Fully integrated simulation and design process for offshore wind turbines including support structures

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Summary

With the developed algorithm based on strict constrained optimization, the optimal wall thicknesses for every shell can be determined. Starting from a set of extreme and fatigue loads the wall thicknesses are optimized with respect to the utilization of axial, shear and total buckling, and the utilization of the welded seams. Steel grade, FAT-Class of welded seams and available wall thicknesses are supplied by the user. This leads to load optimized wall thicknesses for every shell.

In the next step the eigenfrequencies are calculated by Eulerian beam theory taking into account the stiffness of the piled foundation. It is determined self consistently with user supplied p-y curves. If the eigenfrequencies of the load optimized tower do not fulfil the frequency constraints, the stiffness of the tower will be increased. In order to gain a maximum increase in frequency with a minimum amount of steel, the algorithm increases the wall thickness of the shell, where the fraction of frequency gain to additional steel mass ($\Delta f/\Delta m$) is maximal.

To close the gap to the loads a fast load simulation program has been developed capable of doing fully integrated load calculations with state of the art wind and wave models. It features soil-structure interactions for different kinds of offshore foundations, like monopile, tripod, jacket and gravity based. The number of eigenmodes used for flexible parts can be freely prescribed by the user. It is equipped with a complete set of evaluation tools to deliver the new input set for the design tool.

1. Introduction

Steel support structures are among the most costly components of wind turbines. Increasing rotor diameters and installation in deeper water pose high demands on support structures. For water depth up to 40 m monopiles are a very common foundation in OWT offshore installations. The requirements on the natural frequency of the whole support structure become a major cost driver here due to the big overall length end the rather soft piled foundation. To reduce costs and optimize these structures a integrated simulation and design of complete support structures (monopile and tower) is a key factor. We present a systematic approach to design support structures optimized to specific site conditions and hence closing the gap to a fully integrated load calculation. We focus on robust and reliable analysis as well as design tools to speed up the design process considerably. In this paper we describe the principles of constrained optimization for support structures to derive optimal shell layout. The tool is also capable to do optimal flange layout.

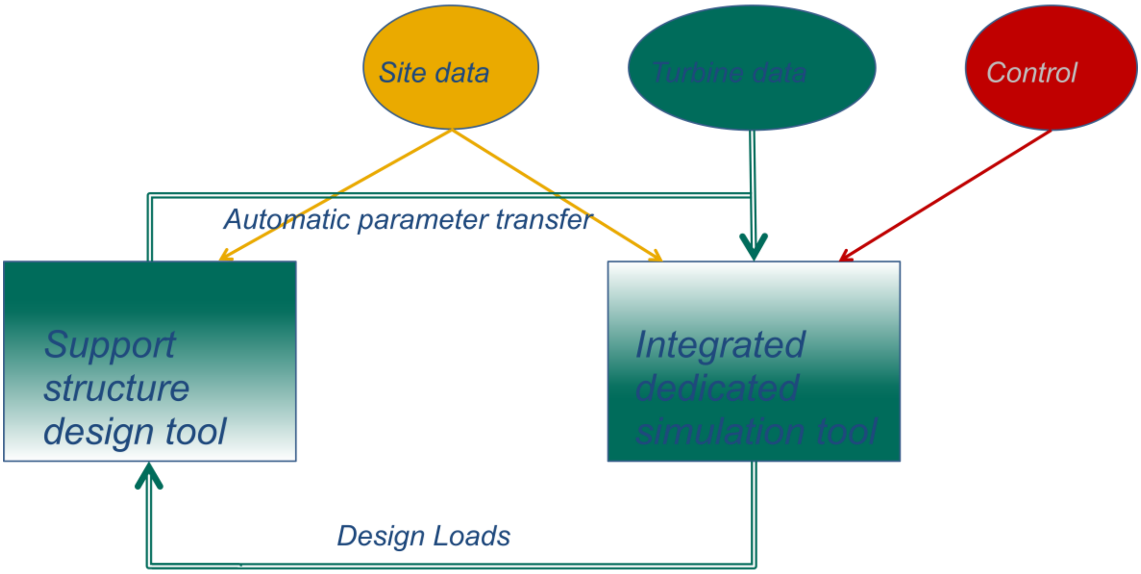

Figure 1: Schematic of the design loop

2. Critical loads for support structures

Tubular steel support structures are typically built of sections (approx. 10-25 m long), which are itself connected by flanges. In turn each section is built of several steel shells (up to approx. 2.90 m), which are welded together. Each shell i has a cylindrical or conical shape with a certain (lower) diameter D_i and wall thickness s_i.

