Validation of an Integrated Simulation Method with High-Resolution Load Measurements of the Offshore Wind Turbine REpower 5M at Alpha Ventus

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The validation of load simulations with offshore field measurements at the research wind farm Alpha Ventus, Germany, is presented in this paper. Simulations are carried out with the integrated load simulation tool Flex5-Poseidon, which treats the aerodynamics, hydrodynamics and elastic motion in a coupled dynamic analysis. The reference wind turbine is the REpower 5M with a jacket substructure installed in the North Sea, 45 km offshore at 28-m water depth. Comparisons are based on stresses and loads at the rotor blades, tower and substructure. High-resolution measurements of a one-year period form the basis for the comparison.

INTRODUCTION

The design of offshore wind turbines with lattice support structures can be optimized using integrated load simulations. This means that the complete offshore wind turbine, including the support structure, is simulated with aerodynamic and hydrodynamic loads concurrently. Such methods have been developed and verified (Fig. 1), but only a small number of offshore measurements, often with limited data, have been conducted to allow extensive validations (Ostermann, 2009).

The aim of this paper is to contribute to the validation of integrated load simulation tools (Fig. 1). For this purpose, the high-resolution measurements at the offshore test site Alpha Ventus are analyzed in detail. The measurements are carried out at the nearby met mast FINO1 and the wind turbine R4, which is a REpower 5M installed on a jacket substructure. The layout of the test site is illustrated in Fig. 2. A wide range of measurement devices have been installed. However, for the validation, the most important information is the environmental conditions and the load measurements. The loads and motions are monitored by strain gauges and accelerometers in the rotor blades, tower and jacket substructure. Most problematic is the derivation of accurate spatial environmental data for the simulations, because only punctual measurements at the met mast or at the nacelle of the turbine are available. Simulations are carried out using Flex5-Poseidon, a coupled integrated approach for dynamic load simulations of wind turbines, in the version of the Stuttgart Wind Energy research group. A model of the REpower 5M has been created and includes the rotor-nacelle assembly, tower, transition piece, jacket substructure, foundation and the control system.

The validation of the software consists of three phases. The first phase is a nacelle rotation under calm weather conditions. This simple load case also enables plausibility checks of the measurement data using hand calculations. The second phase is a direct simulation of a measured time series during quasi-steady environmental conditions. Such conditions support periodic system reactions. The results are presented in frequency and partly in time domain. The last phase shows the statistical comparisons of loads during normal operation using data from January 2011 until December 2011. Presented results usually show normalized data due to the confidentiality.

Fig. 1 Verification and validation of simulation tools

Fig. 2 Location and layout of Alpha Ventus, modified from DOTI (2013)
REFERENCE WIND TURBINE AND MEASUREMENT CAMPAIGN

Reference Wind Turbine: REpower 5M with Jacket

All simulations and measurements results are based on the REpower 5M wind turbine installed at the wind farm Alpha Ventus. The research wind turbine is located to the east of the met mast FINO1. The free stream inflow directions are from 190° to 260° and 280° to 350° with respect to North. The turbine has a hub height of 92 m, a rotor diameter of 126 m and a rated power of 5MW. The total height from mudline to hub is 120 m. The jacket substructure, including the transition piece, has a length of 55.7 m. The four main legs are stiffened by four levels of x-bracings. The main legs are free-flooded by seawater. Braces are sealed and filled with air. Marine growth up to 50-mm thickness occurs at the structure. The mean sea level is 28 m. The foundation consists of four piles, which are driven into the seabed, and a grouted connection links the jacket to the piles.

The simulation model and the controller of the wind turbine are kindly made available by REpower. The jacket and foundation substructure are derived from the construction plans of OWEC Towers, Norway. Figure 3 illustrates the wind turbine model in a simplified way. The simulation model considers marine growth and buoyancy effects of the underwater structure. The transition piece design has a panel between the four legs, which is connected to the main column in the center. Four inclined stiffeners connect the tower bottom flange with the legs. The transition piece is simplified, represented by a beam framework. The panel consists of a quadratic frame and two diagonal braces. The pile foundation is modeled in two options. The first option is an equivalent pile model under each leg. The length is chosen to match the first global natural frequency of the system. The second option is a spring damper bedding along the piles, according to the p–y curves of the soil, and clamped at the lower end. All simulations performed are based on option one: the equivalent piles. All tubular elements of the jacket and the foundation are modeled with Bernoulli beam elements with six degrees of freedom at each node, which means that the shear deformation is neglected.

