Site Sensitive Support Structure and Machine Design for Offshore Wind Farms

T. Fischer, M. Kühn
Endowed Chair of Wind Energy (SWE) at the Institute of Aircraft Design, Universität Stuttgart
Allmandring 5b, 70550 Stuttgart, Germany, Fon: +49-711-685-68253
tim.fischer@ifb.uni-stuttgart.de

Summary

A design approach is investigated to counteract the effect of variable water depth and soil conditions at offshore wind farms with the aid of an offshore-specific and adaptable machine design. So far, one of the design drivers is that the fundamental eigenfrequency shall not be located in the vicinity of the rated rotational speed (1P). Here, a different machine design is proposed, which allows the support structure design to be closer to or right at the nominal 1P frequency. This design can also react to effects of varying soil or water depth conditions, as it allows adjusting the rotor speed characteristics. The result is a less conservative and therefore more cost-effective support structure design.

1 Introduction

Since support structures are one of the main cost drivers offshore and since offshore other rules apply with regards to design and site conditions, different methodologies have to be developed to mitigate the loads on the support structure and therefore to reduce the associated component costs. Until now, only a few offshore-specific turbine types are available on the market and most of them do not include control algorithms for support structure load mitigation adapted to offshore conditions. Furthermore, the design process for support structures of large offshore wind farms applied in the daily business of the industry is oriented at the most onerous site conditions inside the entire wind farm or for certain portions of the wind farm and can consequently result in over-dimensioning the majority of the structures.

2 Background

Reduction of the external wind and wave loads and of the associated dynamic response is, beside optimized manufacturing and installation logistics, an obvious way to achieve more cost-effective design. In the work presented here this is aimed for by integrating the design of the rotor-nacelle-assembly (RNA) and support structure in the design process. Hence, the RNA is considered as an active element in mitigating the loads on the support structure. For support structure load mitigation, different concepts are possible and can be distinguished at three different levels as seen in Fig. 1. The goal is to identify a suitable selection of options to finally obtain an optimized offshore wind turbine design.

Since offshore different design needs are present, one might think about offshore-specific design solutions (first level in Fig. 1). These can range from large turbines with a 2-bladed downwind rotor or light truss tower solutions. As noise restrictions are not as limited as for onshore locations, a higher tip-speed ratio and turbines with higher specific rating (W/m²) are possible. Furthermore, especially for variable site conditions, it might be a promising idea to consider turbines with adjustable operational characteristics able to compensate critical site variations like changing eigenfrequency ranges. These adaptable parameters can also be used to affect the overall design procedure of support structures. Nowadays, these structures have to be designed among other according to extreme loading, fatigue and frequency limitations. If the turbine characteristics can be adapted with the aid of, for example, shifting the rated rotational speed, the frequency limitation like the 1P can be reduced or even eliminated.

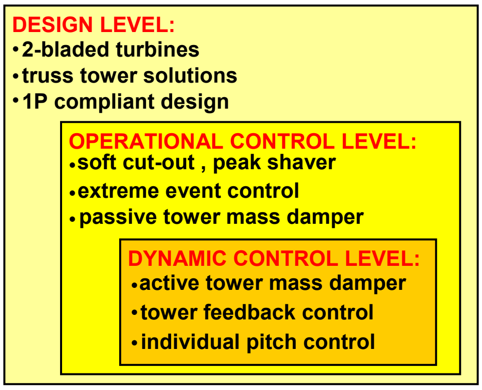

Fig. 1: Levels of load mitigation and associated examples of design concepts [1]

On the operational control level, the need for extreme event control is probably highest, as these loads are very often design drivers, at least for monopile-like structures. However, other strategies for optimized turbine operations and related lower support structure loads may be worth discussing, such as extending the cut-out limit, applying a peak shaver or a passive tower mass damper device.

Finally, on the third level there is a significant potential in using advanced and adapted dynamic control concepts, such as active tower mass damper, torque control or pitch control. The latter can either be implemented as active collective pitch control where the rotor acts as an active damper element as a so-called tower feedback controller. Or it can be used as individual pitch control to counteract sidewise vibrations, for example coming from wind-wave-misalignment.

3 Reference case

3.1 Reference site

The presented study is based on measurement data obtained over a period of 20 years at the Ijmuiden site in the Dutch North Sea [2]. The mean water level at this site is determined to be between 17-20 m, where for the design water depth 3.38 m have to be added due to storm surge and tidal ranges.

