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State-of-the-art design processes for offshore wind turbine support structures

Practical approaches and pitfalls during different stages in the design process

Structural design of offshore wind turbine support structures is a complex process, which has many challenges. In particular in the early phase of a project it is difficult to select the appropriate structural concept and to determine structural masses with reasonable accuracy, without having to go through a time-consuming iterative process. In the more advanced stages, care must be taken that required data for an optimized design has been collected earlier and that the right software tools are available such that all parties involved can execute the design work. In this paper, practical advice is given how this process can be organized and which methods can be used. Furthermore, common mistakes are highlighted, such that those can be avoided.

Entwurfsprozess für Tragstrukturen von Offshore-Windenergieanlagen – Praktische Vorgehensweisen und Fallstricke während unterschiedlicher Phasen. *Der Entwurf von Tragstrukturen für Offshore-Windenergieanlagen ist eine anspruchsvolle Aufgabe. Insbesondere in der frühen Entwurfsphase ist es oft schwierig, die richtige Entscheidung für das Konzept der Tragstruktur zu treffen und die strukturellen Massen mit angemessener Genauigkeit zu bestimmen, da dies häufig in einem zeitaufwendigen Iterationsprozess mündet. Im weiteren Verlauf muss sichergestellt sein, dass alle notwendigen Eingangsdaten für ein optimiertes Design vorliegen und die beteiligten Parteien über die notwendige Software verfügen. In dieser Veröffentlichung werden praktische Hinweise gegeben, wie dieser Prozess durchgeführt werden kann und welche Methoden in welcher Phase angemessen sind. Außerdem werden häufige Fehler beschrieben, damit diese vermieden werden können.*

Keywords: Offshore wind turbine, Monopile, Jacket, Design process, Fatigue design, Offshore-WEA, Entwurfsprozess, Ermüdung

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1 Introduction

As projects go through different phases, support structure designs with varying levels of detail are required. In the initial stages, the support structure concept needs to be developed and overall mass is of interest. This is typically achieved with simplified methods and for selected positions of a wind farm only. Towards the final design, the design and masses are refined and transferred to all individual positions. Approaches suitable for each phase, for both monopiles and jackets, are summarized graphically in Fig. 1 and described in Table 1.

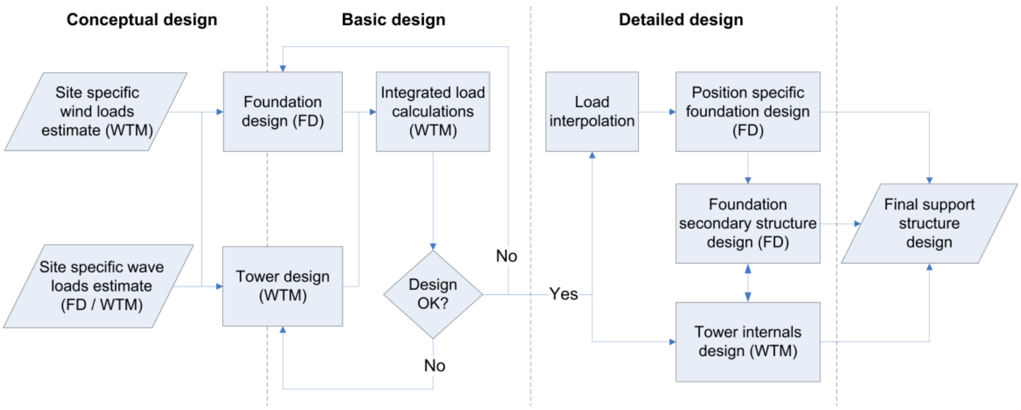

Bild 1. Flussdiagramm für die Entwicklungsstufen

Fig. 1. Flow-chart summarizing different phases

Tabelle 1. Beschreibung der Entwicklungsstufen

Table 1. Description of design phases

Stage	Description
Conceptual Design	Determination of the initial support structure dimensions such as pile diameters, wall thicknesses and pile length. Conceptual layout of secondary structures needs to be defined for the load calculations (e.g. boat landing orientation). Purpose is to define a suitable support structure for the site, provide input to financial models and to define a starting point for detailed load simulations.
Basic Design	Basic design of the support structure for the selected load-design positions in the wind farm, based on detailed time domain load simulations. Basic design is performed in an iterative process between load calculations and structural design; typically 2-3 iterations are performed. Purpose is to obtain well-defined structures for at least the extreme positions and often a few additional representative positions in the wind farm. Overall steel mass can be estimated based on this.
Detailed Design	Detailed design for all positions within the wind farm, using interpolated loads from the load-design positions. This allows position specific optimization of the primary structure. Furthermore, all other design items (e.g. secondary structures, corrosion protection) are finalized at this stage.

