WAVE INDUCED FATIGUE LOADS ON MONOPILES - NEW APPROACHES FOR LUMPING OF SCATTER TABLES AND SITE SPECIFIC INTERPOLATION OF FATIGUE LOADS

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Summary: Offshore wind turbines are subject to dynamic excitation from wave loads. Especially when monopile substructures are used, significant fatigue loads can be induced by waves, which are then governing the design. Calculations in the frequency domain are very efficient to compute such wave induced loads and by applying some simplifications, very compact equations can be derived for the determination of fatigue loads. Based on such simplified formulas further methods for lumping of scatter diagrams and for interpolations of fatigue loads for different positions within a wind farm are presented in this paper.

1 INTRODUCTION

As monopile substructures for offshore wind turbines gain market share in ever deeper waters [1], wave excitation becomes more and more important. It is therefore crucial to gain good understanding of the relevant parameters and to develop tools for rapid calculation of fatigue loads, which are typically governing for the structural dimensions. Calculations in the frequency domain are a helpful method in this respect and with some simplifications, which can be applied to offshore wind turbines supported by monopiles, very compact equations can be derived to compute wave induced fatigue loads. Based on a method developed by the author in [2] some practical applications of the method are discussed in this paper.

2 FREQUENCY DOMAIN ANALYSIS

Calculations in the frequency domain are used frequently in the Oil&Gas industry to compute wave induced response of offshore structures. General information about this method can be found in Hapel [3] and Barltrop [4]. The general theory of frequency domain calculations is not repeated here for brevity. Symbols in general follow the notation used by Hapel [3], unless noted otherwise.

3 A SIMPLIFIED METHOD TO DETERMINE WAVE INDUCED FATIGUE LOADS

The method developed in [2] is briefly summarized in the following. As this paper does not include all notations and relevant background information, it should ideally be read together with [2].

3.1 Assumptions for the proposed simplified method

The following simplifications are made, which are acceptable for offshore wind turbines mounted on monopile substructures:

1. Only the first mode is considered for response calculations, as higher modes are outside of the frequency content from wave excitation.

2. Low structural damping is assumed, typically a modal damping ratio of ξ_0=1.0% is used for offshore wind turbines founded on monopiles.

3. As structural damping is low, the response can be assumed to be narrow-banded and only the region close to the first natural frequency ω_0 is relevant for all terms which are a function of ω.

4. Drag loading is neglected as this is small for fatigue waves.

5. Hydrodynamic damping is neglected as the velocity of the structure is small.

3.2 Summarized formula

With the assumptions listed above, a simplified expression can be derived to compute wave induced fatigue loads. The detailed derivation and definitions can be found in [2]. Fatigue loads are calculated as damage equivalent loads (DEL). See [2] regarding the conversion to other number of reference cylces.

$$\Delta M_{eq,Nref1Hz} = 1.8825 \cdot \sqrt{S_{\zeta\zeta}(\omega_0)} \cdot \frac{\Phi_0(z_{nac})}{K_0} \cdot \sqrt{\frac{1}{\xi_0}} \cdot \omega_0^{3/4} \cdot H_{a,0} \cdot H_{TB} \tag{1}$$

With:

$$H_{TB} = \omega_0^2 \cdot \int_{z=z_{TB}=0}^{z=z_{nac}} \Phi_0(z) \cdot \mu(z) \cdot z \cdot dz \quad \text{Transfer function tower bottom} \tag{2}$$

$$H_{a,0} = \rho \cdot \omega_0^2 \cdot \int_0^d C_M(z) \cdot \left[\pi \cdot \frac{D(z)^2}{4}\right] \cdot \eta_0(z) \cdot \Phi_0(z) \cdot dz \quad \text{Hydrodynamic transfer function} \tag{3}$$

These formulas can be easily evaluated analytically, only modal analysis needs to be performed numerically.

