Optimisation and evaluation of pre-design models for offshore wind turbines with jacket support structures and their influence on integrated load simulations

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Abstract. In recent years many advanced load simulation tools, allowing an aero-servo-hydroelastic analyses of an entire offshore wind turbine, have been developed and verified. Nowadays, even an offshore wind turbine with a complex support structure such as a jacket can be analysed. However, the computational effort rises significantly with an increasing level of details. This counts especially for offshore wind turbines with lattice support structures, since those models do naturally have a higher number of nodes and elements than simpler monopile structures. During the design process multiple load simulations are demanded to obtain an optimal solution. In the view of pre-design tasks it is crucial to apply load simulations which keep the simulation quality and the computational effort in balance. The paper will introduce a reference wind turbine model consisting of the REpower5M wind turbine and a jacket support structure with a high level of detail. In total twelve variations of this reference model are derived and presented. Main focus is to simplify the models of the support structure and the foundation. The reference model and the simplified models are simulated with the coupled simulation tool Flex5-Poseidon and analysed regarding frequencies, fatigue loads, and ultimate loads. A model has been found which reaches an adequate increase of simulation speed while holding the results in an acceptable range compared to the reference results.

1. Introduction
Offshore wind turbines (OWT) and their support structures are designed based on loads from aerelastic and hydrodynamic load simulations. Large wind turbines with jacket support structures are one of the preferred concepts for moderate water depths between 25m and 50m. The coupling of the jacket dynamics and the wind turbine dynamics can be taken into account by so-called integrated simulation methods [1]. Such dynamic couplings plays a significant role in load analyses of large OWT, due to their flexibility and significant contribution of the vibration to the internal loads [2]. However, integrated simulations require significant computational effort. This becomes a drawback during the pre-design phase where many design iterations are necessary in order to determine an optimal structural design. Hence, computational efficiency becomes an important factor [3].

Integrated simulations under combined aerodynamic and hydrodynamic loading are carried out with Flex5 and Poseidon [4]. The paper discusses the modelling of an existing system, consisting of a REpower 5M wind turbine with a jacket support structure developed by OWEC Tower AS, such as...
installed in Germany's first offshore test field “alpha ventus” [5]. The rotor-nacelle-assembly (RNA) and the tower are simulated in Flex5 based on modal reduced models. The substructure and the foundation are modelled in Poseidon using finite Bernoulli beam elements. The modal approach in Flex5 is computationally very efficient and the optimisation potential lies, therefore, mainly in the reduction of the finite element model of the substructure and foundation.

The research presented in this paper is part of a thesis [6] within the RAVE project OWEA - “Verification of offshore wind turbines” [7]. The aim is to introduce several possibilities to reduce the level of modelling detail and evaluate their influence on the quality of the simulation results.

2. Potential boundary conditions for the design and load simulation models

This chapter presents factors that influence the results of a load simulation. Since this study deals with a real OWT, solely factors will be considered which are relevant for the location of alpha-ventus. The evaluation was carried out using the present design basis “Borkum West” [8].

2.1 Soil condition

The soil conditions affect the static and dynamic behaviour of an OWT and will, therefore, affect the load simulation results [9],[10]. For the consideration of the soil conditions a model, which was developed parallel to this thesis, was used. In this soil model, the piles were divided into equal elements. On each element, two combinations of a spring and a damper element were arranged in a rectangle. This means three nodes were used, to model each part of the pile. The variation of the soil discretisation is to show the connection between model depth and simulation results. It will clarify the question, how detailed the soil must be modelled in order to still obtain acceptable results.

2.2 Water level and splash zone

The splash zone is the range of an offshore structure which is exposed to air and water due to the tidal and wave movement. It is located within the 2nd and 3rd brace. It is necessary to implement the splash zone and the water level in the model for accurate consideration of element properties (e.g. marine growth and hydrodynamic loads). 24 nodes are needed for a detailed consideration of the splash-zone.

2.3 Scour

The seabed sediment around the support structure’s foundation can be prone to erosion. It leads to a degradation of soil stiffness and changes the p-y curves. This study assumes a scour protection. Hence, occurrence of scour is not considered. Nodes in addition to the already used nodes are not necessary.

2.4 Marine Growth

On-site plant, animal and bacteria life causes marine growth on structural components in the water and in the splash zone. Marine growth adds weight to a structural component and influences the geometry and the surface texture, but does not contribute to any additional stiffening. The consideration of marine growth does not need any additional nodes and has no influence on the computing time, if the property is constant over one element. Marine growth is anyway included in all models to assess the variation of water level and splash zone.