2 Design approaches for Monopiles

Monopile and Transition Piece dimensions are dominated by wave induced fatigue loads for the current turbine size of 6-8MW and water depths typically in the range of 20-40m. Only parts of the design are driven by extreme loads, this typically applies to the tower top region, flanges and other connections (grouted joints) and the pile embedment length. As "wind only loads" are fairly well and easily predictable based on the wind conditions at site, the main effort is on wave induced loads.

2.1 Design Basis

The Design Basis should thoroughly cover met-ocean conditions; in particular the following should be included:

For calculation of FLS (Fatigue Limit State) design load cases:

- Omnidirectional scatter tables for V_{Hub}-H_S and H_S-T_P for initial design stages (V_{Hub}: Wind speed at hub height, H_S: Significant wave height, T_P: Peak period).
- Full directional information on wave conditions as a function of wind speed and wind direction, i.e. H_S-T_P-scatter diagrams for 12 wind directions (30° intervals), 12 wave directions and ~35 wind speeds (up to ~35m/s in 1m/s intervals). This results in ~5040 scatter tables. Opposite directions can be added, reducing the number of wind and wave directions to 6 each, resulting in ~1260 scatter tables in total.

For calculation of ULS (Ultimate Limit State) design load cases:

- Extreme sea states (ESS) and extreme wave heights (EWH) should also be included for 12 directions. This is beneficial, as appurtenances like boat landings can increase wave loads significantly and taking into account their locations vs. directional wave heights reduces extreme loads.
- In cases where wave breaking might occur, extreme sea states should be specified conditional on direction and water level. For sites with relatively shallow water, the lowest water level often drives extreme wave loads.

2.2 Conceptual Design

2.2.1 General remarks

For the conceptual design, the initial question is about feasibility of the monopile, considering current weight limits for fabrication and installation. In order to arrive at a reasonable estimate of fatigue (FLS) and extreme (ULS) loads, the following steps need to be completed:

1) Firstly, it is extremely important to realize that the wind turbine manufacturer cannot a priori deliver any sensible "generic loads" which are combined wind-wave loads applicable to the site. In particular fatigue loads are too dependent on site conditions. Any combined wind-wave load set which does not take soil and wave conditions from the site into account can thus only be termed "arbitrary" loads and any reasonable design process must involve calculation of site specific combined wind and wave loads.
2) The most important input for support structure load calculations concerns soil stiffness / soil-structure-interaction. It is therefore not a good approach to start with conservative values of soil strength parameters and stiffness models. Such conservatism can lead to unrealistically high support structure masses, resulting in incorrect conclusions about monopile feasibility / economics. It is therefore important to apply state-of-the-art methods for soil-structure-interaction, see e.g. Versteijlen et al. [1].

3) If monopile feasibility is deemed to be on the verge, minimizing hub height is one of the important levers to limit masses.

2.2.2 First steps of the design process

To initiate the design, a starting point is needed. This is done with the following steps.

4) Based on experience, a first support structure geometry is created.
5) The first natural frequency of wind turbine and support structure is calculated and compared with the allowable frequency band (given by the turbine manufacturer, e.g. to avoid resonance with the blade passing frequency). Furthermore, modal damping for the first fundamental eigenmode is calculated / estimated. If passive damping devices are used, their damping contribution is also determined.
6) FLS and ULS loads are then estimated as described in the following and used for refinement of the structure.

During this stage, no load simulations in the time domain are required.

2.2.3 Estimation of fatigue loads (FLS loads)

The initial structure is used in the following to estimate fatigue loads (FLS loads). Those are at this stage presented as “Damage equivalent loads” (DELs), i.e. load spectra with one load range only.

7) Wind turbine manufacturer (WTM) provides “wind only” loads, based on hub height, wind conditions and natural frequency. It is important to note that such loads are not very sensitive to natural frequency, unlike wave induced loads.
8) Furthermore, WTM needs to provide information on fore-aft and side-side aerodynamic damping during production and idling. This can be done in a simplified manner, lumped over all wind speeds and directions, or in a more sophisticated way (e.g. dependent on wind speed and direction).
9) As idling conditions typically result in the highest loads for the support structure, the technical availability of the wind turbine needs to be agreed upon.