The simulation model considers very carefully the location of the measurement devices. This is essential for the validation, especially for the strain gauges at the jacket.

Overview of the Measurement Campaign and Sensors

The REpower 5M wind turbine (number R4) in Alpha Ventus is extensively equipped with measurement devices. Data are continuously available for the research since 2011. A separate measurement project, RAVE-Messserviceprojekt, is running in parallel to ensure accurate measurements offshore and to maintain the equipment. The past three years have shown that this is a very challenging task. The responsible measurement institute for the REpower wind turbine is GL Garrad Hassan Deutschland GmbH (Link, 2010). The most interesting measurements for the purpose of validating the simulation tool are strain gauges, accelerometers and measurements for the environmental conditions. The sampling rate of the strain gauges and accelerometers is 50 Hz.

Wind speed and wind direction are available from the nearby FINO1 met mast at several heights. A buoy is placed close by to capture averaged sea state information. Additionally, pressure and temperature measurements are available.

Loading is monitored at all load-carrying parts of the turbine. The present analyzes focus on the rotor blade root, the tower top, the tower bottom, the jacket legs and the bracings. Flapwise and edgewise bending moments are available for all three rotor blades. They are calculated by means of the raw signals considering crosstalk. Crosstalk denotes that some flapwise strain is monitored in the edgewise direction and vice versa, which occurs due to the location of the strain gauges.

Values of the tower bending moments are available in [kNm] in the data archive, not as basic strain data. The coordinate system of the tower bending moments corresponds to the diagonal lines A1B2 and A2B1 of the jacket. Figure 4 depicts the top view of the layout. Data are available at three tower cross-sections: close to the yaw bearing, at the tower midsection, and at the tower bottom.

The measurements at the jacket are available as strains with the unit micro strain [µm/m]. With the law of elasticity, the signals can be converted into stresses. At every measurement location, at least four strain gauges are installed around the circumference of the tubes numbered with _1 to _4 at the end of the sensor names. They are installed at least one diameter away from a joint to avoid local stress concentrations. The sensor locations at the northwest side of the jacket are illustrated in Fig. 5. The naming convention is based on the joint numbers. Every station of a leg, from where

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Fig. 3 Sketch of the REpower 5M with Jacket

Fig. 4 Orientation of the wind turbine R4 at Alpha Ventus

Fig. 5 Measurement locations at the northwest side of the jacket
a brace is attached, is assigned a joint number. This results in
numbers N1 to N5 for the north leg, W1 to W5 for the west leg,
and so on. The name for the x-joints uses combined numbers to
specify the level. For instance, the position N1W2 denotes the
lowest x-joint at the northwest side. A full name, for example,
reads R4_D-N2/W1_3. It specifies the third strain gauge at turbine
R4 at the bracing from joint N2 to W1, which is installed close to
N2. The same convention is used for the other three faces of the
jacket. However, they are not equipped in such high detail.

First assessments of the measurement data show that some devices
are defective and most of them cannot be repaired. Approximately
one-third of the planned measurements are not available anymore.
Statistical data from January to March 2011 have been used to
filter defective measurement devices. In most cases, it is sufficient
to check the 10-minute mean, maximum and minimum values of a
sensor over a period of time to prove the operational reliability.
Defective sensors usually have constant values or show an extreme
oscillating trend.