Shells (Extreme loads)

Extreme loads (mainly the bending moments) in the support structure tend to induce buckling in the shells. The guideline Eurocode 3 [1] contains an analytical approach of buckling analysis for steel shells. With this method, time consuming detailed FEM analysis can be avoided.

The parameters for this analytical analysis are the diameter D_i and wall thickness s_i of the shell i, the length of the section l_j and the steel grades yield strength which result in certain maximum allowed stresses, which in turn are compared to the extreme shear and axial stresses which result from the load calculations extreme bending moment in the corresponding shell.

Shells (Fatigue loads)

Essentially the support structures welded seams (and bolts in the flanges, see below) are the weak points according to the fatigue loads. A respective analytical analysis is given in guideline Eurocode 3 [2]. Just like for the buckling analysis, a FEM analysis can be avoided.

Based on the on the diameter D_i and wall thickness s_i of the shell i, and the load calculations rainflow count of the bending moments in the corresponding shells, the present stress cycles $\Delta\sigma_i$ are computed. Finally, with the appropriative S/N-curve [2] based on the chosen welded seam detail category, the damage during the WEC's lifetime can be determined and analyzed.

Natural frequency

Tubular steel support structures can be properly approximated by beam theory. Within the Euler beam theory, each shell of the support structure is approximated by point masses with certain stiffness. The mass and stiffness is based on the density and Young's modulus of the material (here steel), the diameter, and the thickness of the shell.

For stiff foundations, the computation of the natural frequency is well-known within the beam theory. However, the implementation of raft foundations and piled foundations is more challenging. In the case of raft foundations, the soil spring is calculated according to the model of Hsieh and Lysmer, see for example Ref. [3]. For monopiles we adapted the widely used p-y-curve model, see for example Ref. [4]. The p-y-curve describes the soil resistance p to a soil deflection y for certain soil materials.

To minimize the WEC's loads, a severe excitation of the support structures natural frequency has to be avoided. Typical designs of support structures (see for example Campbell diagrams in Figure 2) for three bladed WECs ensure a certain gap between natural frequency and 1P-/ 3P-rotor frequencies because the 1P and 3P rotor frequencies are primarily responsible for exciting the support structures frequency.

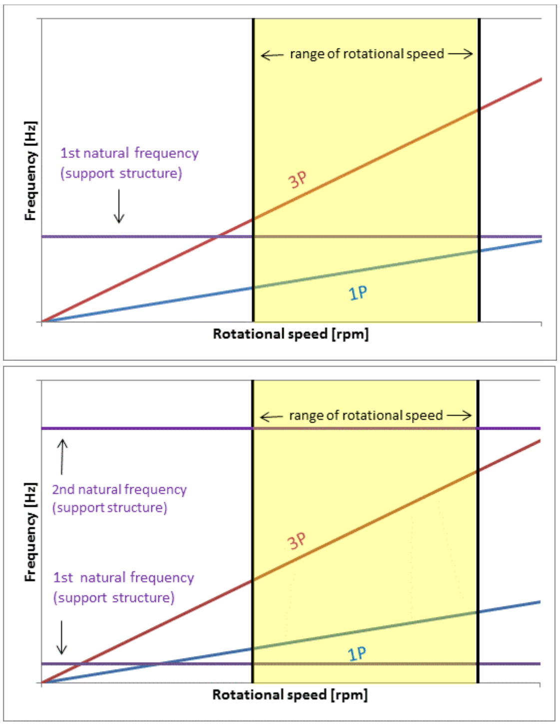

Figure 2: Schematic Campbell diagram of soft-stiff support structure (upper figure) and soft-soft support structure (lower figure).