Foundation designer (FD) needs to calculate wave induced fatigue loads. This can be done by time domain simulations, but this is time consuming. It is much more practical, yet still very accurate, to use frequency domain methods to determine wave induced fatigue loads. Depending on available tools, simplified approaches as described by Seidel [2] or full frequency domain calculations can be used. At this stage, the omnidirectional H_S-T_P scatter diagram can be used as input.

Superposition of wave induced loads with wind only loads needs to be performed. A simplified approach assuming a “representative misalignment” angle $\alpha_{Misalignment}$ has proven to give sufficiently accurate results at this stage, see Fig 2.

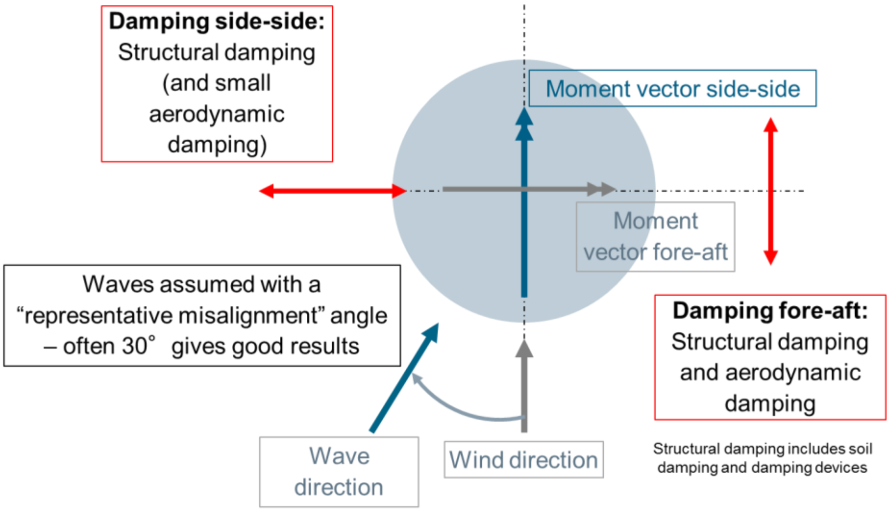

Bild 2. Verwendung einer repräsentativen Abweichung zwischen Wind- und Wellenrichtung für die Ermittlung der welleninduzierten Ermüdungslasten

Fig. 2. "Representative misalignment" approach for superposition of wind and wave induced fatigue loads

The following steps are required:

10) During both production and idling, the wave load is distributed according the representative misalignment angle:

$$WaveLoad_{Prod,Wave,Fore-aft} = WaveLoad_{Prod,Wave} \cdot \cos(\alpha_{Misalignment}) \tag{1}$$

$$WaveLoad_{Prod,Wave,Side-side} = WaveLoad_{Prod,Wave} \cdot \sin(\alpha_{Misalignment}) \tag{2}$$

In time domain simulations, the wave can also be applied at an angle, if different damping ratios can be implemented in the two directions. In the frequency domain, separate calculations are needed, where the distribution of wave loads is considered in the hydrodynamic transfer function.

11) Wave induced fatigue loads (life-time equivalent loads) are calculated for different directions and damping levels:
    a. Fore-aft direction during production
    b. Side-side direction during production
    c. Fore-aft direction during idling
    d. Side-side direction during idling

12) Wind and wave induced fatigue loads for both directions are superimposed using Kühn's rule [3], e.g. for production:

$$DEL_{Prod,combined,Fore-Aft} = \sqrt{DEL_{Prod,Wind,Fore-Aft}^{\;2} + DEL_{Prod,Wave,Fore-Aft}^{\;2}} \tag{3}$$

This calculation is done for both production and idling and for both directions.

13) Finally, loads are combined according to relative occurrence of normal production and idling. The mean inverse slope of the S-N-curve (typically m=4) is used for this combination:

$$DEL_{tot} = \sqrt[m]{Occ_{Prod} \cdot DEL_{Prod}^{\;m} + Occ_{Idling} \cdot DEL_{Idling}^{\;m}} \tag{4}$$

Occ_{Prod} and Occ_{Idling} are percentages of normal operation and idling during lifetime, e.g. 0.90 and 0.10, if 10% unavailability is assumed.