INTEGRATED SIMULATION ENVIRONMENT

The applied software is a coupled simulation method for the
integrated analyses of offshore wind turbines. The models of both
programs are coupled on the level of the equations of motion during
runtime. Flex5 is a tool for the dynamic simulation of onshore
wind turbines and offshore wind turbines with monopile support
structure. The applicability has been improved by coupling Flex5
with general finite element codes (Kaufer et al., 2009), which allow
the simulation of wind turbines with more advanced substructures
such as jackets. Couplings are implemented to Poseidon (Kaufer,
2008) and ANSYS ASAS. Poseidon is a linear finite element code
specially designed for wave-loaded space frame structures. The
main advantage of this coupling is the possibility to use cluster
techniques to increase the simulation speed for design load cases
with many 10-minute time series. The hardware requirements are
very low. The software, in the version of the Stuttgart Wind Energy
research group, has been verified in the Offshore Code Comparison
projects OC3 (Jonkmans and Musial, 2010; Vorpahl et al., 2013)
and OC4 (Popko et al., 2012) under the IEA Task 23 and 30 and
furthermore in the dissertation of Böker (2010).

VALIDATION USING A NACELLE ROTATION
ANALYSIS

The first step of the validation considers a controlled rotation of the
REpower nacelle. Ideally, such a maneuver is made during
calm weather conditions with low wind speed, small wave heights
and idling or braked rotor. The loading in the structure is driven by
the overhanging mass of the rotor-nacelle assembly. Additionally, it
is possible to check the order of magnitude of the measurements
by comparing them with hand calculations.

Such a maneuver was carried out on 31st January 2011 from
0:50 a.m. until 1:20 a.m. (30-min period). The mean wind speed
was 2.28 m/s from 188°, which is almost from the south. The
significant wave height was 1 m with a zero-up-crossing period of
6.5 s and a direction from 340°. The turbine was idling and the
pitch angle was 90°. The time series of the shorter simulations are
stretched to fit into the time frame of the measurements, which
allows a clearer comparison of the charts.

Results of the Rotor Blade Load Comparison

The idling rotor is problematic during the nacelle rotation. It
is not possible to achieve exactly the same rotor position in the
simulation that allows a comparison in the time domain. However,
a quasi-stable period with a rotor angle of roughly 7° was present
in the measurements, which is used in the simulation for a discrete
comparison. The bending moment at the blade root depends on the
rotor blade mass m, its center of gravity r, the tilt angle, the cone
angle and the azimuth angle φ. For a 90°-pitched rotor blade, the
following expressions can be used as an approximation for the
dowise and the flapwise bending moments at the root considering
a rigid rotor:

\[ M_{\text{Flap}}(\phi) = m_{\text{Blade}} \ast g \ast r \ast \cos(\text{tilt}) \ast \sin(\phi) \]  
\[ M_{\text{Edge}}(\phi) = m_{\text{Blade}} \ast g \ast r \ast \sin(\text{tilt} + \text{conus} \ast \cos(\phi)) \]

The azimuth angle is 0° if the blade is pointing vertically down. A
positive tilt and cone angle denote an increased blade-tower gap. For
example, this results in a 679-kNm edgewise bending moment and
475-kNm flapwise bending moment of blade 2 (ψ = 7°). Figure 6
shows the normalized results of the measurements, simulation and
estimation at every blade root for the flap- and edgewise bending
moment. The flapwise bending moment of blade 3 is used for the
normalization.

The results of the estimation are in acceptable agreement with
the simulation results. Some differences remain, which are a
consequence of the simplified approach neglecting any aerodynamic
forces in the estimation. The average wind speed is 2.28 m/s
and influences the loading clearly. The measurement results of
the edgewise bending moment of blades 2 and 3 are also well
comparable. The other measurement results show larger deviations,
which are not even physically realistic to some extent. This might be
the consequence of an incorrect calibration or invalid measurements
in this time period. For example, blade number 3 is pointing
almost to the 3 o’clock position, which should result in the largest
flapwise loading, as it is the case in the simulation and estimation
(pitch = 90°). Finally, this means that a closer assessment of the
blade root loads is not useful during this particular nacelle rotation.
Another nacelle rotation was conducted in March 2011, but the
accessible measurement data of this rotation are incomplete and
cannot be used.

