Investigation of Local Vibration Phenomena of a Jacket Sub-Structure Caused by Coupling with Other Components of an Offshore Wind Turbine

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This paper presents results from an in-depth investigation of local vibration phenomena and their impact on the fatigue loads of a jacket sub-structure. The analysis is performed in a coupled, aero-hydro-servo-elastic tool ADCoS-Offshore that is based on the finite element method (FEM). Possible regions of resonance are identified from modal analysis studies and a Campbell diagram. Numerous high-frequency vibrations in the range of 3.1 Hz–5.0 Hz involving local eigenmodes coupled with higher order rotor modes are found. Time-domain simulations are run for deterministic and stochastic load case categories, where local jacket dynamics are examined. Impact of marine growth on fatigue loads of the lowest braces is presented. Finally, recommendation on relative comparison of local vibration influence on the fatigue loads is given.

INTRODUCTION

A significant share of the total cost of an Offshore Wind Turbine (OWT) is associated with its support structure. For deeper water locations, a jacket support structure is considered to be a more cost-effective solution than a monopile. This type of sub-structure has already been utilized in the offshore oil and gas industry. However, significant differences in the loading conditions and dynamics associated with a wind turbine on top (Vorpahl et al., 2013b) create new engineering challenges. During initial load analysis studies of an OWT with a jacket sub-structure, out-of-plane vibrations of its braces have been reported (e.g., by Seidel and Foss (2006)). These vibrations may affect the fatigue life and therefore the design requirements of the sub-structure. So far, there are very few research papers available in the public domain that address this issue to a greater extent. Kjetså and Saaghus (2010) analyzed local vibration phenomena in Jacket Analysis Code using a sequential approach, whereas Böker (2010) studied local jacket vibrations in Flex5 and Poseidon implementing various approaches. In the sequential approach, simulations of the wind turbine and the support structure are separated. A support structure is replaced at the interface node by reduced stiffness, mass and damping matrices. The Guyan reduction (Guyan, 1965) is utilized to reduce the sizes of mass and stiffness matrices. A drawback of this method is that only stiffness parameters are fully preserved, whereas inertial forces are not (mass matrix is reduced). This results in only an approximated eigenvalue solution, the quality of which decreases for the higher eigenmode numbers. The sequential approach can significantly overestimate or underestimate out-of-plane vibrations, depending on the excitation frequency, as observed by Böker (2010) and Kjetså and Saaghus (2010). Therefore, the sequential approach is not recommended for the investigation of local vibration phenomena.

The existence of local vibration phenomena was also observed by Popko et al. (2012) in the scope of the Offshore Code Collaboration Continuation (OC4) project—Phase I, focused on the coupled simulation of an OWT with a jacket support structure. Most of the state-of-the-art simulation codes for OWT were represented in this project. A number of these multibody- and FEM-based tools detected local vibration of the lowest braces coupled with higher eigenmodes of the rotor. So far, there was neither a study of the relative contribution of local vibration to the fatigue loads of jacket braces performed in a coupled tool nor any suggested methodology for such a comparison presented in the public domain. This paper presents results of the in-depth investigation of the local vibration phenomena and their impact on fatigue loads in the jacket sub-structure. It also suggests a low-pass filter method for the assessment of the relative impact of local vibration phenomena on fatigue loads.

The investigation of local vibration phenomena is performed in the ADCoS-Offshore software, which is a nonlinear aero-servo-hydro-elastic tool for the time-domain simulation of OWT. More detailed information regarding the tool can be found in Kleinhasl et al. (2004) and Vorpahl et al. (2007).

DEFINITION OF OFFSHORE WIND TURBINE MODEL

An OWT consisting of the NREL 5-MW Offshore Baseline Turbine defined by Jonkman et al. (2009) and supported by the UpWind reference jacket model developed by Vemula et al. (2010) and later adapted for the OC4 project (Vorpahl et al., 2013a) is utilized in this study. The analyzed support structure consists of a jacket sub-structure, a transition piece and a tower. Four legs of the jacket are supported by piles modeled as clamped at the seabed. The legs are slightly inclined from the vertical axis and stiffened by four levels of braces. Additionally, mudbraces are placed just above the mudline to minimize the bending moment at the foundation piles. The jacket and the tower are connected through a rigidly modeled transition piece. The height of the entire support structure is 88.15 m, whereas the hub height is located at 90.55 m from the seabed. The OWT is analyzed for a site of 50-m water depth.