A complete example is given in Table 2. The last column refers to the numbered steps as described before.

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Tabelle 2. Zahlenbeispiel für die Überlagerung von Wind- und Wellenlasten

Table 2. Worked example for superposition of wind and wave induced fatigue loads (values are DELs)

Production:	90.0%		9)
Fore-aft (along-wind) direction			
Wind	25000	kNm	7)
Wave	44413	kNm	11) a. using fore-aft aerodynamic damping during production
Combined	50965	kNm	11)
Side-side (across-wind) direction			
Wind	20000	kNm	7)
Wave	60383	kNm	11) b. using side-side aerodynamic damping during production
Combined	63609	kNm	11)

Idling:	10.0%		9)
Fore-aft (along-wind) direction			
Wind	5000	kNm	7)
Wave	104586	kNm	11) c. using aerodynamic damping during idling
Combined	104706	kNm	11)
Side-side (across-wind) direction			
Wind	5000	kNm	7)
Wave	60383	kNm	11) d. using aerodynamic damping during idling
Combined	60590	kNm	11)

Combination of production + idling			Note: Maximum of both directions is governing
Fore-aft direction	69035	kNm	13)
Side-side direction	63332	kNm	13)

2.2.4 Estimation of extreme loads (ULS loads)

ULS loads usually vary much less with soil conditions, i.e. the load levels at the interface from tower to transition piece are mostly governed by hub height and wind conditions. Nevertheless, they are also influenced by dynamic reaction induced by extreme sea states and/or deterministic waves. Below interface, quasi-static extreme wave loads are obviously increasingly important. Based on this, a simplified approach can be devised with only two load cases:

14) The maximum load at interface is combined with a reduced (quasi-static) wave load. This load case governs the upper part of the substructure.
15) A reduced load at interface is combined with the maximum (quasi-static) wave loads. This load case often governs the lower part of the substructure.

The loads at interface need to include typical inertia loading, i.e. shear force and moment resulting from accelerated masses. Applying a dynamic amplification factor (DAF) to the quasi-static wave load is not correct in this case, see section 4.4.

2.2.5 Structural design

The following advice can be given for efficient structural design at this stage:

16) Use of damage equivalent loads (DELs), i.e. load spectrum with only one load range, is appropriate. Correct application of DELs is discussed in section 4.5.

17) ULS is usually only relevant for tower top, flanges, grouted connection and embedment depth. ULS checks can be omitted otherwise.
18) Overall dimensions and mass are governed by FLS. Therefore, FLS checks need to be performed with good accuracy. The following items are important:
    a. Estimate of stress concentration factors for relevant attachment (e.g. boat landings)
    b. Consideration of stress concentration factors for girth welds (thickness transitions)
    c. Appropriate choice of S-N-curves depending on corrosion protection concept

2.3 Basic Design

Based on the conceptual design geometry, load simulations are performed to refine the previously estimated load levels. The focus of the design work is therefore to optimize all relevant input for fatigue load simulations, mainly the setup of FLS loads cases, damping estimates and soil stiffness modelling, in order to accurately predict natural frequency and mode shape.

2.3.1 Fatigue Limit State (FLS) loads

During Basic Design, fatigue loads are determined through time domain simulations. For the fatigue load cases according to IEC 61400-3, up to 30000 time series are being simulated per load iteration for one load position. In order to arrive at optimized load levels, it is important to consider full directionality and all misalignment situations, as already discussed in section 2.1. Simplifications can be made, e.g. by omitting separate simulations for opposite wind / wave directions and lumping occurrences in post-processing.

Furthermore, it is important that all items that attract wave loading are defined (e.g. boat landings, anode cages). Relevant properties to define are:

- Dimensions and elevations
- Positions on circumference
- Areas and hydrodynamic coefficients for wave load calculations

Frequency domain calculations are still valuable at this stage, as they can be used to cross-check time domain results and to estimate the sensitivity to considered changes in geometry, natural frequency, soil stiffness assumptions, etc.

2.3.2 Ultimate Limit State (ULS) loads

For ULS, the estimates used in the Conceptual Design are replaced by the full load case table acc. to IEC 61400-3. For exposed sites, extreme wave loads are important and the following should be considered:

- Appurtenances (like boat landings) increase extreme wave loads significantly. It is therefore beneficial to take into account directional extreme waves, if major appurtenances are not placed such that they are hit from the worst direction.
- The worst case wave load has to consider all parameters: Water level, contemporaneous current speeds, wave height and wave period. The governing combination of these parameters can in most cases be determined with quasi-static wave load calculations. In cases with very steep waves, additional checks on significance of dynamic reaction with varying wave periods might be required.