Results of the Tower Bending Load Comparison

A nacelle rotation should result in sinusoidal trends of the tower
bending moments. The amplitude depends on the overhanging
masses of the blades as a function of the azimuth angle, the hub
and the nacelle. This amplitude is 4370 kNm at the yaw bearing
using the aforementioned rotor position of 7° azimuth angle. Tower
and blade deflections are neglected. The wind speed increases the
bending moment around line A2B1 (Fig. 4) at the tower bottom.

![Fig. 6 Comparison of the blade root bending moments using the rotor azimuth angle ψ = 6.7°](image-url)
due to drag forces. The rotor, hub and nacelle drag results in approximately 320 kNm of additional bending moment at the tower bottom. The tower drag needs to be integrated along the tower height and results in approximately 31 kNm. The summed estimate for the tower bottom bending moment is 4721 kNm, which is 8.5% higher than at the yaw bearing.

Figure 7 shows the tower top bending moment around the jacket diagonal A2B1. The measurement sensor name is R4_DT-A23o_1_2. The sinusoidal characteristic is present, and the amplitude of the tower top loading agrees well between the simulation, measurement and analytical estimation. The measurement shows a dent at the tower top chart. The vertical distance of the measurement device to the yaw bearing is 1.53 m and might result in disturbances of local stresses.

Amplitudes of the bending moments at the tower top and bottom are summarized in Table 1. The minimum and maximum amplitudes of a sensor differ slightly, which is a consequence of the fluctuating aerodynamic drag force. The small amount of bending due to this unidirectional drag adds to and reduces the gravity-based bending moment, which is a function of the nacelle position. The difference between the minimum and maximum amplitudes at the tower top is small due to the short effective lever of the drag forces. Simulation and analytical estimation agree well. The measurements show smaller amplitudes at the tower bottom than at the tower top, which is not plausible. Unfortunately, the raw signals of the strain gauges are not available to check whether the calibration or calculation of the bending moments is inexact. The accuracy of the tower bottom measurements at this point in time is in question and has to be taken into account in subsequent validations.

![Fig. 7 Tower top bending moment in [kNm] from measurements and simulation data during the nacelle rotation](image)

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>around A2B1</td>
<td>around A1B2</td>
</tr>
<tr>
<td>local-y</td>
<td>local-x</td>
</tr>
</tbody>
</table>

Table 1: Overview of amplitudes of the tower bending moments during nacelle rotation of measurements, simulation and estimation in [kNm]

![Fig. 8 Scatter plot of the wind direction of the met mast and the azimuth of the wind turbine, given as 10-min mean values from 2011](image)

The bending moment in the wind direction is higher than the orthogonal direction, as expected. The orientation of the coordinate systems of measurement and simulation is shown in Fig. 4.

A misalignment of the yaw azimuth sensor of the wind turbine was found. The coordinate system of the tower measurements is orientated on the jacket legs. Hence, the maximum tower bending moments are expected if the hub is pointing to one of the jacket legs. There is an offset of approximately 10° when correlating the bending moments with the azimuth direction. The same results can be found in the correlation between the wind direction of the met mast and the nacelle direction of the wind turbine. Figure 8 shows the correlation.

**Results of Local Jacket Stresses**

Discrete analysis of strains or stresses in the jacket is not practical, because the signals are only slope-calibrated and not offset-corrected. The reason is that the installation of measurement devices was made on land during different stages of the jacket assembly and unknown loading condition. Therefore, all presented results are normalized to the mean value of a time series. Amplitudes and ranges of the signals remain unaffected because these are relative information.