3.3 Conclusions

Some important conclusions can be drawn from this expression:

1. DELs are proportional to $(1/\xi_0)^{0.5}$ – i.e. if damping is e.g. doubled, then fatigue loads decrease by 30% ! This illustrates that damping is one of the major factors to assess reliably. Furthermore, damping assumptions should not be overly conservative to enable an economic design.
2. Damage is proportional to the square root of spectral wave energy at the first natural frequency. This is important when lumping of the scatter diagram shall be performed, as will be shown later.
3. Mode shape and hydrodynamic properties around the still water level are of particular importance. The hydrodynamic transfer function is linearly proportional to mode shape amplitudes in the wave loaded zone, as can be seen from Eq. (3). Reducing modal amplitude below still water level is therefore particularly helpful to reduce fatigue loads.
4. In total, fatigue loads are proportional to ω_0^3, when all other parameters are unchanged. This is an indication that a large head mass (from the turbine) is not necessarily disadvantageous, as this decreases the natural frequency.

4 LUMPING OF THE SCATTER DIAGRAM

In order to decrease the required number of calculations, the scatter diagrams (wind speed vs. wave height and wave height vs. wave period) are often condensed (or “lumped”). Ideally, lumping of the H_S-T_P-diagram is done in a way that both the quasi-static contribution and the dynamic (resonant) contribution is captured.

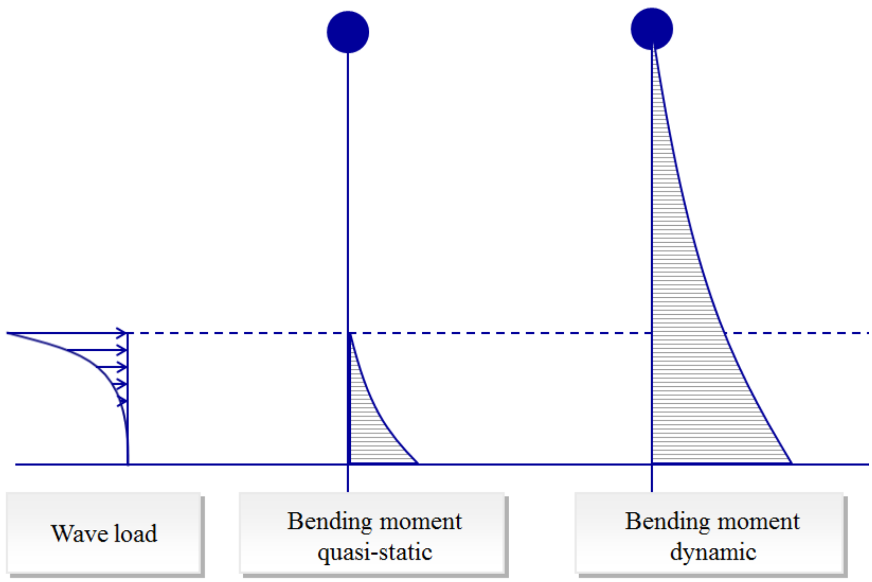

Figure 1: Quasi-static and dynamic moment lines for a wave-loaded monopile

This is schematically shown in Figure 1. The quasi-static moment line does only show internal member forces below the highest point of wave load attack. The dynamic moment line shows load all over the structure, this moment line is dominated by the structural response in the first mode.

4.1 Weighting

Damage incurred by a certain sea state is proportional to $(DEL)^m$, where m is the negative inverse slope of the S-N curve. Codified S-N-curves for welded details have values of m=3 and m=5. In order to calculate DELs, a S-N-curve with only one slope must be used, and m=4 is then used as the representative value. This must be considered when lumping sea states.

4.2 Quasi-static lumping: Equivalent significant wave height

Wave loads on individual members do have a quasi-static effect, i.e. the wave loads cause internal member forces in the members where they apply. Wave loads are described by the well-known Morison's equation (4), see e.g. Hapel [3] for details.

$$F(t) = \frac{\pi}{4} \cdot \rho \cdot C_M \cdot D^2 \cdot \dot{u}(t) + \frac{1}{2} \cdot \rho \cdot C_D \cdot D \cdot u(t) \cdot |u(t)| \qquad (4)$$

Wave induced forces are therefore proportional to the water particle acceleration (Eq. (5)) for the inertia term and the square of water particle velocity (Eq. (6)) for the drag term. Water particle acceleration and velocity are linearly dependant on wave amplitude for linear waves:

Water particle velocities (horiz.): $$u(t) = \zeta_a \cdot \omega \cdot \frac{\cosh(k \cdot (h+z))}{\sinh(k \cdot h)} \cdot \cos(k \cdot x - \omega \cdot t) \qquad (5)$$

Water particle accelerations (horiz.): $$\dot{u}(t) = \zeta_a \cdot \omega^2 \cdot \frac{\cosh(k \cdot (h+z))}{\sinh(k \cdot h)} \cdot \sin(k \cdot x - \omega \cdot t) \qquad (6)$$

It follows that quasi-static fatigue loads can be assumed to be proportional to H_S^{λ}, where λ is 1 if the wave loading is inertia dominated and 2 if the wave loading is drag dominated.

An equivalent wave height can therefore be computed for each wind speed as:

$$H_{s\_eq} = \left(\frac{\sum_n H_{s,n}{}^{\lambda m} \cdot p(n)}{\sum_n p(n)} \right)^{\frac{1}{\lambda m}}$$

As wave loads on monopiles are inertia dominated, $\lambda = 1$ applies.

4.3 Resonant (dynamic) lumping: Equivalent peak period

Additional to the (local) quasi-static contribution, global dynamic excitation does occur. For slender structures, like monopiles, this is often the dominant effect. For stiff structures, like jackets, this effect may be negligible.

Dynamic fatigue loads are proportional to $\sqrt{S_{\zeta\zeta}(\omega_0)}$ (see Eq. (1)), where $S_{\zeta\zeta}(\omega_0)$ is the spectral energy of the wave spectrum at first natural frequency. This has been derived for a narrow band response, which is a good approximation in case dynamic excitation is significant.

Weighting on basis of the spectral value at the natural frequency is the idea of following approach, as dynamic fatigue loads are proportional to $\sqrt{S_{\zeta\zeta}(\omega_0)}$. The following relationship does then apply:

$$\sqrt{S_{\zeta\zeta}(\omega_0)}_{eq} = \left(\frac{\sum_n \left[\sqrt{S_{\zeta\zeta}(H_{S,n} \mid T_{P,n} \mid \omega_0)}\right]^m \cdot p(n)}{\sum_n p(n)} \right)^{1/m} \tag{7}$$

with p(n): Probability for sea state n with $H_{S,n}$ and $T_{P,n}$

The spectral values $S_{\zeta\zeta}(H_{S,n} \mid T_{P,n} \mid \omega_0)$, depending on wave height, peak period and first natural frequency, have to be determined for each entry in the scatter matrix. As the gradient of the wave spectra is high adjacent to the peak period, a peak period bin size of one second (which is typically the case) will not lead to accurate results. Hence, a refinement of the peak period by a factor of 10 is recommended by means of a spline interpolation.

The spectral values are computed based on the refined scatter matrix. After the application of the weighting formula shown above, an equivalent spectral value is determined for the respective wave height row of the matrix. Based on the equivalent spectral value and the significant wave height the equivalent peak period can be recalculated. This is a back-calculation (iterative procedure) which ensures that the target value for the spectral energy at natural frequency is achieved.

Two solutions exist for this back-calculation, one T_P value on the ascending part of the spectrum and one T_P on the descending part (see Figure 2 for an example). For monopile configurations with Multi-MW turbines the higher T_P in general is the representative one as the natural frequency of the turbine is low. This must be identified for each specific case.