3. Optimal shell design

Every design of support structures has basically to ensure, that the structure will last the respective load calculations extreme and fatigue loads. Further, certain stiffness has to be reached in order to gain a suitable structure natural frequency.

An optimal shell design by means of material usage is obtained, when the constraints described above are met with minimal material usage.

Parameterization

Within our model, all shells i of the support structure are defined by the lower diameter D_i, wall thickness s_i, material parameters (Young's modulus E_i, density ρ_i, yield strength $f_{y,i}$), the vertical position within the support structure h_i, additional dead loads M_i and the welded seam detail category Ω_i. Further, the location of the flanges defines the length l_i of the shells superior section.

Loads

In order to design suitable support structures, the dedicated load calculation program provides the extreme and corresponding simultaneous loads $\underline{F}$ and $\underline{M}$ (forces and moments in the principal axes) for every parameterized shell height. Further, the rainflow counts (p pairs of load cycles ΔM and corresponding load cycle number $N_{\Delta M}$) of the bending moments $(\Delta M_y, N_{\Delta My})_{I,p}$ and $(\Delta M_z, N_{\Delta Mz})_{I,p}$ are provided by the load calculation in every shell i. The exchange of loads and design parameters is automated between design tool and load calculation.

Constraints

The constraints according to the extreme and fatigue loads are for every shell i (see Refs. [1], [2]):

$$\frac{\sigma_{x,\mathrm{Ed},i}}{\sigma_{x,\mathrm{Rd},i}} \leq 1 \qquad (1)$$

$$\frac{\tau_{x\theta,\mathrm{Ed},i}}{\tau_{x\theta,\mathrm{Rd},i}} \leq 1 \qquad (2)$$

$$\left(\frac{\sigma_{x,\mathrm{Ed},i}}{\sigma_{x,\mathrm{Rd},i}}\right)^{k_x} + \left(\frac{\tau_{x\theta,\mathrm{Ed},i}}{\tau_{x\theta,\mathrm{Rd},i}}\right)^{k_\theta} \leq 1 \qquad (3)$$

$$d_i < 1 \qquad (4)$$

The first and second constraint represents the axial and shear buckling analysis with the load calculations extreme tensions $\sigma_{x,Ed}$, $\tau_{x\theta,Ed}$ and the shells resistance tensions $\sigma_{x,Rd}$, $\tau_{x\theta,Rd}$. The third constraint represents the total buckling analysis for extreme tensions. For the description of exponents k_x and k_θ see Ref. [1].

The fourth constraint is the total damage $d_i = \sum_p w_{i,p}$, the sum of all p partial damages $w_{i,p} = N_{e,i,p}/N_{a,i,p}$ in shell i. $N_{e,i,p}$ and $N_{a,i,p}$ are the present and allowed number of load cycles according to the load calculations bending moments (rainflow counts) and S/N-curve.

The dependencies of the constraints to the parameterization and loads are:

$$\sigma_{x,\mathrm{Ed},i} = \sigma_{x,\mathrm{Ed},i}\,(\underline{X}, D_i, s_i) \qquad (5)$$

$$\tau_{x\theta,\mathrm{Ed},i} = \tau_{x\theta,\mathrm{Ed},i}\ (\underline{S}, D_i, s_i) \quad (6)$$

$$\sigma_{x,\mathrm{Rd},i} = \sigma_{x,Rd,i}\ (D_i, s_i, E_i, f_{y,i}, l_i) \quad (7)$$

$$\tau_{x\theta,\mathrm{Rd},i} = \tau_{x\theta,Rd,i}\ (D_i, s_i, E_i, f_{y,i}, l_i) \quad (8)$$

$$N_{\mathrm{e},i,p} = N_{\mathrm{e},i,p}(N_{\Delta \mathrm{M}_{y},i,p}, N_{\Delta \mathrm{M}_{z},i,p}) \quad (9)$$

$$N_{\mathrm{a},i,p} = N_{\mathrm{a},i,p}(\Delta M_{y,i,p}, \Delta \mathrm{M}_{z,i,p}, \Omega_i) \quad (10)$$

It should be noted here, that the uppermost shells are typically loaded additionally by the carding moment resulting from the load introduction at the yaw bearing. To account for that, estimations can be made inside the design tool with optional safety factors (from experience approx. 1.3 – 1.7) for the corresponding shells in order to cover these higher loads. A similar strategy can be applied for openings etc.