The stress ranges in the jacket legs can be estimated as a function of the tower bottom bending moment. It is assumed that all local bending moments in the legs are negligible due to the strong slope of the legs, and the hydrodynamic loading is neglected. Hence, the tower bending moment is transferred into a pair of axial forces in the jacket. The normal stress range depends on the distance to the tower center line $r$ and the cross section $S$ of the legs. Both are changing along the vertical coordinate of the jacket. The stress range in a leg is equal to the difference between maximum and minimum loading, which is present if the nacelle is pointing over or away from the leg. With the tower bending moment $M_{BT}$, the normal stress range equals:

$$\Delta\sigma_N = \frac{M_{BT\text{max}} - M_{BT\text{min}}}{2S \ast r}$$

(3)

The factor 1/2 is necessary, because the diagonal opposing leg is loaded equally. Assuming an equivalence of minimal and maximal tower bending moment, Eq. 3 is reduced to:

$$\Delta\sigma_N = \frac{M_{BT\text{max}}}{S \ast r}$$

(4)
Table 2 Estimated normal stress ranges at the four measurement levels of the jacket west leg

<table>
<thead>
<tr>
<th>Measurement location with respect to mean sea level</th>
<th>Normal stress range $\Delta \sigma_N$ [N/m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R4_D-W5/W4 (+18m)</td>
<td>$4.6 \times 10^6$</td>
</tr>
<tr>
<td>R4_DT-W2/W3 (−9.95m)</td>
<td>$3.3 \times 10^6$</td>
</tr>
<tr>
<td>R4_D-W2/W1 (−13.4m)</td>
<td>$3.2 \times 10^6$</td>
</tr>
<tr>
<td>R4_DT-W1 (−25m)</td>
<td>$2.3 \times 10^6$</td>
</tr>
</tbody>
</table>

There are four measurement levels along the jacket west leg, according to Fig. 5. With Eq. 4 and the estimated tower bottom bending moment of 4721 kNm given in Table 1, the stress ranges can be calculated, as presented in Table 2.

In total, 47 strain gauges are used for the validation. The presented charts focus on stresses in the west leg and in the northwest braces. One strain gauge per measurement location is displayed. The other devices result in qualitatively similar diagrams. Figure 9 shows the time series of the stresses at the four different measurement levels of the west leg during the nacelle rotation from top to bottom (Fig. 5). The algebraic signs of the measurements are not consistent and probably occurred during initiation of the measurements where cables might become inverted. However, this is not of importance for a qualitative comparison of the stress ranges. The sinusoidal trend is clearly visible in both the measurement and the simulation results. The orders of magnitude of the stress ranges compare well with the estimated results shown in Table 2. The amplitudes of the overlaid higher frequencies are increasing from the upper to the lower positions. Furthermore, they are more pronounced in the measurements than in the simulation, explicitly at the sensor R4_D-W5/W4 above water level. At the time 0:58, there is a peak which correlates with the motion of the nacelle. The nacelle rotation was realized counter-clockwise but it was initiated with a short clockwise startup.

The comparison of local stresses of a brace at R4_D-N1/W2 is shown in Fig. 10. It includes the two strain gauges _1 and _4, which are arranged in a 90° offset pattern. The location is close to the center of the lowest x-brace of the northwest side of the jacket. Wave direction was from the north-northwest, on average from 340° relative to north. The angle between the longitudinal axis of the brace and the wave propagation direction is 80° when looking from top-down. Hence, lateral motion of the brace is stimulated.

The sinusoidal trends agree very well between the simulation and the measurement. In comparison to the stress ranges at the jacket leg, the ranges of the higher frequencies at the brace obtain almost the same order of magnitude as the stress range due to the slow nacelle rotation. At time 0:58, the clear peak is very pronounced. The aforementioned startup of the nacelle rotation introduces a strong torsional excitation, which is visible in the bracings of the jacket.

VALIDATION USING DIRECT COMPARISONS IN THE TIME AND FREQUENCY DOMAIN

This section shows the results of a simulation in order to reproduce a measured time series. For this reason, calm environmental conditions are used to support homogenous dynamic behavior of the turbine. Moderate wind speed at partial load with low turbulence and low wave excitation are preferred. The aim of this section is to show that the simulation can reproduce the measured frequencies of the structure.