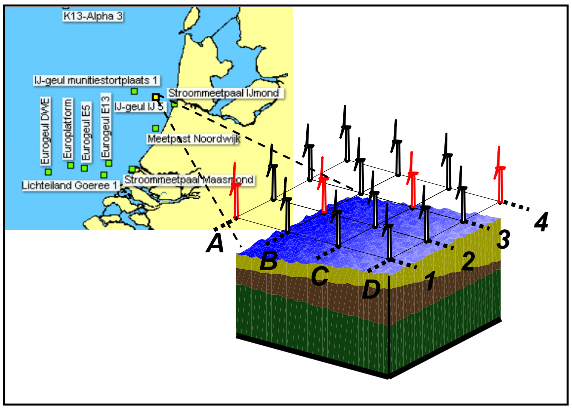

Fig. 2: Illustration of the studied offshore wind farm

For the site sensitivity study conducted here, a fictitious soil distribution is chosen to be able to verify the methods proposed later. Therefore, the soil ranges from moderate to very soft conditions. Fig. 2 illustrates the proposed wind farm at the given site. In one direction the design water level is constantly increased from 20 m to 24 m (Fig. 2, row *D to A*), where on the other axis the soil is changed from moderate to soft (Fig. 2, column *4 to 1* respectively). Thus, the diagonal through this wind farm represents the trend from the best conditions (shallow water level and hard soil, location *D4*) to the worst conditions (deep water and soft soil, location *A1*). This is also shown in Fig. 3.

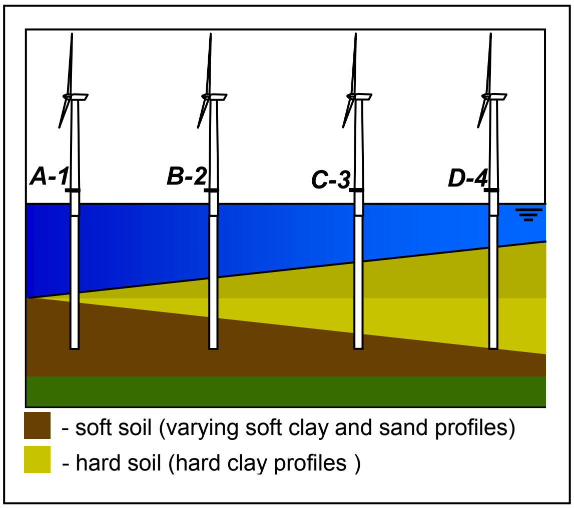

Fig. 3: Diagonal path through the studied offshore wind farm

3.2 Reference turbine

The reference turbine design used here represents a possible offshore-specific design solution.

Tab. 1: Comparison of rotor-nacelle assembly designs

	Basic Design	***Adapted Design***
rated power	3.6 MW	
rotor diameter	90 m	
nacelle and rotor mass	200 t	
rated rotor speed	17.4 rpm	19.1 rpm
rated tip speed	85 m/s	93.5 m/s
flapwise blade fatigue loading (DEL with m=10)	100%	102.2 %
edgewise blade fatigue loading (DEL with m=10)	100 %	100.7 %

It unites a high specific rating (W/m²) and a high tip speed ratio by choosing a smaller rotor diameter in connection with a high rated rotational speed. Besides, the tower top mass is assumed to be moderate with 200 t to enable economical support structure designs. This design is called *Basic Design*, according to Tab. 1.

For some monopile designs in larger water depths, for poor soil conditions and/or a larger machine with increased nacelle weight the support structure design might not be driven by the wind and wave loads but mainly by the requirement of sufficient dynamic stiffness in order to achieve a fundamental eigenfrequency at least 10% higher than the rated rotational frequency of the machine (1P). For such stiffness-driven designs one might think about using the RNA as active element to enable designs close to or at the nominal resonance frequencies like 1P. The idea is to be able to adjust the rated rotational speed of the turbine to exclude any possibility of 1P resonances.

In [3], three different controller setups were tested to achieve this. The simplest solution is reached by reducing the rotational speed and keeping all other operational characteristics the same. Thus limiting the torque to its rated value, the turbine has to run in a reduced power mode. But it is also possible to maintain the rated power level by changing the torque-speed-characteristics. Two setups were tested – one with a higher rated operational speed and a lower rated torque and one with a lower speed and higher torque, respectively. The study showed that the only economical and feasible solution is to aspire to the higher rotational speed concept with a lower torque level.