Very costly and therefore essential constraints arise from the requirements on 1st and/ or 2nd natural frequency f_{1C} and f_{2C} of the support structure. The constraints according to the frequency are:

$$f_1 \geq f_{1C} \quad (11)$$

$$f_1 \leq f_{1C} \text{ and } f_2 \geq f_{2C} \quad (12)$$

For a stiff foundation, both natural frequencies f_1 and f_2 depend on the parameters of all n shells and the tower top mass m_{top}:

$$f_{1,2} = f_{1,2}\left(D_i, s_i, m_i, E_i, \rho_i, m_{\mathrm{top}}\right)_{i=1,n} \quad (13)$$

Apparently, the constraints (1)-(4) are local constraints (the analysis of each shell does not depend on other shells), whereas the constraints (11) and (12) are non-local.

The algorithm allows to predefine the relevant dynamic behavior (mainly first and second vibration mode) such that that different dynamically equivalent designs will not change the overall WEC loads. This feature enables us to reduce the necessary number of load calculation loops in the design phase of a certain turbine.

Depending on the user requirements, it is also possible to find the optimum diameter within a certain range (soft towers with requirements for second vibration mode).

Optimization algorithm

The optimization variable is the thickness s_i. Within our approach, the discretization of s can be adjusted to certain project shell thickness availabilities. For example $s_i \in$ [8, 10, 12, 14, …, 50 mm].

For every shell, s_i is varied until the constraints (1)-(4) are fulfilled with the smallest possible s_i and hence least usage of steel. Due to the locality of these constraints, the variation is done for every shell separately. This leads to optimized wall thicknesses for the extreme load constrains $s^{\mathrm{E}}_{\mathrm{opt},i}$ and optimized wall thicknesses for the fatigue load constrains $s^{\mathrm{F}}_{\mathrm{opt},i}$. Finally, the load optimized wall thicknesses are $s_{\mathrm{opt},i} = \max(s^{\mathrm{E}}_{\mathrm{opt},i}\ , s^{\mathrm{F}}_{\mathrm{opt},i})$.

If the optional constraint (11) is claimed and $f_1 < f_{1C}$ the support structure is also frequency tuned afterwards. To raise f_1 with the least usage of steel, the change in frequency Δf_1 and shell mass $\Delta m_{shell,i}$ is determined in every shell with increased wall thickness $s_{\mathrm{opt},i} + \delta s$. The smallest ratio $\Delta f_1 / \Delta m_{shell,I}$ yields the optimal shell i. This procedure is repeated until constraint (11) is fulfilled.

If constraint (12) (soft-soft design, see Figure 2) is chosen and not fulfilled, basically the approach described above is selected. However, to meet two frequency constraints is much more challenging, because of the non-locality of both constraints. It might even not be possible, to meet the two constraints at once, because raising the 2nd natural frequency will in most cases also raise the 1st natural frequency. Also to get an optimal design, this already challenging frequency tuning must be applied with the least amount of steel.

Our first approach was to vary only the shell thicknesses as already described for constraint (11) but with the aim to raise the 2nd natural frequency while keeping the 1st frequency small enough with the least amount of steel. It turned out, that also a variation of the shell diameter is required to get satisfying results.

Two diameter variation approaches were developed by us. Within the first approach we start with the maximal allowed diameter in every shell and adjust the shell thicknesses according to the respective loads (constraints (1)-(4)). If constraints (12) are violated, the diameter in every shell are reduced consecutively in order to lower the 1st natural frequency and to keep the 2nd frequency above the claimed frequency. This algorithm works fast but does not converge in some ill conditioned cases. Thus, also a brute force algorithm was developed, which analyzes all possible diameters within a certain discretization.

