2.1 WAVE HEIGHT EXCEEDANCE DATA

The long term properties of the sea at the evaluated site are taken into account by developing a wave height exceedance diagram. This is based on the probability distribution of the different sea states which are commonly displayed in a wave-scatter-diagram. This study uses among others the wave-scatter-diagram for the North Sea presented in fig. 1 as it can be found in the literature, see Hogben [4].



H_s-class i [m]	T_z-class j [s]									fi
	<4	4..5	5..6	6..7	7..8	8..9	9..10	10..11	>11	
0..1	19	86	94	41	10	2				302
1..2	3	49	121	99	40	10	2			318
2..3	1	17	63	73	40	13	3	1		193
3..4		6	27	39	26	10	3	1		98
4..5		2	11	19	14	6	2	1		47
5..6		1	4	9	7	4	1			22
6..7			2	4	4	2	1			11
7..8			1	2	2	1	1			6
8..9				1	1	1				2
9..10				1	1					2
fj	65	201	332	250	109	33	8	2		1000

probability of sea-states [parts per thousand]

Fig. 1: Wave-scatter diagram of North Sea, according to Hogben [4]

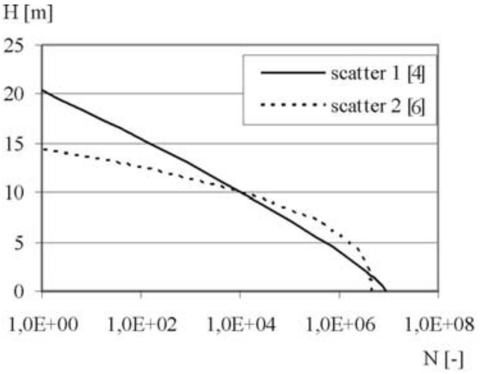


Fig. 2: Wave height-exceedance diagram, determined for wave-scatter-diagrams of North Sea

It is assumed in accordance with Hapel [3] that the probability distribution of the wave height classes can be fitted well using a Weibull-distribution. The parameters of the Weibull-distribution are calculated with a linear regression of the probability of the different wave heights. Using this distribution it can be determined how often a certain wave height will be exceeded, which leads to the wave height exceedance diagram as it is illustrated in fig. 2 for the parameters of fig. 1. In addition, fig. 2 shows the curve for another wave-scatter-diagram for the North Sea which can be found in [6]. The two curves show significant differences. Curve 1 leads to a higher value for the wave height exceeded once in a year. Curve 2 on the other hand shows higher numbers of waves with heights in the range from 2 to 10 meters. The effects of these differences are presented in chapter 4.

2.2 STRESS - WAVE HEIGHT DATA

The stress ranges corresponding to certain wave heights have to be calculated in the next step. For the determination of wave loadings regular waves are considered. Because regular waves are described by wave height and period the corresponding wave period has to be chosen.

The relationship between wave height and period is essential for the received stress ranges because it has an influence on the properties of the wave and on the dynamic response of the structure. One possibility is to take analytical assumptions which can be found in the literature, see e.g. [3]. Here two different assumptions are taken into account, further referred as method 1 and method 2.

Method 1 $T_{[s]} = 3{,}352 \cdot H_{[m]}^{0{,}559}$ (1)

Method 2 $T_{[s]} = 0{,}7 + 4{,}2 \cdot H_{[m]}^{0{,}4}$ (2)

Another possibility is to use the mean value of the wave periods for different wave heights derived from the wave-scatter-diagram, further referred as method 3. It should be noted that in this case the relationship between the mean wave height and the zero-crossing period is used.

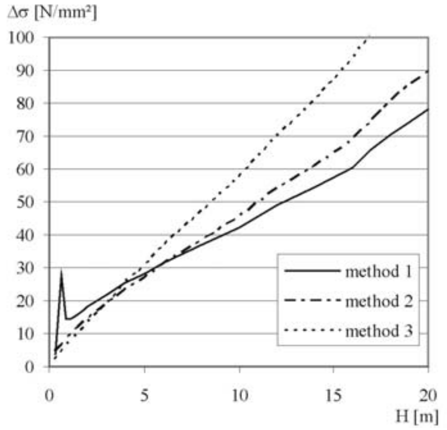


Fig. 3: Stress – wave height diagram for an example monopile, using different methods for the relationship between wave height and period for model 2

To refer to the dynamic behaviour of the structure a frequency response analysis is carried out for every considered wave to determine corresponding dynamic amplification factors. A further method of determining the dynamic amplification factor which is based on a combined deterministic-time-domain analysis is described in [5]. In fig. 3 stress – wave height diagrams are presented for an example structure using the three methods mentioned above. In this case, the methods 1 and 2 lead to quite similar curves. Only for small waves method 1 gives significantly higher stress ranges, which is an effect of the dynamic amplification factor because of the match between the wave period and the natural period of the structure. Method 3 results in significantly higher values for the stress range in case of wave heights more than 4 m.