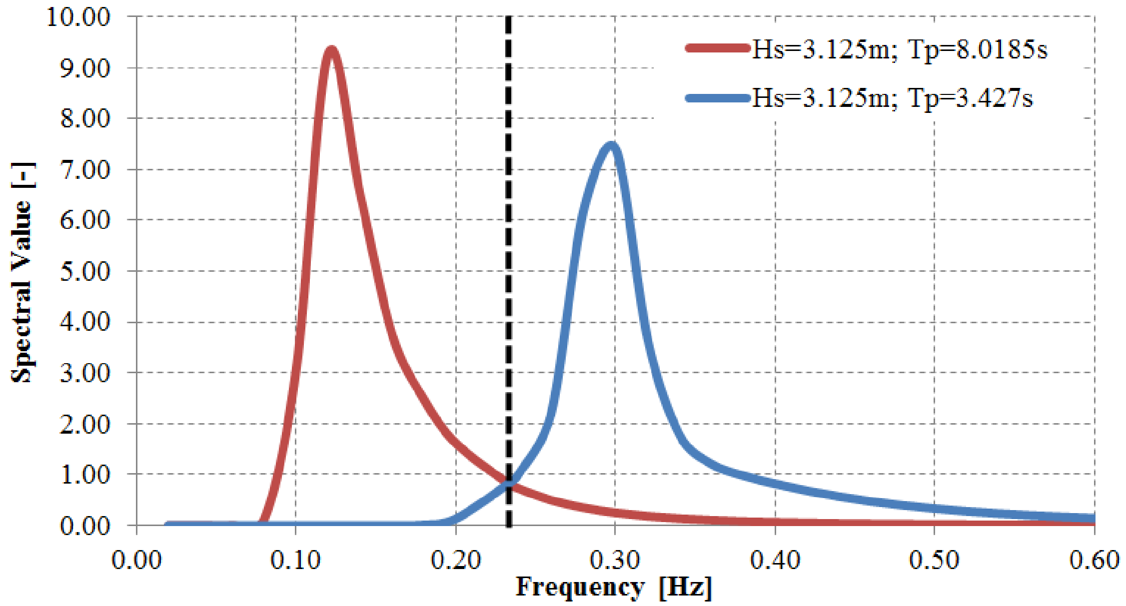

Figure 2: Identification of the correct equivalent peak period (JONSWAP) – T_P=8.0s is most representative for a wave height of H_S=3.125m and is selected; natural frequency marked by dashed line

5 SITE PARAMETER

When fatigue loads for a complete wind farm need to be calculated, it is often not practical (or even impossible) to perform load iterations for every position. A few positions (with varying structural properties, soil conditions and water depths) are then calculated and these loads must be applied to all structures. This can be done conservatively or some sort of interpolation must be adopted.

One possible parameter to choose for interpolation is natural frequency. The results from five different complete load simulations for a North Sea wind farm are shown in Figure 3. The data sets cover different water depths, but also different load iterations with differences in structural dimensions. The general trend shows what can be expected: The fatigue loads decrease with a higher natural frequency, which can be attributed to smaller wave excitation. But although the general trend is captured, large differences can be seen for the regression line vs. actual results. Such an interpolation quality is not suitable for design purposes.

Water depth as an parameter provides even poorer correlation, as the impact of soil stiffness is not captured in this case.

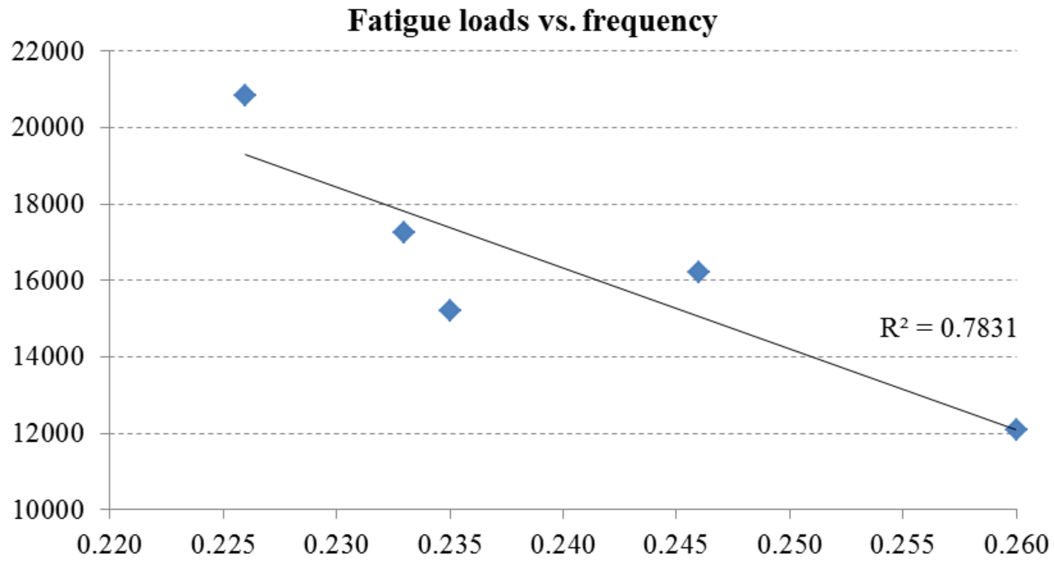

Figure 3: Fatigue loads (at unspecified elevation) plotted vs. first natural frequency of the combined structure