2.3.3 Structural design

For the structural design, the following refinements are made:

- Fatigue loads are now processed as load spectra or Markov matrices. Using DELs is not appro-

priate any more at this stage.
- Stress concentration factors (SCFs) for appurtenances and other attachments are confirmed by detailed Finite Element Analysis (FEA).
- Additional geotechnical design checks (e.g. accumulation of permanent displacements and pore pressure) are carried out.
- The corrosion protection concept is detailed to such a level that all aspects affecting structural design are defined.
- The functional concept (e.g. location of electrical components) is fixed, such that locations of platforms, flanges, etc. are known.

2.4 Detailed Design

Detailed Design is mainly a continuation of Basic Design, amending minor details. For structural design, the outstanding item might be interpolation from the limited number of load design positions to all positions within the wind farm. This interpolation needs to take into account all relevant parameters:

- Water depth
- Soil stiffness
- Natural frequency and mode shape
- Damping (if assumed differently across the site)

A method how this can be achieved is described by Seidel [4].

3 Design approaches for Jackets

Jacket design differs significantly from Monopile design, as jackets are governed by wind / turbulence induced loads for both FLS and ULS. Extreme wave loading is in most cases only relevant for the lower part of the jacket and the foundations (piles or suction buckets).

3.1 Conceptual Design

For the conceptual design, “wind only” loads at interface are sufficient. These can be determined by the wind turbine manufacturer based on site parameters and estimated natural frequency.

For FLS analysis, the use of DELs is possible, but requires some simplifications and comparison / experience with full designs is needed to make this a reliable process. Generally, the following can be applied (for both FLS and ULS):

- Jacket legs are dominated by shear / moment at interface and good results can be achieved by simultaneous application of these loads for assessment.
- Bracings and nodes are dominated by torsion, but also some in-plane bending (IPB) originates from shear / moment. As torsion and shear / moment are uncoupled load effects, a simplified assessment can be justified where e.g. the following is applied:
  - 100% shear/moment + 50% torsion
  - 50% shear/moment + 100% torsion
  - The maximum of the above combinations is used for design
- For superposition of wind and wave loads (for overturning force/moment) a practical approach is presented in [5]. Based on statistical considerations, a superposition following “Turkstra’s rule” is suggested, where mean loads of one source are combined with maximum loads from the other source.
- Waves are mostly irrelevant for FLS. This can be checked separately and if significant contribution from waves is found, then some margin should be left.

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- For long and slender bracings, local vibrations can be a significant contribution to fatigue loads. This is difficult to assess at this stage and estimates based on experience need to be made. It is useful to compare natural frequencies of the local brace modes with excitation frequencies from the turbine, in particular multiples of the rotational and blade passing frequencies, and try to avoid those.

Based on the conceptual design results, the main design parameter can be fixed, i.e.:

- Three legged or four legged jacket
- Number of bays
- Brace layout
- Foundation concept

3.2 Basic Design

During Basic Design, a major step is to move towards integrated load simulations. It is important to note that only the following methods are acceptable:

1. Model the jacket by means of superelements with sufficient number of internal modes (convergence), see [6].
2. Fully coupled models – those are not practical due to the excessive simulation time needed. The superelement method is equivalent in accuracy, yet much faster.

In case of coupling the WTG and tower model to a jacket superelement, special care should be taken to maintain model consistency during the process. It is not acceptable to e.g. use different software packages for generation of superelements and recovery of internal forces, as those will always have differences, which can have a major impact, even though they might be perceived as minor.

The availability of suitable software to the jacket designer is therefore essential. Such software must have the following features:

1. Capability to generate superelements and associated generalized loading
2. Cluster-based computation to process a large number of time series (i.e. no license restrictions)
3. Ability to perform recovery runs to generate internal member forces, mostly by transient recovery runs using interface forces/moments or displacements/rotations. The latter is preferred, as using forces/moments is more sensitive to small modelling discrepancies.
4. The most robust and time efficient method (but requiring exchange of larger data sets between turbine manufacturer and foundation designer) is direct expansion of superelement results. This requires converged superelements (i.e. including many modes). The superelements need to be created by the FD, such that he has access to the reduction basis. This is visualized in Fig. 3.