2.3 FATIGUE ANALYSIS FOR DETERMINISTIC APPROACH

In the last step the fatigue analysis is carried out using the results of the first two steps by dividing the range of the wave heights in the wave height exceedance diagram in classes and determining the number of waves within these different classes. The corresponding stress range for every class is derived from the stress – wave height diagram. With this information the damage for every wave height class is calculated with Miner's rule.

$$D = \sum_i \frac{n_i}{N_i} \qquad (3)$$

In the examples mentioned in this paper nominal stresses are calculated and the allowable cycle number N is determined from the S-N-curve for a transverse butt weld which is treated very similar in different codes, as described in [10]. This approach can also be applied to complex joints if suitable stress concentration factors and adequate S-N curves are used.

3. TIME DOMAIN APPROACH

Any sea state in the real world would not consist of regular waves as mentioned above. Instead, a real sea state can be described by the superimposition of a large number of regular waves with a random phase shift:

$$\eta(t) = \sum a_i \cdot \cos(\omega_i \cdot t + \alpha_i) \qquad (4)$$

where a is the amplitude of partial wave i, ω its circular frequency and α_i an equally distributed random phase angle between 0 and 2π.

By simulating this superimposition of partial waves one gets a time series of sea state dependent water waves. In combination with the structure that is investigated a time series of structural strain results.

3.1 SEA STATES – WAVE ENERGY SPECTRA

The energy that is contained in the waves of a certain sea state can mathematically be described by certain wave energy spectra. Commonly used spectra are the Pierson-Moskowitz-Spectrum and the JONSWAP-Spectrum, which is a variation of the PM-Spectrum, adopting it especially to the conditions normally found in the North Sea [11] with limited fetch length. These spectra describe the wave energy depending on the two parameters significant wave height H_s and an associated wave period T_z, which both can be taken from a wave scatter diagram, see fig. 1.

The time domain approach uses the wave energy spectra to produce time series of a sea state by dividing the spectrum into as many slices as partial waves are needed for the superimposition. Thus, the amplitudes of the partial waves result to:

$$a_n = \sqrt{2 \cdot S_{zz}(\omega) \cdot \Delta\omega_n} \qquad (5)$$

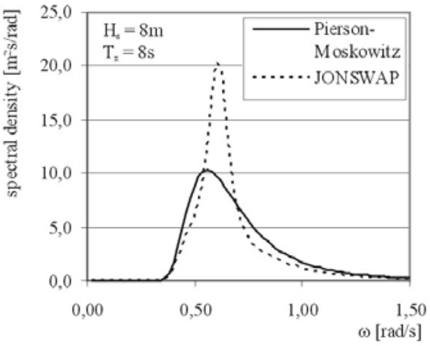


Fig. 4: Comparison of Pierson-Moskowitz- and JONSWAP-spectrum, both for a sea state characterized by H_s=8m, T_z=8s.

There are several different ways to achieve the discretisation of the spectrum [7]. The easiest way is to divide the spectrum into n slices of width $\Delta\omega$. A method producing intervals behaving irrational to each other has proven to be more feasible, because it reduces the periodicity in the generated time series of water motion :

$$\Delta\omega_n = \sqrt{\frac{n}{n+1}}\,\frac{\omega_{\max}}{\sum\sqrt{n/n+1}} \qquad (6)$$

The result of the discretization of the wave energy spectrum is a particular wave amplitude and period for each partial wave. This is used to calculate the kinematics of the partial wave using linear wave theory. The velocities and accelerations of the water particles of each partial wave can then be superimposed according to equation 4.

Since the applied linear wave theory is theoretically limited up to the still water level, the kinematics are calculated only up to this height. To consider values of the kinematics of the particles up to the calculated wave crest, in this study the so called Wheeler Stretching method is used, see [12].

The result of the process described above is a time series of water wave motion for the sea state characterized by the two input parameters H_s and T_z.

3.2 LOAD SPECTRA

The strain of the structure caused by the water motion is calculated by Morison´s equation. The structural response, e.g. in means of structural stresses, can be determined by using appropriate analysis methods. In order to take into account dynamic influences on the results the analysis carried out to calculate the stresses should be a transient analysis considering mass and damping forces of the structure.

The fatigue assessment is normally done using Miner's rule, see equation 3. Therefore, different stress ranges and the numbers of their occurrences are needed. Hence, a process that generates a load spectrum of the form stress range/number of occurrences out of the time series of structural stresses is needed. In this study, this is done by the Rainflow-Counting-Method [2].

4. APPLICATION AND COMPARISON OF METHODS

Software tools have been developed within the research project GIGAWIND to perform the operations that are required by these different approaches. The tools are based on the programmed simulation of the described regular waves and irregular sea states and are combined with a standard FE-program for the solution of the structural response. To compare the described methods for fatigue calculations of OWECs under wave loading in North Sea environment a number of calculations have been done. The basic environmental conditions had been chosen according to those which can be expected in the area of the first planned offshore wind parks in the German Exclusive Economic Zone (AWZ) and are described in more detail in [10]. For the foundation of the example structures monopiles are considered. Different sizes of the wind energy converters are taken into account by variing the top mass between 90 and 320 to. This leads to different diameters of the monopile and different eigenfrequencies of the structure.