On 23rd March 2011 between 1:30 p.m. and 4:00 p.m., such smooth environmental conditions were found. The average wind
A speed is nearly constant and the standard deviation is very low, and consequently the turbulence intensity is also low. The time series from 3:00 p.m. to 3:10 p.m. is used. The average wind speed at the met mast is 6.5 m/s and the turbulence intensity is 1.6%. The inflow direction is 261° with respect to north. The significant wave height is 0.89 m with a zero-up-crossing period of 8.4 s and a wave direction of 340°. The average rotational speed is 8.5 rpm. This results in a 1p and 3p frequency of 0.142 Hz and 0.425 Hz, respectively.

It has to be noted that these parameters of the environment form the basis for the simulation input. These environmental parameters are measured in a few points in the space. Therefore, the spatial variations of the wind field and waves may differ significantly between the simulation and the actual conditions at the site. The results of such a re-simulation of a measured time series should be used with caution.

Results of the Rotor Blade Load Comparison

The edgewise bending moment is dominated by a periodic 1p sinusoidal oscillation with the amplitude equal to the rotor blade mass times the center of gravity times the acceleration of gravity. Simulation and measurement results agree very well. Figure 11 shows the amplitude spectra of the edgewise signal.

The flapwise bending moment has overlaid oscillations of the fore-aft motion of the tower and the rotor revolution. Figure 12 shows the time series plot of the flapwise bending moments for all three rotor blades. The figure presents a short extraction of four rotor revolutions for clarity reasons. The amplitudes of the measurement signals between the three rotor blades differ significantly. The 10-minute mean flapwise bending moment of blade 2 is 17% higher than that of blade 1, and blade 3 shows a 25%-lower mean flapwise bending moment. Such large differences are clearly not realistic. Expected are trends of the same order of magnitude as can be seen in the simulated flapwise signals. Only the measurement signal of blade 1 is roughly comparable with the simulation results. The blade measurements or the calibration might be defective, which makes a further validation of the event in the time domain or by using fatigue loads unreliable. The spectrum of the flapwise bending is only suitable for a qualitative comparison. The characteristic frequencies of the rotor agree well between the measurements and the simulations. Figure 13 shows exemplarily the amplitude spectrum of blade 1. The 1p rotor revolution frequencies and the multiples of them are well visible. The second peak represents the first global natural frequency of the turbine.

Results of the Tower Bending Load Comparison

This subsection presents results of the tower bottom measurements in the frequency domain. In this case, the validation uses the resulting bending moment R4_DT_A12u_Mres. Typically, this
bending moment is perpendicular to the mean wind direction. Time series comparisons are not meaningful in this case, because the measurements and simulation results do not represent identical wind and wave conditions, as previously explained. Furthermore, the results of the nacelle rotation comparison demonstrated that the calibration of the tower measurements might be defective. Consequently, the comparison of amplitudes and ranges is not meaningful. The frequencies of the signals are unaffected, and therefore it makes more sense to look at the frequency spectra. Figure 14 shows the amplitude spectra of the resulting tower bending moment. The qualitative results are representative for the other two measurement locations in the tower.

The measured frequency peaks are correctly captured by the simulation, whereas the simulation signal also shows further frequency animations. The frequencies above 2 Hz contain very little energy. The tower loading in normal operation is dominated by the aerodynamic effects. The excitations due to the rotor revolution (1p, 3p, 6p and 9p) contain more energy than the peak at the first global support structure frequency, which is approximately 0.3 Hz.

Results of the Jacket Stress Comparison

The validation of the jacket stresses is also based on frequency domain analyses. Further comparisons of the time series are not meaningful as was the case for the nacelle rotation comparison. Two examples of measurements are shown: R4_DT-W1_1 and R4_D-W1/N2_3. The first strain gauge is installed at the west leg underneath the lowest joint W1 (Fig. 5). The second sensor is installed at the brace welded to this joint, arranged in parallel to the northwest side of the jacket. The amplitude spectra are shown in Fig. 15 and Fig. 16, respectively.