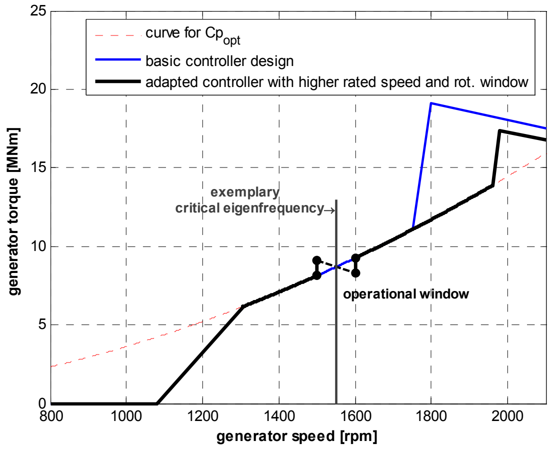

Fig. 4: Turbine generator speed vs. torque curvature

Based on this, the *Basic Design* introduced in Tab. 1 was extended by an adjustable concept, here called *Adapted Design*. This adapted solution enables the turbine to operate with an up to 10% higher rotational speed value by decreasing the corresponding torque, which leads to a higher tip speed of 93.5 m/s and higher fatigue loads on the blades, here based on a comparison of damage equivalent loads (DEL). However, compared to the gains from the following introduced adapted concept and the connected savings in support structure costs, those increases are still within a trade-off.

Fig. 4 illustrates the generator speed versus torque response of the variable speed controller. It can be seen that in the proposed concept another effect could be achieved by increasing the rated speed value. For the adapted controller design the curvature follows the optimal power coefficient value, C_p much longer. In this way, power performance can be increased. Still, the higher loadings for the blades are the negative consequence. However, this effect on the power coefficient is only a side effect for this certain case, which has not been the original intention.

Furthermore Fig. 4 shows another controller characteristic. If a critical frequency (like 1P) appears in the variable rotor speed range of the turbine, which can be the case if the rated speed value was shifted to a higher value, the turbine can avoid the resonance by applying a so-called rotational speed window. In this case the torque is increased / decreased while keeping the rotor speed constant until a switch in speed and torque is possible and the turbine can jump to a higher/lower curve-value.

4 Concept studies

As discussed in chapter 2, different concepts are available to optimize the design of offshore support structures. In this section the reference site and turbine is used to show a new design approach with the main goal to counteract possible variability in site conditions like water depths and soil stiffness. Besides, a comparison between a well-established / classical support structure design procedure and an adapted one is presented, which leads to less conservative design solutions.

4.1 Classical design approach

Offshore wind farm design nowadays follows a more or less established procedure. In a pre-defined group of structures the worst possible combination of conditions is assumed as to water depth, soil conditions, marine growth and turbine weight and is then taken as design drivers for all structures in the group. In the wind farm studied here (as shown in Figs. 2 and 3), this corresponds to location *A1* with the deepest design water level of 24 m and the soil conditions with lowest bearing capacity. Following the classical design approach the structure has to fulfil both – eigenfrequency and fatigue limitations. The frequency limit is given by the turbine characteristics; here for the *Basic Design* turbine the 1P-frequency is equal to 0.29Hz, which corresponds to the rated rotational speed value of 17.4rpm. To take dynamic amplification into account, at least a 10% margin has to be added to this 1P-value, which finally results in a lower frequency limit of 0.31Hz. Now the first eigenfrequency of the support structure has to be above this value and below the higher harmonics of the minimum rotor speed like the 3P. This design region between 1P and 3P is called soft-stiff, which is commonly used for current designs, and also in the study presented here. If the design frequency is located above the 3P range, the design would be called stiff-stiff, resulting in very high support structure masses, leading to unacceptably high costs. A soft-soft design with an eigenfrequency below the rated rotational frequency requires an exclusion window for the rotor speed as previously explained. And a design below the entire 1P range would be suffering excessive tower movements and would be susceptible to large wave excitations.

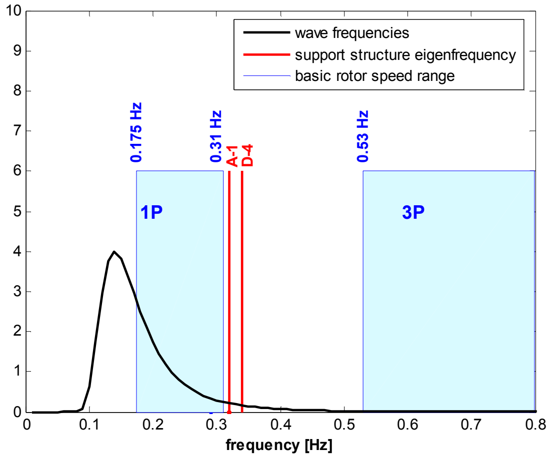

Fig. 5: Frequency ranges based on classical design approach (design driver is structure A-1)

If the frequency limitations are taken into account, a structure has to be designed that is stiffer, but as close as possible to the 1P frequency (including the 10% safety margin), as this ensures the lightest and therefore most cost-effective design solution. Fig. 5 shows the result based on the given design driving location *A1*, which has a first eigenfrequency of 0.32Hz. This value corresponds with pile diameter of 4.5 m and a penetration depth of 20 m for location *A1*. The resulting structural mass of the support structure is estimated to be 580 t.