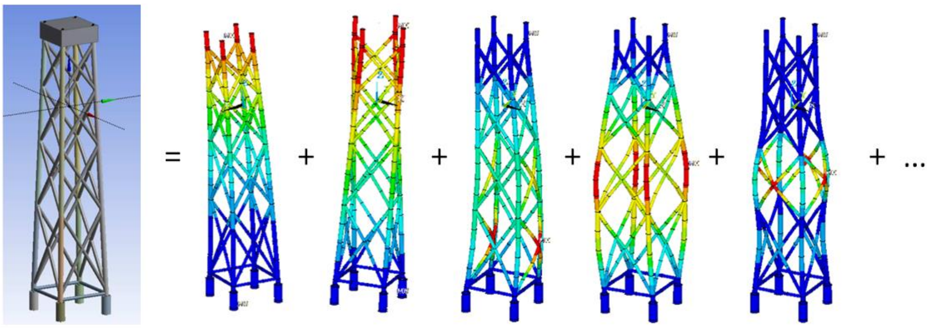

Bild 3. Modale Superposition

Fig. 3. Modal superposition

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3.3 Detailed Design

During detailed design, the final decision is made on grouping of locations and jacket heights. Also, individual design for foundations is performed – at least in case of piles, while grouping might be more suitable for suction buckets.

4 Important design aspects / pitfalls

4.1 Lumping of sea states

Often, correlations are used for the sea states to correlate H_S-V_{hub} and H_S-T_P. This is possible, but it should be noted that correct lumping of sea states is frequency dependent, see Seidel [4].

When selecting representative sea states for simulation, it needs to be realized that spectral energy varies rapidly with frequency. As an example a sea state with a peak frequency of T_P=4.5s is shown in Fig. 4. If that sea state is applied to a structure with f_0=0.222Hz, then the spectral energy is more than 3 times higher compared to applying it to structures with f_0=0.20Hz and f_0=0.25Hz.

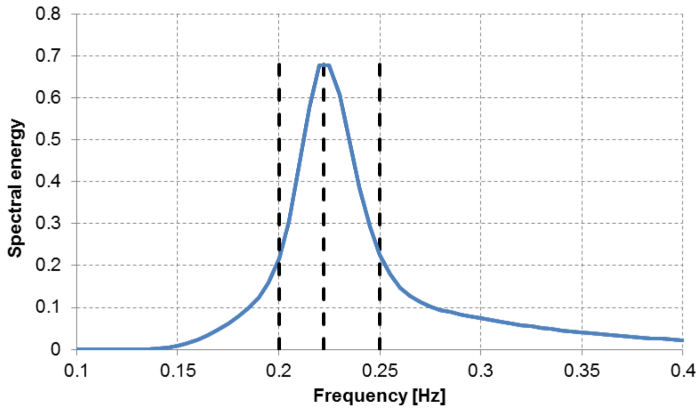

Bild 4. Beispiel für ein JONSWAP-Spektrum für H_S=2.0m und T_P=4.5s - die vertikalen Linien markieren Frequenzen von 0.2Hz, 0.222Hz and 0.25Hz

Fig. 4. Example of JONSWAP spectrum for a significant wave height of H_S=2.0m and a peak period of T_P=4.5s – vertical lines mark frequencies of 0.2Hz, 0.222Hz and 0.25Hz

Based on this, an “equivalent spectral energy” $S_{\zeta\zeta}(\omega_0)_{eq}$ can be calculated as follows, see [2] for details:

$$S_{\zeta\zeta}(\omega_0)_{eq} = \left[\left(\frac{\sum_n \left[\sqrt{S_{\zeta\zeta}(H_{S,n} \mid T_{P,n} \mid \omega_0)}\right]^m \cdot p(n)}{\sum_n p(n)}\right)^{1/m}\right]^2 \tag{5}$$

This equivalent spectral energy can easily be computed and is a good indication of how much fatigue loads vary with first natural frequency of the structure.

4.2 Effect of stiffness changes for monopiles

Stiffness changes due to structural changes and/or changes in soil stiffness assumptions have a severe impact on resulting loads levels. This effect has two main sources:

- Effect of equivalent spectral energy with decreasing natural frequency (see previous section) – typically, the equivalent spectral energy at the first natural frequency increases with decreasing frequency (see Fig. 5).
- Effect of the mode shape – a larger (relative to hub height) mode shape amplitude around mean sea level (MSL) causes higher generalized loading, which leads to higher loads even for unchanged natural frequency. This is often the governing effect.