A better parameter can be found based on the method derived before. If Eq. (1) is simplified, it can be stated that fatigue loads are proportional to the following parameter S:

$$S = \frac{\omega_0^{0.75}}{K_{0,norm}} \cdot \sqrt{S_{\zeta\zeta}(\omega_0)}_{eq} \cdot \sqrt{\frac{1}{\xi_0}} \cdot H_{TB} \cdot H_{a,0} \quad (8)$$

This expression is valid if the fatigue loads are governed by dynamic wave excitation, which is often the case for monopiles. If wind loads are governing (i.e. for a very stiff system) then this site parameter would not be a good choice.

This site parameter can be used to evaluate fatigue loads for all positions within a wind farm. Load simulation can be performed for the sites having minimum and maximum site parameter and interpolation can be used in between. Interpolation can be performed with much simpler tools (e.g. Excel) as all steps can be done in a spreadsheet, except for the modal analysis for each site. The latter can be performed in a structural analysis program (or even that can be done in Excel, but this requires a bit more work).

Results are shown in Figure 4 for the same data set as used for Figure 3. It can be seen that the correlation is now very good, which makes the site parameter a suitable parameter to perform interpolation, esp. during the stage where design iterations are performed and quick response cycles from structural designer to load calculations engineer are required.

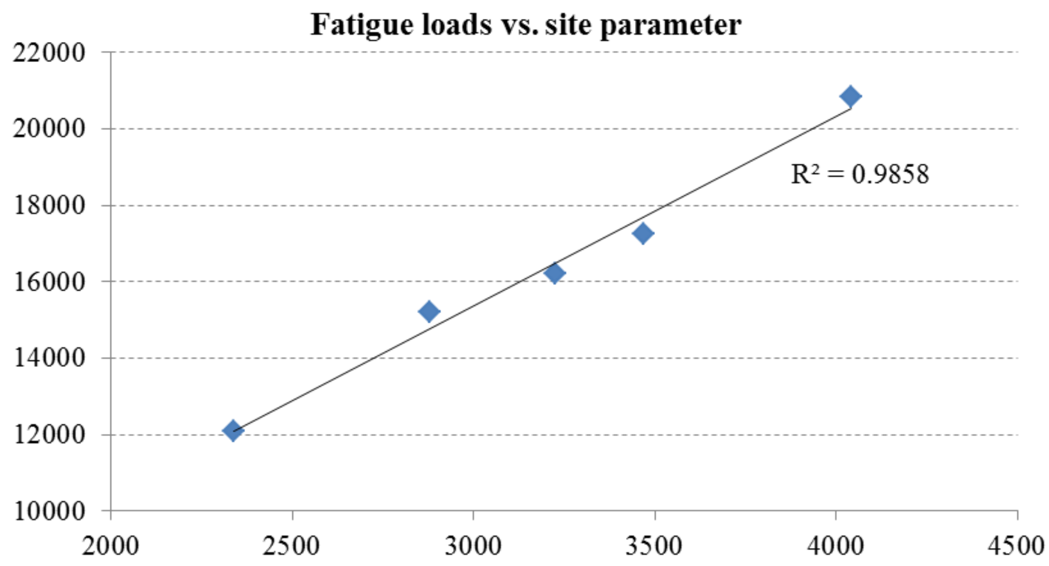

Figure 4: Fatigue loads (at unspecified elevation) plotted vs. site parameter

6 Summary

In this paper, new approaches for lumping of a scatter diagram (scatter matrix) and interpolation of site specific fatigue loads have been demonstrated based on on frequency domain considerations. Simplifications relevant for monopile substructures have been used to determine a compact formula which allows rapid calculation of wave induced fatigue loads. These approaches allow for more accurate and fast calculations of wave induced fatigue loads for offshore wind turbines with monopile support structures.

7 References

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