2.5 Corrosion

Corrosion influences the properties of the metal component. It can lead to impairment of the function of the component or the whole system. In order to prevent corrosion so-called sacrificial anodes are used. Measurement data, used to validate this model, only incur at the beginning of the unit’s lifetime. Hence, it can be assumed that the corrosion rate is very low. Corrosion is, therefore, not implemented.

2.6 Hydrodynamic added mass and buoyancy

The jacket is mounted in a water depth of 28 metres. The lower part of the jacket is surrounded by water. If the Jacket oscillates the surrounding water decelerates the oscillation. Hydrodynamic added
mass is not considered automatically in the FE-code. For consideration of this effect the mass must be added manually to the element via an element distributed mass.

Buoyancy results from pressure differences on the surface of the body. One must distinguish between flooded and sealed sections. The pressures, which are determined by the water density, the global acceleration and the height of the water column above it, act perpendicular to the surface of the object. Both factors do not require additional nodes and do not affect the computing time. The factors are included anyway in all models to assess the variation of water level and splash zone.

2.7 Secondary structures
Besides the main load carrying elements many so-called secondary structures are present at the jacket. Structures such as ladders, access platforms or tubes for measurement equipment increase the hydrodynamic loading, but they do not contribute to the stiffness or dynamics of the global structure. The paper is designated to optimising pre-design models where only poor geometry information of these elements are available. Therefore, the secondary structures are neglected. One simple approximation can be achieved by increasing the drag coefficients and the mass of the main structure, where the secondary parts are attached to. This approach will also not influence the simulation speed.

3. Reference model and the developed model variations
In this paper models with different details and accuracy are considered. The specifications of the simplified models derivate from the reference model M10 will be discussed in this chapter. In particular the number of nodes used to model the jacket structure is of interest, since it is directly connected to the computational effort necessary to perform a simulation of the OWT. These nodes are displayed as red dots in the following figures and describe the connection between two or more elements. Posseidon applies a meshing of each element before a simulation is performed. This discrete representation automatically divides each element in two subelements, but does not change the properties of the element. The number of degrees of freedom is not proportional with the number of nodes, but it is sufficient for a comparison of the models to provide the number of the nodes as a reference value since the meshing is the same for each model.

The models considered in this study can be divided in five categories. The first category M1x includes the reference model of the OWT, while the second to fifth category consist of simplified models. Models of the second category are simplified regarding the splash zone, while models of the last three categories are modified with respect to the pile modelling. The main differences are shorter piles, piles without support for the lower part, and piles with reduced support for the lower part for category M3x, M4x, and M5x, respectively.

3.1 System specification of the reference model
In order to give an indication of quality for the reduced models, it is necessary to create a model with a high accuracy. This model serves as a reference for further comparisons. The so-called reference model M10 includes all points mentioned in Chapter 2, which might have an influence on the simulation results and affect the computing time. The foundation was modelled by dividing the piles in ten equal parts. This leads to a number of 120 nodes for the bedding of the piles. 55 nodes were used for the correct representation of the jacket support structure, 24 nodes for the modelling of the splash-zone, 8 nodes for the connection between piles and jacket, and 4 nodes for the clamping at the bottom of the piles. The model includes 211 nodes. A visualization of the model can be found in Figure 1 (a).

3.2 Modelling approaches for variation
The first simplification was made by approximating the splash zone. Nodes, located close to the original position of the splash zone are used to represent the approximated splash zone. This affects the influence of the drag coefficient, marine growth and the buoyancy of the model. This first variation is called model M20 and consists of 24 fewer nodes as the reference model M10. A visualization of model M20 with the approximate position of the splash zone can be found in Figure 1 (b).
The analysis of mode shapes showed that the piles oscillate in the lower part only slightly. Therefore, further reductions are made by varying the number of nodes, which are used for the soil-pile-interaction. The static condensation of the entire piles would be an alternative to the spring-damper approach used in this study, but it is outside the scope of this study.

The variations can be divided in three categories. For models in category M3x only a part of the upper pile nodes is used. This leads to a shorter pile length (see Figure 1 (c)). The second number in the name of the model declares the number of the nodes, which were used to model the piles. Model M35 for example uses the first five nodes of every pile. It is always counted from the top of the pile to the bottom. The pile ends at the sixth node where it is clamped rigidly. The properties of the upper springs and dampers were not changed compared to model M10. The removal of spring and damper combinations at the lower part of the piles results in lower accuracy when considering the soil conditions, but there is always an improvement in simulation time when compared to other models, due to there being fewer nodes. Table 1 shows this correlation.