The excitations are dominated by the rotor rotation. Frequencies 1p, 3p and the multiples are clearly visible. Furthermore, peaks at 0.12 Hz and 0.3 Hz are present, which correlates with the zero-up-crossing frequency of the sea state and the first global bending frequency, respectively. In the frequencies of 2.1 Hz to 2.3 Hz, combined modes of the jacket substructure and the rotor blades have been identified in the natural frequency analysis of the simulation model. Additionally, the 15p rotor frequency is also located in this region. In the logarithmic scale, random noise without any clear peak can be found at frequencies above 2.5 Hz in this 10-minute time series. Amplification of such higher frequencies might occur under harsher conditions.

VALIDATION USING STATISTICAL DATA OF 2011

Measurements are available since the beginning of 2011, and detailed data from more than one year of load measurements are
The charts are normalized to the absolute largest value of either measurements or simulation results. The algebraic signs are swapped where necessary for comparison purposes. It should be noted that this might result in swapped minima and maxima in the plots (Fig. 18). Two types of plots are presented for each sensor. The first one is a scatter plot of the standard deviation over the wind speed. The second is a combined scatter plot with maximum, minimum and mean values over the wind speed.

Results of the Rotor Blade Load Comparison

The measurements of the rotor blade flapwise bending loads are questionable when considering the findings of the previous sections. But the mean loading of rotor blade number 1 is still in an acceptable range compared to the simulated and the estimated results of the nacelle rotation analysis. Therefore, the statistical results are shown only for this rotor blade. Figures 17 and 18 show the flapwise bending moment. The charts correlate with a typical thrust curve of pitch-controlled wind turbines with a distinct thrust maximum around the rated wind speed. The simulation and the measurement results correlate surprisingly well. The
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Fig. 19 Normalized scatter plot of the edgewise bending moment of blade 1 with mean, maximum and minimum

standard deviation differs strongly at wind speeds from 13 to 16 m/s. Potentially, this is associated with differences in the pitch control behavior or the approximated amount of wind shear or turbulence intensity, which influence the amount of flapwise loading significantly in this region. The mean bending loads predicted by the simulation are slightly higher than in the measurement, which was also the case in the validation results above.

There is an excellent agreement between the edgewise bending moments of the simulations and measurements. Figure 19 shows the scatter plot of mean, maximum and minimum values over the wind speed. Standard deviation is not explicitly shown, because it is dominated by cyclic loading due to gravity, and the normalized standard deviation equals almost 1 in the partial load range. Above rated wind speed, it decreases continuously. This is a consequence of the pitch action. While pitching, the edgewise signal includes portions of the out-of-plane loads, which have fluctuating load character with lower standard deviation.

Results of the Tower Bending Load Comparison

Figures 20 and 21 show the scatter plots of the resulting bending moment at the tower bottom. Mean loading is dominated by the rotor thrust with a clear thrust maximum analogous to the flapwise bending moment. Standard deviation is much lower than that of the rotor blades. The simulation predicts slightly higher loading.

Fig. 21 Normalized scatter plot of the resulting tower bottom bending moment with mean, maximum and minimum

Results of the Jacket Stress Comparison

Two measurement locations are presented in this subsection. The first is the strain gauge R4_DT-W1_1, which is installed below the lowest joint of the west leg of the jacket. The second is R4_D_W2/S1_1, which is installed at the brace welded to this joint at the southwest side close to the joint W2. Wave and wind are approaching from the southwest, and the brace is loaded laterally. Similar to the results of the nacelle rotation, all the scatter plots of the jacket measurements are corrected by the mean value of the time series. The missing offset calibration of the strain gauge measurements makes this step essential for the comparison.

Fig. 22 shows the plot of the standard deviation, and Fig. 23 shows the plots of the mean, maximum and minimum values of the sensor R4_DT-W1_1. The simulation and measurement results agree very well. The stress range is increasing with the wind speed. There is no strong dropout above rated wind speed, as is the case for the tower bottom measurements. The decreasing rotor

Fig. 20 Normalized scatter plot of the standard deviation of the resulting tower bottom bending moment

Fig. 22 Normalized scatter plot of the standard deviation of the sensor R4_DT-W1_1
thrust due to pitch action is compensated for by the increasing wave loading, which leads to increased axial stresses in the legs. The spreading of the simulation results per wind speed class is smaller. This is a consequence of the averaging method applied to the environmental measurements. The comparisons of other sensor locations at the jacket legs lead to equal results.