The numerical implementation of the OWT has to be complex enough to mimic behavior of the real system and to capture local...
vibration phenomena. On the other hand, its complexity should be limited in order to keep the simulation time at a reasonable level. For simplification reasons, it is decided not to include appurtenances on the jacket structure, such as boat landings, J-tubes, annodes, cables, ladders, etc. Also, joint cans are not taken into account in the setup of the model. It was shown in Cordle et al. (2011) that the modeling of joint cans does not lead to significant changes in the simulated loads. Furthermore, the local joint flexibility is neglected in this study for the reason of setup simplification. However, it has to be noted that a slight reduction of overall jacket stiffness (1%–2%) in the case of local joint flexibility modeling might be present (Klose et al., 2007). A reduction of bending moments at joints due to the local joint flexibility is expected as joint connections are softer. This may have an impact on local vibration frequency and its energy content. However, for this preliminary study, a more complex numerical model of the jacket was not available with the complexity that is suitable for loads simulation. In the analyzed model, the connecting nodes of elements are defined at the intersection points of the members’ centerlines. Structural damping of 1% is used for the sub-structure model. The influence of this factor was already studied by Kjetså and Saaghus (2010) showing the reduction of damage-equivalent loads (DEL) of the lowest braces for increasing value of damping. The additional masses, such as hydrodynamic added mass and water in flooded legs and marine growth, have a strong influence on the dynamic response of the structure (Moll et al., 2010) and therefore are included in the model implementation.

DEFINITION OF LOAD CASES

For the investigation of local vibration phenomena in ADCoS-Offshore, a stepwise approach similar to those proposed by Böker (2010), Vorpalh et al. (2013c) and Popko et al. (2012) is chosen. Four groups of load cases (LC) of increasing complexity are set up and listed in Table 1.

In LC I, a modal analysis is performed where there is no external loading applied on the OWT. Diverse eigenmodes with contribution of local vibrations in the jacket braces are identified based on their visualization. In LC II group, only deterministic wind load is utilized to examine the influence of the harmonic loading on local vibrations of the sub-structure resulting from the spinning rotor and the tower passage of the blades. Here, wind speeds between cut-in \( V_{\text{cut-in}} = 4 \text{ m/s} \) and the rated wind speed \( V_r = 12 \text{ m/s} \) are analyzed. Within this region of partial loading, the rotor speed varies by what the frequency of harmonic excitation is also changing. In LC III group, a stochastic wind field is used for examination of the coupling effects between the rotor-nacelle assembly (RNA) and local vibration modes. Here, apart from the harmonic excitation from the spinning rotor, the OWT is also excited by a broad range of frequencies coming from the turbulent wind. Finally, in LC IV group, the OWT model is simulated under the stochastic wind and wave loading that act simultaneously. This group of load cases is based on DLC 1.2 and DLC 6.4 from the IEC 61400-3 standard (IEC, 2009). These two cases represent the biggest part of the turbine lifetime and therefore are the main fatigue drivers. In all stochastic simulations from LC IV group, an OWT availability of 100% is considered, which is a conservative approach for the fatigue loading of the jacket sub-structure, as found by Popko (2010) and Fischer et al. (2010b).

Long-term wind and wave statistical data, such as turbulence intensity, significant wave height, peak-spectral wave period, probability of occurrence, wind and wave directionality, etc., are taken from the UpWind design basis (Fischer et al., 2010a) where meteorological data from a Dutch North Sea site are collected. Scattering of wind and wave directionality data in LC IV group results in a huge number of individual load cases and therefore considerable simulation effort. To decrease this effort, a reduction method proposed by Kühn (2003) is utilized. A detailed description of the reduction procedure for the UpWind site data that are used in this research can be found in Popko (2010). The reduced LC IV group consists of 468 individual load cases (396 for DLC 1.2 and 72 for DLC 6.4), which is still a considerable number.