The fourth category was developed to analyse the importance of the original length of the piles. The so-called M4x models are identical with the models M3x, except for the length of the piles. As with the category M3x, the second number in the name of the model indicates the number of spring-damper-combinations which were used to model the soil. Therefore the model M45 also uses the first five nodes of a pile to constitute the soil condition. No combination of spring and damper is used from node five to the original end of the piles. Hence, the bottom of the pile is clamped rigidly at the sixth node.

Thus the original length of the piles is used for models of the category M4x, but the lower part of the piles is modelled with just one beam element. An example can be found in Figure 1 (d). As with the model category M3x, the values of the used springs and dampers were not changed. This
simplification of the piles will also affect the results of the load simulation. The total number of nodes for a model from model category M4x is equal to the total number of nodes for a model from model category M3x, if the second number of the model matches. Therefore the simulation time for the corresponding models is nearly the same. The reduction of the simulation time for different models can be found in Table 1.

Again, the analysis of the mode shapes led to a new category. Since antinodes occur at the bottom of the piles for models of the category M4x, an additional spring-damper combination was located at the lower part of the piles. This spring-damper-combination is located exactly in the middle of the last regular spring-damper-combination and the end of the pile. Only one beam element was used for the part between these two nodes in models from the category M4x. For the upper springs and dampers the stiffness was not changed compared to model M10. The stiffness for the spring and damper located on the lower part of the pile was calculated using the spring-damper-combinations which were previously removed. As an example from the category M5x, model M55 is shown in Figure 1 (e). The stiffness of the spring and damper at node number eight is a combination of the second part of the nodes at the pile which were previously removed. In the case of model M55, these nodes are number six to ten. Again, reducing the number of nodes will impact the simulation results. Due to the fact that the soil conditions of the lower part are taken into account, more accurate simulation results are expected. A model from the category M5x always has 12 nodes more than the corresponding model from the category M4x. This number correlates with the four spring-damper combinations placed on the lower part of every pile.

Each variation of the reference model consists of a different number of nodes. An overview of the number of used nodes can be found in Table 1. The number of nodes correlates with the required simulation time. The relation between the number of nodes and the simulation time is also shown in the table. The percentage of the simulation time refers to a 10-minute load case performed with the baseline model M10. All simulations were carried out on the same machine. Depending on the model variation the simulation speed has been increased up to five times in contrast to the reference case.

Table 1. Computing time for the model variants in relation to the reference model

| Model | Piles | Number of Nodes Total | Simulation Time |
|-------|-------|-----------------------|-----------------|
| M10   | 120   | 55 24 12 211          | 100.0%          |
| M20   | 120   | 55 - 12 187          | 76.4%           |
| M31   | 12 55 | - 12 79             | 21.6%           |
| M32   | 24 55 | - 12 91             | 24.7%           |
| M33   | 36 55 | - 12 103           | 28.4%           |
| M35   | 60 55 | - 12 127           | 36.1%           |
| M37   | 84 55 | - 12 151           | 48.2%           |
| M42   | 24 55 | - 12 91             | 24.7%           |
| M43   | 36 55 | - 12 103           | 28.3%           |
| M45   | 60 55 | - 12 127           | 35.8%           |
| M53   | 48 55 | - 12 115           | 31.8%           |
| M55   | 72 55 | - 12 139           | 41.4%           |

4. Selection of load cases for the fatigue and ultimate load analyses

Four design load cases (DLCs) were selected for the comparison. They are set up according to “Design requirements for offshore wind turbines” published by IEC 61400-3 [10].

The DLC 1.2 was selected for the fatigue load analyses. In this design situation the OWT is running and connected to the electric load. Eleven wind bins with a width of 2 m/s in a range from 4 m/s to 24 m/s were simulated for this DLC. Every wind bin has three wind seeds with a wind misalignment of -8 deg, 0 deg or +8 deg.
Three DLCs were selected to consider the ultimate loads, all of which belong to the same design situation DLC 7.1. In the selected design solution, the OWT is parked. Deviations from the normal behaviour of a parked wind turbine, resulting from the faults in the yaw system appear. A yaw misalignment of up to 120° is considered, depending on the DLC. The fault conditions are combined with extreme wind and wave conditions.

For the calculations of the DLCs a wind sector has been selected from 180 degrees to 360 degrees. This sector included the main wind direction. 70 percent of wind and 90 percent of the waves occur in this sector according to the design basis “Borkum West” [8]. A representation of the wind and wave distribution can be found in Figure 2.

The sector from 180 degrees to 360 degrees is weighted higher in the subsequent consideration of the loads due to the negligence of the remaining 180 degrees. This is reasonable for the comparison since the jacket is symmetric and the wave height and wind speeds from the neglected sector are lower. Thus, no higher loads are expected.