Figures 24 and 25 show the basic statistics of the sensor R4_D-W2/S1_1 at the bracing. The simulations correlate very well with the measurements, and again the stress range is increasing with the mean wind speed. A very strong dependency between the standard deviation and wind speed is present, and high wind speeds correlate with significant wave heights. Normalized standard deviation of 1 denotes pure alternating loading. Wave loading is an alternating load type with high standard deviations. In contrast, aerodynamic loading is a pulsing load type with a lower standard deviation. This leads to the fact that the stresses in the braces will be affected more by hydrodynamic loads than aerodynamic loads.

CONCLUSIONS

This paper highlights the necessity of the validation of state-of-the-art simulation tools with measurements. Measurements from the wind farm Alpha Ventus and, more precisely, the load and the environmental measurements of the REpower 5M with jacket substructure have been analyzed to validate a simulation method. Load sensors of the rotor blades, the tower and the substructure are compared. The integrated simulations are carried out with a coupled software solution for the simulation of offshore wind turbines under combined aerodynamic and hydrodynamic loading. An integrated simulation model is implemented, and the sensor positions are carefully defined to match the measurement locations. The validation is based on a three-step approach with increasing complexity: the nacelle rotation analyses, the direct comparisons of a 10-minute data set in time and frequency domain and the statistical analyses using one year of measurement data.

A nacelle rotation analysis is recommended to evaluate the quality of the measurements and of the simulations. It has been shown that the measurements for the blade flapwise bending moments, the tower bottom bending moments and the azimuth angles are questionable to some extent, and the calibration of this particular time series should be reviewed. A direct re-simulation of a 10-minute time series during normal operation is challenging due to the limited level of detail of the environmental data. This is still the case if events with homogenous environmental conditions are considered. The assessment of such a comparison should be made qualitatively and the findings cannot be generalized. The comparison of frequency spectra is recommended in such cases.

The comparisons of the 10-minute statistics are based on a one-year measurement period. The results are generally very good, in particular the results of the jacket sensors. Considering the presented statistical results, it can be said that the simulation results are within the spreading of the measurement results, which is potentially caused by the averaging method for the simulation input. Therefore, a single simulation can be both conservative and non-conservative, depending on the selected time series and the approximated environmental conditions. Hence, it is recommended to vary the environmental conditions significantly for the load simulations.

Overall, this first load validation is successful, and it can be stated that the coupled simulation is well suited for the analysis of offshore wind turbines with jacket support structures. However, the following annotations and recommendations should be pointed out:

- Integrated load simulations are suited for the analysis of offshore wind turbines with jackets.
• The relationship between brace and rotor blade dynamics has been identified in the frequency analysis of the brace loads.
• A nacelle rotation maneuver offers a good opportunity to check the order of magnitude of the loading. Furthermore, it allows crosschecks with load estimations made by hand.
• Two or three nacelle revolutions should be made continuously to minimize transient effects. Overnight and daytime maneuvers should be planned.
• The calibration of the rotor blade bending loads should be based on rotor revolution maneuvers with 0° and 90° pitch angle instead of a nacelle revolution.
• Estimation of simulation input data using point measurement is very challenging. The results from the simulation are limited in comparability to the measurements, since the actual conditions at the site may differ from the simulated wind and wave field. More accurate acquisition of the three-dimensional wind field and the sea state will be of major importance for future measurement campaigns and also for the implementation in the simulation.
• Long-term statistics include a multitude of environmental and operational states and are therefore suited for model validations. The upcoming research tasks will be associated with a comparison of the results with more simplified simulation methods. This will answer the questions of the necessity of the integrated simulation methods and the applicability of the more simplified methods for offshore wind turbines using jacket support structure concepts.

ACKNOWLEDGEMENTS

The research is part of the RAVE projects OWEA—“Verification of offshore wind turbines” and OWEA LOADS. It is funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). The authors thank REpower Systems SE for the support and the possibility to validate the simulation model using measurement data.

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