4. Integrated load simulation

In order to close the design loop a load calculation tool SiWEC dedicated to offshore wind turbines has been developed. It is based on a strict multi body approach to the mechanical system. Since it is dedicated to wind turbines it consists of 7 submodels (blades, hub, drivetrain, nacelle, tower, substructure, foundation) coupled mechanically. These submodels resemble the bodies in the MBS. All bodies and there interconnections are parameterized in a way that enables a wide variety of different realization for every part. For example the offshore substructure can represent a monopile, a jacket, a tripod or a gravity based foundation. The degrees of freedom which are accounted for can be defined for each body separately. The advantage of the restriction to a fixed sequence of bodies lies in a essential speed up compared to general multi body systems due to the fact that the mapping relating the accelerations in the system degrees of freedom to accelerations of the single body can be given explicitly. This avoids numerical gradient calculations in every time step. The program is equipped with an aero-elastic code based on state of the art extensions to blade element theory. Wave loads are implemented using Morrison equation. Furthermore structure soil interaction is included in the foundation model. For monopiles we used the standard p-y-curve approach. Wind fields and waves are calculated in accordance with IEC guideline. For the wind field the user may choose between Kaimal and Mann model.

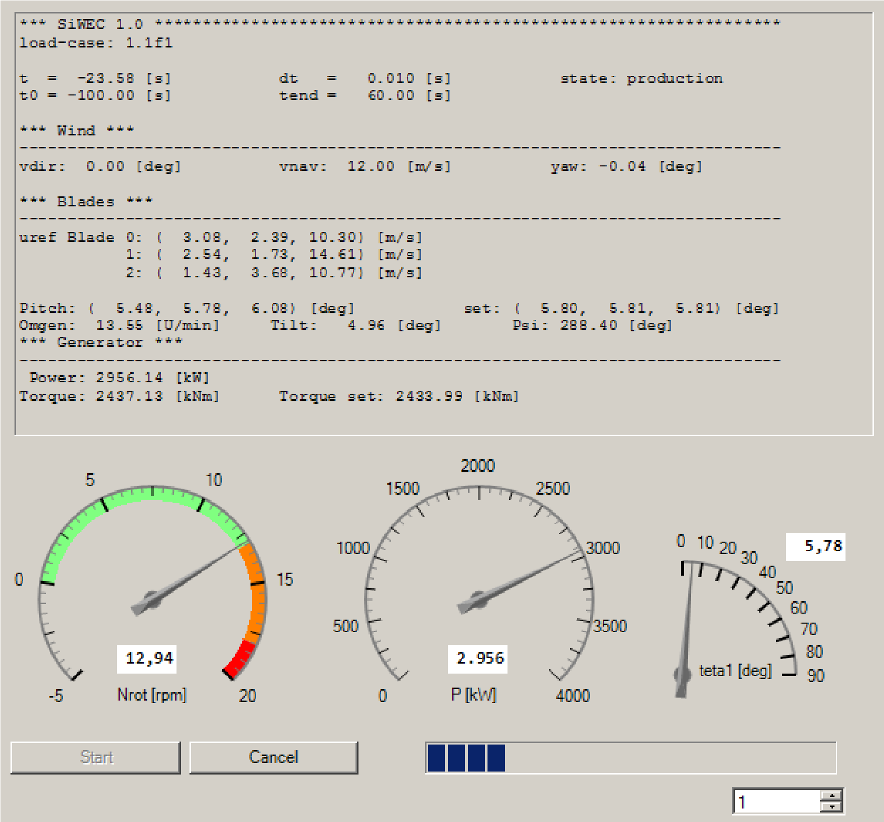

Figure 3: SiWEC interface during load calculation

The load calculation tool is equipped with a variety of analysis tools ranging from extreme and fatigue load evaluation to system frequency analysis and c_p-λ curve generation.

The essential point for the design of optimal offshore support structures is that the data can be exchanged directly between the design tool and the load calculation tool. This speeds up the overall design process considerably and at the same time it reduces error sources.

5. Conclusions

Using fast and robust analysis and design tools a considerable speed up in the iteration process for an optimized support structure design can be achieved. Due to the fully integrated design process a mass reduction of 5% to 10% compared to a sequential approach can be reached. Depending on the variation of soil conditions and water depth there is an additional saving potential by adapting the support structure to site conditions.

Working further along this integrated design path the next step will be the implementation of a common data base for design tools and load calculation.

References

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