According to the IEC Guideline [10], the total period of load data should be long enough to ensure statistical reliability of the estimate of the characteristic load. Therefore three 660-second stochastic realisations are applied for each wind speed and wind direction. The first 60 seconds of each simulation are cut off to remove transient effects.

To compare the models afterwards it is necessary to use data of member forces, moments and stresses. Each model contains a wide range of sensors. The spots for the sensors are oriented by the real measurement spots applied at the research OWT R4 in alpha ventus. Additional sensors were added on jacket elements which seemed interesting for further load case comparisons. However, the comparison of jacket loading is only based on axial forces and bending moments, as lattice structures are naturally dominated by these load components. Local shear forces or torsion in the jacket are very small and negligible for the design.

5. Evaluation of the derived pre-design models
Eleven models were developed for the comparison with the reference model M10. Each model includes 253 load sensors, which are placed at the rotor blades, tower top, tower base and the jacket. Overall, four DLCs are used with different wind directions, wind speeds, wind bins and misalignments with a total simulated time of 46.5 hours per model. This implies the evaluation of an exceedingly large amount of data, if all of the models should be considered accurately. Hence, a pre-selection of the models is made first by comparing the eigenfrequencies. The reduction of the simulation time is
also considered. Afterwards the fatigue and ultimate loads of the selected models were compared. All diagrams are normalised, if they contain in-house or confidential data from the manufacturer.

5.1 Eigenfrequencies results
The dynamic behaviour of an OWT can simply be represented by showing the eigenfrequencies. The first 20 eigenfrequencies of the entire OWT are considered. The diagram illustrated in Figure 3 shows one model of each model category with the best match to the eigenfrequencies of the reference model M10. Model M32 is also shown in this diagram due to the positive relation of simulation time and the results of the comparison of eigenfrequencies. The first eigenfrequency is omitted as it does not provide an informative value since it results from the free rotating shaft of the wind turbine.

![Figure 3. Eigenfrequencies of selected models, normalised to second eigenfrequency](image)

Overall the considered model variants are in good agreement to the reference model. Slight differences occur above mode number eleven. The eigenfrequencies of model M45 are in good accordance with the eigenfrequencies of the reference model M10. Model M45 also provides a good reduction of the simulation time. Model M32 achieves the best reduction of the calculation time while the results of the eigenfrequency comparison are still satisfactory. Therefore, both models, M32 and M45, are selected for detailed comparisons.

5.2 Results of the fatigue load analyses
For the comparison of fatigue loads, the rainflow-counting algorithm, followed by the identification of the damage equivalent loads (DELs) for different S-N slopes, was conducted. The number of reference cycles is set to 5 \(10^6\), which is the standard number of cycles for fatigue tests.

According to the design basis of alpha ventus, expected wind conditions and the probability of wind speed occurrence on the considered site are described by a Weibull distribution. By integrating the Weibull distribution and multiplying it by the annual probability of occurrence for the corresponding wind direction, it is possible to determine the frequencies of occurrence for a particular class width of the wind speeds in a certain wind sector.
Figure 4. Number of DELs, distribute in accuracy levels

| DEL_{Mx} | DEL_{M10} | M32 | M45 |
|----------|-----------|-----|-----|
| < 1%     | 153       | 208 |
| 1% - 10% | 76        | 31  |
| > 10%    | 24        | 14  |

The fatigue calculation in this paper is based on a lifetime of 20 years. The weighting of a class width of the wind speed is obtained by multiplying the previously calculated frequencies of occurrence with the lifetime of 20 years. It must be noted that three wind seeds occur per class width. Thus the part of a wind bin is one third of the total share of a class width. The fatigue calculation considers a wind sector of 180 degrees to 360 degrees (see Chapter 4).

The DELs are calculated for all relevant sensors. For the comparison of the sensors the Wöhler coefficient $m$ is set to 4 for the steel construction, and to 10 for the rotor blades. These values are typically used for simplified calculations for designing wind turbine rotor blades. The models M32 and M45 are compared with the reference model M10 by calculating the ratio of DELs between model M32 and M10 and model M32 and M10, respectively. No further investigation is necessary for sensors with a ratio close to one. This is the case for 153 sensors of model M32 and for 208 sensors of model M45. The number of sensors with a ratio in the range above 1% can be found in Figure 4. The observation of divergences within the range of ±10% is freely chosen by the author to allow qualitative comparisons. An overview of the comparison of the ratios for the DELs of model M32 and model M45 is present in Figure 4.