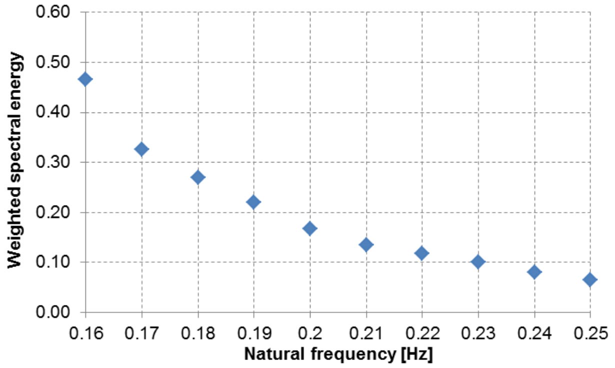

Bild 5. Äquivalente (gewichtete) spektrale Energie in Abhängigkeit der ersten Eigenfrequenz

Fig. 5. Equivalent (weighted) spectral energy vs. first natural frequency

4.3 Wave load generation

For time domain simulations, the wave spectrum is discretized into a finite number of individual wavelets, and structural response occurs at the frequencies of the individual wavelets. For monopile structures with low damping, the response occurs almost exclusively around the first natural frequency of the structure, as the dynamic amplification function (DAF) is very steep, with a maximum of DAF=50 at the first natural frequency for a damping of 1% of critical damping (see Fig. 6). It is therefore important that wavelets around the first natural frequencies are sufficiently closely spaced to accurately capture this narrow peak. This can be achieved by refinement of wavelet density around the first natural frequency. Note that the dynamic amplification factor should not be used as a multiplier for use with quasi-static loads, but only as an indication where structural response occurs, also see next section.

When generating time series of wave loads, care should be exercised regarding the discretization of line loads and treatment of partially wetted members. This usually requires a sufficiently small element size within the wave loaded zones to avoid step changes in wave loading.

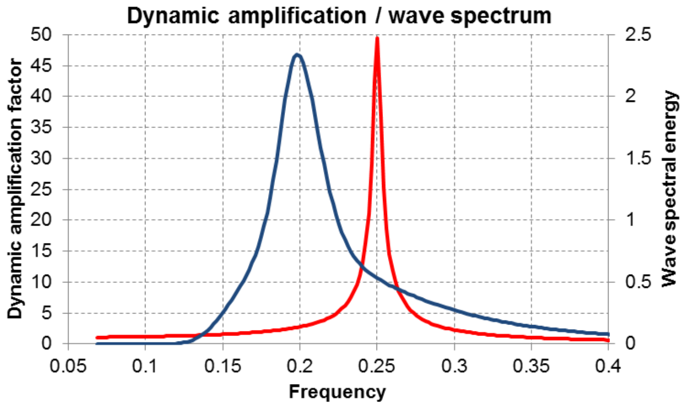

Bild 6. Wellenenergiespektrum (blaue Kurve, recht y-Achse) und dynamischer Überhöhungsfaktor (rote Kurve, linke y-Achse)

Fig. 6. Wave spectrum (blue curve, right y-axis) and dynamic amplification factor (red curve, left y-axis)

4.4 Inappropriate calculation methods

Sometimes, calculation methods are used by designers which are not appropriate. A prominent example is the application of "Dynamic Amplification Factors" (DAFs) to wave loads. Such DAFs are meaningful if the general shape of the bending moment line is similar for external loading and inertia (acceleration) induced loads. This is e.g. the case for a chimney under wind load. For general offshore structures, this concept is already questionable, but due to the limited impact this concept is still sometimes applied. For offshore wind turbines, this method delivers completely erroneous results, as the moment shapes from wave loading and inertia induced loads are different:

- Quasi-static wave loading creates moments only below wave crest.
- Inertia induced loading, originating from vibrations in the fundamental mode, is dominated by the inertia forces from the nacelle mass. This results in a moment line which increases almost linearly from tower top to mudline (some contribution from the support structures masses makes the shape slightly curved).

It is obvious that any factor on the quasi-static wave loading will not result in the correct contribution from inertia. This principle is illustrated in Fig. 7.