The results of the time domain calculations are influenced by a number of parameters. It is very important to consider an appropriate time step for the wave loading and for the response of the structure. Due to the randomness of the simulated wave loading the length of the simulation has to be taken into account to make sure that the simulated time series represents the behaviour of the structure within the considered sea state realistically. The results presented in this paper are based on the following assumptions: the wave loading is calculated every 0.5 s and is interpolated between these points every 0.1 s, which is the time step for the calculation of the dynamic response of the structure. These parameters have shown a quite good agreement with calculations of smaller time steps for the examples presented here. The duration of the simulation has been considered with 600 s. This relatively short length has been chosen because of the huge amount of calculation time for the determination of the results for all the states of the wave scatter diagrams. Further calculations have shown that longer simulation durations may have an influence on the result. This is subject of further studies.

For reasons of a better comparison between the results the calculations using the described approaches are done with the same numerical model of the structure, see fig. 5, and the same theoretical background for the calculation of wave forces. This means that linear wave theory in combination with wheeler stretching is applied in both cases. To take into account the influence of steep waves the still water level is corrected for the calculation of regular waves as mentioned in [1]. The parameters in table 1 describe the structural properties and the dynamic behaviour of the structures that have been analysed in the presented calculations. The results of the calculation are compared in fig. 6 based on the damage at mudline for the above-mentioned detail category. It is assumed that the results of the time domain approach are more realistic than those of the deterministic approach. Beside the scatter diagram of fig. 1, which is referred as scatter 1, another diagram, referred as scatter 2, has been considered. Its wave-height exceedance diagram is displayed in fig. 2. The deterministic approach has been carried out using the three different methods for the relationship between wave height and period as described in chapter 2.2. It can be noted that the results of the time domain and the deterministic approach show good conformity for the scatter diagram 2 and the same behaviour for scatter diagram 1 even if there are some differences using the different wave height – period relationships.

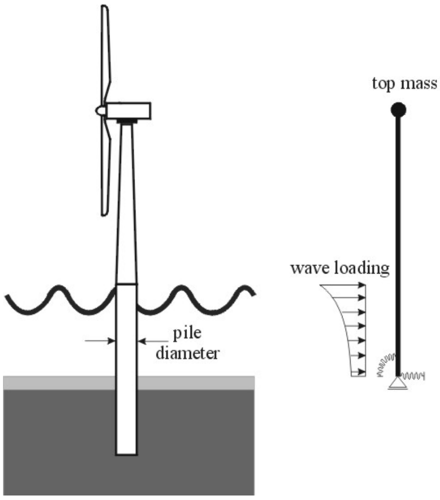


Fig. 5: Numerical model for calculations

Model [-]	hub height [m]	top mass [to]	pile dia- meter [m]	1. EF [Hz]
1	70	90	4	0.372
2	70	90	4.5	0.425
3	80	320	5.5	0.306

Table 1: Structural parameters of the models

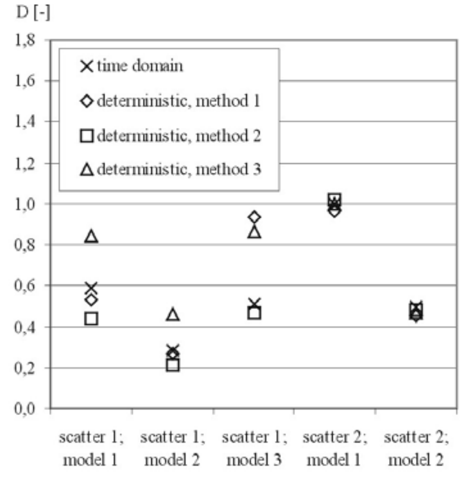


Fig. 6: Damage values for butt weld for different scatter diagrams, models and approaches

Method 2 shows the best results compared to the time domain analysis. An explanation for this behaviour can be found in the characteristics of the scatter diagrams. The probability of sea states whose mean period is close to the first natural period of the structure is significantly higher. This underlines that the described way of considering the dynamic effects within the deterministic approach is sensitive to the applied method for the relationship between wave height and period and should be used with caution. On the other hand, it can give a good hint which role is played by the fatigue damage of the waves for the structure with reasonable advantages concerning the calculation time.

5. CONCLUSIONS

In this paper two different approaches for a fatigue assessment of offshore structures under wave loading are presented. The approaches are applied on typical foundation structures for OWECs in North Sea environment. It has been shown that the deterministic approach leads to calculated values of structural damage which could be used for a very fast estimation of the fatigue that could be expected from the wave loading. Major uncertainties arise from the selected relationship between wave height and period. Therefore, in preliminary design this method could play a certain role for the evaluation and comparison of different types of structures. For a final design assessment in combination with the wind loading on the tower, calculations in the time domain are strongly recommended. Further investigations will be focused on the development of the deterministic approach for a better prediction of the damage. Furthermore, the quantification of the influence of simulation time for the time domain approach has to be clarified.

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