For each load case, the outputs are recorded at a number of nodal points (called sensors) located on the RNA and the jacket support structure, as shown in Fig. 1. Sensor names result from leg

<table>
<thead>
<tr>
<th>Load case group</th>
<th>Comments</th>
<th>Wind Conditions</th>
<th>Wave Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC I</td>
<td>Modal analysis</td>
<td>No wind</td>
<td>No water</td>
</tr>
<tr>
<td>LC II</td>
<td>Power production under deterministic wind</td>
<td>Steady wind ( V_{\text{hub}} = 4 \text{ m/s}, 6 \text{ m/s}, ..., 12 \text{ m/s} ) ( \alpha = 0.14 )</td>
<td>No water</td>
</tr>
<tr>
<td></td>
<td>5 individual load cases</td>
<td></td>
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<tr>
<td>LC III</td>
<td>Power production under stochastic wind</td>
<td>NTM (Kaimal) ( V_{\text{hub}} = 4 \text{ m/s}, 6 \text{ m/s}, ..., 12 \text{ m/s} ) ( \alpha = 0.14 )</td>
<td>No water</td>
</tr>
<tr>
<td></td>
<td>5 individual load cases</td>
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<tr>
<td>LC IV</td>
<td>Power production under stochastic wind and wave loading, based on DLC 1.2 from IEC (2009)</td>
<td>NTM (Kaimal) ( V_{\text{hub}} = 4 \text{ m/s}, 6 \text{ m/s}, ..., 24 \text{ m/s} ) ( \theta_{\text{wind}} = 0^\circ, 30^\circ, ..., 330^\circ ) ( \varphi = -8^\circ, 0^\circ, 8^\circ ) ( \alpha = 0.14 )</td>
<td>Irregular Airy with PM, ( H_s, T_p ) ( \theta_{\text{wave}} = 0^\circ, 30^\circ, ..., 330^\circ )</td>
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<tr>
<td></td>
<td>396 individual load cases</td>
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<tr>
<td></td>
<td>Idling under stochastic wind and wave loading, based on DLC 6.4 from IEC (2009)</td>
<td>NTM (Kaimal) ( V_{\text{hub}} = 2 \text{ m/s}, 30 \text{ m/s} ) ( \theta_{\text{wind}} = 0^\circ, 30^\circ, ..., 330^\circ ) ( \varphi = -8^\circ, 0^\circ, 8^\circ ) ( \alpha = 0.14 )</td>
<td>Irregular Airy with PM, ( H_s, T_p ) ( \theta_{\text{wave}} = 0^\circ, 30^\circ, ..., 330^\circ )</td>
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<tr>
<td></td>
<td>72 individual load cases</td>
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</table>

NTM – Normal Turbulence Model in IEC (2005); PM – Pierson-Moskowitz wave spectrum; \( \alpha \) – wind shear exponent [-]; \( \varphi \) – yaw error [°]; \( \theta_{\text{wave}} \) – wave direction [°]; \( H_s \) – significant wave height [m]; \( T_p \) – peak-spectral wave period [s]; \( V_{\text{hub}} \) – average wind speed at the hub height [m/s]; \( \theta_{\text{wind}} \) – wind direction [°]

Table 1 Overview of load cases
numbering, side numbering, height level and joint type. The position of sensors is carefully chosen to provide maximum information regarding the OWT behavior with the minimal effort necessary for data acquisition and post-processing. Those sensors located on the RNA are meant to capture the aeroelastic response of the RNA in order to identify any possible coupled vibrations. The support structure sensors are used for capturing global and local dynamics of the jacket. Local vibrations of the structure are studied at several places on the lowest braces, whereas global bending moments and forces are calculated at the mudline.