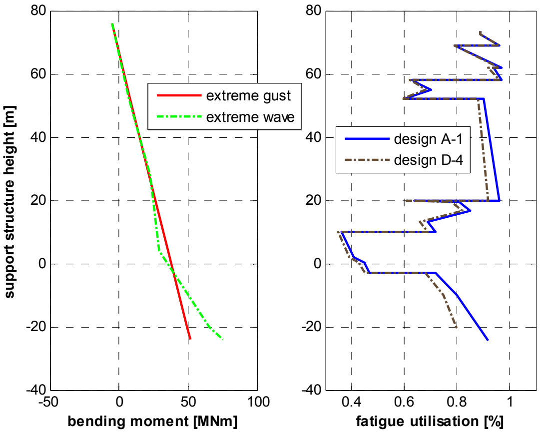

Fig. 6: Loading and fatigue utilization based on classical design approach

Besides the frequency limitations, the structure has of course to fulfil strength criteria, too. For the given site it was found that the extreme events are driving the design instead of fatigue loads. The most critical aerodynamic event was the extreme operating gust as defined in design load case (DLC) 1.6 according to [4], where for the extremes from the hydrodynamics the 50 year design wave, DLC6.1c according to [4] was critical. The corresponding bending moments of those two extreme load cases are shown in Fig. 6 (left) for the classically designed support structure. It can be seen that the hydrodynamic extreme loads are taking over the highest load contribution in comparison to the extreme operating gust approximated 5 m above mean sea water level. It is clear that in this area the wave impact affects the structure the most.

To prove whether that the structure lasts for the design lifetime of 20 years, a fatigue strength utilisation is calculated with the monopile design and optimization tool MonOpt [5]. This utilisation comprises all effects of aerodynamic and hydrodynamic fatigue and extreme loading and has to be below 1 to fulfil the lifetime and strength criteria. Of course the materials should be utilized as closely as possible to unity by varying the pile diameter, thickness and penetration depth. Fig. 6 (right) illustrates the result for the design discussed here. It can be seen that the structure has a rather good capacity utilisation. Only at the grouted joint region of the transition piece and for some sections with flanges the utilization is low.

After ascertaining the frequency and the fatigue limits for the classical design approach, the disadvantages of this procedure are becoming clear. Only for the design driving site, here the worst design location *A1*, the design is reasonably well utilized. All other locations in the studied wind farm have a lower water depth and/or better / stiffer soil conditions. This leads to the fact that their eigenfrequencies are becoming even more uncritical (as seen in Fig. 5 for the best location *D4*) and their utilisations contain buffers that are not needed (see Fig. 6, right). Of course they all fulfil the frequency and strength criteria, but all of them are overdesigned and therefore not cost-effective.

4.2 Adapted design approach

Beside the classical design procedure described above, another concept is possible. Again one specific site in a pre-defined group of support structures is taken as design driver for the full number of structures. But here the location with the least challenging conditions regarding water depths and soil conditions is taken as design driver for all structures. For the offshore wind farm studied here, this best site in terms of environmental conditions is located in *D4* (see Fig. 2 and Fig. 3) with a design water level of 20 m and hard clay soil profiles. Again, the structures have to follow the fatigue limitations and capacity utilisation (see Fig. 8). But in the adapted design approach proposed here the eigenfrequency is not a limiting factor anymore. As before the design driving structure (here *D4*) is designed as close as possible to the 1P frequency. But for the other structures (both for deeper waters and/or softer soil conditions), the frequencies are becoming critical as they shift into the 1P exclusion range. In those cases the *Adapted Design* turbine introduced in section 3.2 is applied. Fig. 7 shows that the eigenfrequency of the structure at location *A1* comes quite close to the rated rotor speed. In this example, it is right in the 1P frequency range. Hence, the rated rotational speed characteristics of the turbine are adjusted to a higher value, to avoid resonance. The shift of the 1P region to higher values, caused by a higher rated rotational speed, is illustrated as a dashed line in Fig. 7. For the frequency value within the variable rotor speed region, the rotational speed window described in section 3.2 can be used to avoid resonances.