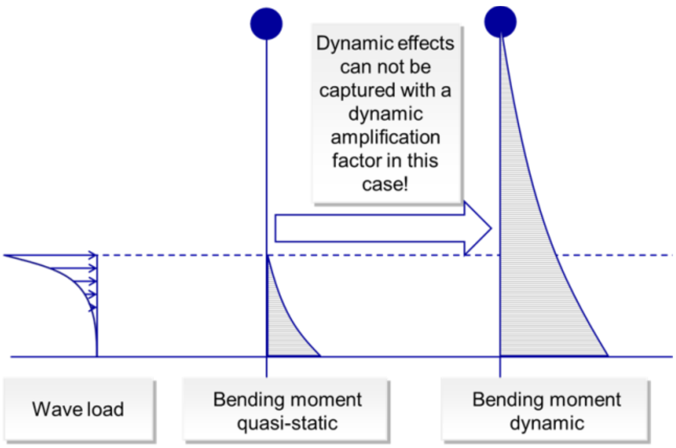

Bild 7. Falsche Anwendung des dynamischen Überhöhungsfaktors [4]

Fig. 7. Incorrect DAF concept application [4]

4.5 Correct use of damage equivalent loads (DELs)

Another mistake which has repeatedly been made in the past is incorrect application of damage equivalent loads (DELs). DELs are calculated based on the assumption of a single slope S-N-curve, often m=4 or m=5 for steel. Therefore, also the design checks need to be performed with the same single slope! Applying DELs together with codified S-N-curves (which often have slopes of m=3 and m=5), leads to incorrect results.

In Fig. 8 two options are shown how S-N-curves can be chosen to arrive at meaningful results:

- A conservative approach is to use DELs for m=5 together with an S-N-curve where the m=5 part of the curve is extended “backwards” (i.e. towards smaller number of cycles). Difference in S-N-curves between Eurocode and DNV-GL with different number of cycles at the knee point must be observed.
- A practical approach, which is less conservative, is to use DELs for m=4 with an S-N-curve (with m=4), which intersects the codified S-N-curve at N=2E6 (this is the reference number of cycles in Eurocode 3).

DELs can easily be converted to different number of reference cycles if needed:

$$\Delta M_{eq,Nref2} = \Delta M_{eq,Nref1} \cdot \left(\frac{N_{ref1}}{N_{ref2}} \right)^{(1/m)} \tag{6}$$

Note that conversion to another S-N-curve slope m is not possible!

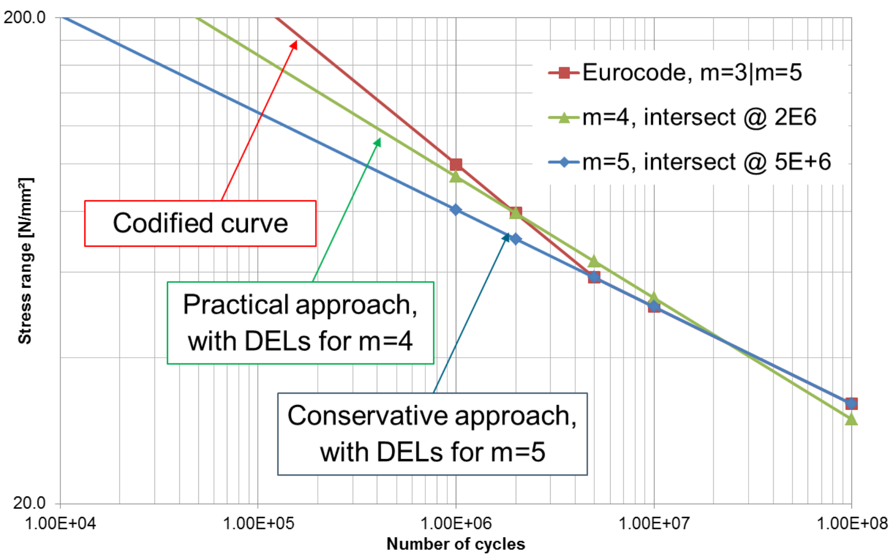

Bild 8. Ermüdungsfestigkeitskurven (S-N-Kurve) für die Verwendung mit Einstufenkollektiven

Fig. 8. S-N-curve to be used with DELs

5 Summary

In this paper, methods have been described which can be used during different stages of the design process of support structures of offshore wind turbines. The authors hope that the publication of this knowledge enables project owners and designers to organize their design processes more efficiently and to avoid common mistakes.

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