As seen in Figure 4 model M45 provides better results for the calculated DELs in comparison to model M32. However, there are 14 sensors of model M45 with a percentage deviation of more than 10 percent. On closer inspection it can be stated that all of these sensors are located at elements on the lowest braces. Figure 5 shows the corresponding elements.

Figure 5. Overview of elements with higher deviations in DELs
5.3 Results of the ultimate load analyses

The comparison of fatigue loads has shown that model M45 provides better results in relation to model M10 than the simpler model M32. Therefore, only model M45 is used for the following comparison of ultimate loads.

253 sensors which are implemented in the reference model M10 are used for the comparison of ultimate loads. For the comparison the extreme values that occur in the DLCs of each sensor are determined. Each simulated wind direction and wind speed was taken into account. The resulting values represent the ultimate loads that occur in the whole simulation of the DLC.

In a first step these extreme values of model M45 are compared with the corresponding extreme values of the reference model M10 by calculating the percentage deviation.

If the deviation for the extreme load is in between a range of $\pm 10\%$ the sensor of model M45 provides data which is in a sufficient quality to the reference model M10. No further consideration of these sensors is necessary. This affects 231 sensors of the DLC 7.1 and 239 sensors of DLC 1.2.

Again a range of $\pm 10\%$ is selected for the qualitative evaluation. A list with the exactly number of the sensors which are without any deviation to model M10 or which are in a range between $\pm 5\%$, $\pm 10\%$, $\pm 15\%$, and $\pm 20\%$ can be found in Figure 6.

| Percentage deviation | DLC 1.2 | DLC 7.1 |
|-----------------------|---------|---------|
| $<1\%$                | 123     | 166     |
| $1\% - 5\%$           | 91      | 61      |
| $5\% - 10\%$          | 17      | 12      |
| $10\% - 15\%$         | 8       | 6       |
| $15\% - 20\%$         | 8       | 8       |
| $20\% - 25\%$         | 6       | 0       |

Figure 6. Number of sensors from model M45 sorted by percentage deviation

As shown in Figure 6 the main part of the sensor data from the reduced model M45 are in very good agreement with sensor data from the reference model M10. However, all sensors with a deviation of more than $\pm 10\%$ need to be further investigated. A lot of these sensors have extreme values close to zero or their absolute deviation related to the oscillation amplitude is very small. Their percentage difference is, therefore, very large and overrated. This counts for 40 sensors for DLC 1.2 and 35 sensors for DLC 7.1. These sensors are neglected for the further investigation.

Some sensors are still remaining which have higher percentage deviation and cannot be explained with the aforementioned criteria. These are solely load sensors in the jacket support structure. All of them are located at the lowest braces. The associated elements are the elements 102, 103, the elements 300, 301, 302, 303 and the elements 400 and 402. These are exactly the same elements, which had also slightly higher deviations during the comparison of fatigue loads. They are shown in Figure 5.

6. Conclusion

The research presented in the paper focuses on optimising the relation of accuracy and simulation speed of integrated load simulation models, which is a key factor in fast and meaningful pre-design tasks. For this purpose a reference model of an OWT with jacket support structure is developed in the simulation tool Flex5-Poseidon. In total eleven model variations are assessed. Two of them, model M32 and M45, are found as adequate substitutes for the reference model M10. Simulation speed has been reduced by 75% and 65%, respectively. On the other side fatigue and ultimate load analyses based on DLC 1.2 and 7.1 show acceptable agreements with the reference model results.

The comparison considers local forces and bending moments all over the structure. The majority of sensors are in a range of less than 5% difference to the reference model. A small number of sensors
have larger differences of over 10%, which need to be distinguished in two categories. First category occurs at spots with very small absolute values around zero. For example tiny force components at a brace can result in high relative deviations. Looking at the total loading capacity of such a spot, this small force is negligible in contrast to bending moments. The second category is of more importance. These sensors are found at the braces close to the mudline and the loading cannot be seen as negligible small. The reason is found in the different soil-pile models, which influences the mode shapes slightly and thus local forces and bending moments.

A further result of the research is the evaluation of the influence of the different jacket support structure models to the tower and RNA. The variations of the applied jacket parameters do not have a significant influence on the behaviour of the components above the jacket.

The performance of the derived models needs to be placed in relation to the application of such models. The aim is to determine the global dynamic behaviour, developing and setting up control algorithms, power performance calculations, and global loading assessment, which are based on a very large number of load cases, where speed becomes a factor and the presented models offer a very good opportunity. For detailed design of local elements more sophisticated tools should be applied and fed with the output of such pre-design models.

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