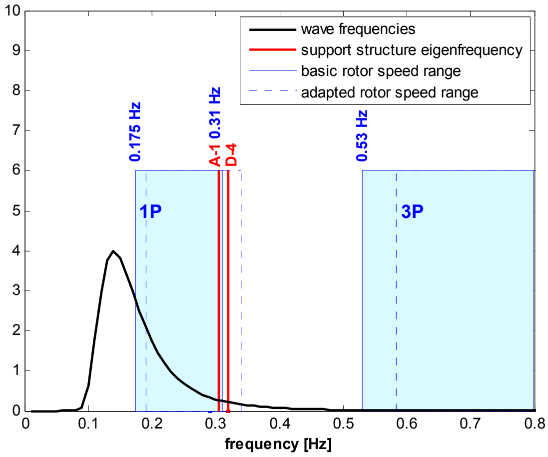

Fig. 7: Frequency ranges based on classical design approach (design driver is structure *D-4*)

By applying this different design concept, the too conservative design of the classical procedure can be avoided and critical frequency cases can be controlled. For this second adapted solution the structure maintains its pile diameter of 4.5 m, but the wall thicknesses and especially the penetration depth could be reduced significantly. The new design results in a total structural mass of 538 t, which means 7% mass and corresponding cost savings compared to the former classical design approach.

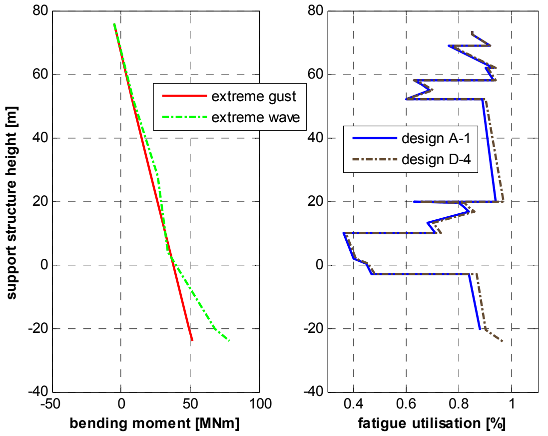

Fig. 8: Loading and fatigue utilization based on adapted design approach

5 Conclusion and outlook

The study presented here considered a different design approach for offshore support structures. This approach comprises an offshore-specific turbine design, which, on account of its adjustable rotor speed characteristics, can react to critical eigenfrequencies arising from the new design concept proposed here or from variable site conditions over the turbine's lifetime. Due to this, eigenfrequency requirements are no longer driving the design as much as this might be the case for the classical approach. The proposed approach seems feasible if the eigenfrequency criterion is the design driver for all locations within a design group. Both extreme and fatigue loads are generally increasing for decreasing eigenfrequency. Here it is assumed that the softer design still provides sufficient strength and fatigue resistance

The conceptual study described above showed that approximately a 7% support structure cost reduction with a maximum of 2% higher blade loads can be achieved for the studied offshore wind farm. However, due to the higher relative cost contribution of support structures compared to offshore wind turbine blades, a qualitative trade-off is given. Still, the implications of the increased rotor speed for example on extreme loads should be further investigated.

Acknowledgements

The presented work was funded by the Commission of the European Communities, Research Directorate-General within the scope of the Integrated Project "*UpWind – Integrated Wind Turbine Design*" (Project No. 019945 (SES6).

References

[1] Fischer, T. and Kühn, M.: Definition of control requirements for mitigation of aerodynamic and hydrodynamic loads, UpWind Report 4.1.1, Stuttgart, 2006

[2] Fischer, T., deVries, W. and Schmidt, B.: Design Basis - UpWind shallow water site, Stuttgart, 2009

[3] Fischer, T. et al.: Integrated design of offshore wind turbines for compensation of site variability, DEWEK, Bremen, 2008

[4] Germanischer Lloyd: Rules and regulations; Guideline for the certification of offshore wind turbines, Hamburg, 2005

[5] MonOpt 4.01, M. Kühn Consulting, Herrenberg, 2004

[6] Braam, H. and Eecen, P.J: Assessment of wind and wave data measured at Ijmuiden Munitiestortplaats; ECN-C-05-060, Den Helder 2005

[7] Fischer, T. et al: Report on design integration studies on bottom-mounted support structures, UpWind Report 4.1.3, Stuttgart, 2009