The simulation time for the deterministic load cases is set to 60 s and, for the stochastic load cases, is set to 600 s for statistically correct turbulence representation. Additional pre-simulation time that is not included in the results is added to remove initial transients. The simulation time step for all load cases is set to 0.01 s. Simulation results are presented in terms of power spectral densities (PSD) and damage-equivalent loads (DEL). DEL are calculated for 20 years of turbine lifetime.

SELECTED RESULTS

This section presents the selected results of the coupled simulations of OWT that are focused on examination of local vibration phenomena. The most interesting load cases and output sensors, according to the authors, are presented herein.

Eigenanalysis and Campbell Diagram

A large number of eigenmodes containing contributions of local vibration of braces are detected in ADCoS-Offshore in the frequency range between 3.19 Hz–6.70 Hz. These modes involve motion of the rotor blades, tower and jacket with local out-of-plane displacement of braces.

The vast majority of these global eigenmodes are governed by higher frequency flapwise and edgewise modes of the blades, as they have the largest energy content. These rotor vibrations are suspected to occur together with local vibration of braces located in the lower part of the jacket, where braces are the longest and therefore have the lowest natural frequency.

Some selected mode shapes with local vibration of braces (pointed with arrows) and higher rotor modes are shown in Fig. 2.

Aspects such as hydrodynamic added mass, water in flooded legs, and marine growth are accounted for in the modal analysis. Gravity and damping terms are not taken into account, as their impact on eigenfrequencies is proved to be marginal, as shown by Popko et al. (2012).

Possible resonant vibrations of the braces resulting from interaction with the spinning rotor are identified in the Campbell diagram, where system frequencies are plotted versus the rotational speed of the rotor. The results are presented in Fig. 3. The OWT eigenfrequencies are depicted as horizontal lines. This is a simplification, as in reality these frequencies would vary slightly depending on the rotational speed of the rotor (the effect of centrifugal stiffening). However, only static frequencies are used herein. The inclined lines are multiples of 1P (rotor full revolution) and 3P (the tower passage of the blades) frequencies. The resonance may occur when the inclined lines intersect with the horizontal eigenfrequency lines. Such resonance regions are marked with circles for two exemplary wind speeds of 8 m/s and 12 m/s, respectively. Two vertical lines denote these wind speeds. At the wind speed of 8 m/s, there are four regions where local vibrations may be amplified: at around 3.2, 3.7, 4.6 and 4.9 Hz. At the rated wind speed of 12 m/s, there are two regions identified at around 3.7 and 4.9 Hz, respectively.
Investigation of Local Vibration Phenomena of a Jacket Sub-Structure Caused by Coupling …

Deterministic Wind

The findings from the modal analysis and the Campbell diagram are further verified by the examination of dynamic response of the OWT under the deterministic wind of 8 m/s, at which four resonance regions with presence of local vibrations were identified. In the case of deterministic wind, the OWT is only influenced by harmonic excitation that results from the spinning rotor.

Figure 4 shows the PSD of out-of-plane displacement at the X4E sensor located in the middle of the lowest brace, as presented in Fig. 1. Spectral energy peaks at the subsequent rotor harmonics are clearly pronounced. There is an increase of the energy content in the vicinity of higher rotor harmonics in the frequency region of 3.2 Hz–5.0 Hz where local vibrations are expected (values above 5.0 Hz are not shown, as the total mean energy content diminishes).

On the other hand, there is no distinct increase in spectral energy for the same frequency band as above, for the out-of-plane displacement at the K4SE sensor (see Fig. 1) located at the leg, as shown in Fig. 5. This sensor is a good indicator of the global behavior of the jacket in the vicinity of the braces that are studied here. Another indicator of the global behavior of the OWT is the horizontal shear force $F_y$ at the mudline. The respective PSD are presented in Fig. 6. Here, in contrast to Fig. 4, the spectral content decreases in the frequency region where local vibrations are expected. The differences in the spectral energy trends on these three charts (1) prove the local nature of the high-frequency brace vibrations found in the modal analysis and (2) confirm couplings with higher harmonics of the rotor.

Stochastic Wind

An OWT influenced by stochastic wind not only experiences harmonic loading, but it is also excited by a broad range of frequencies resulting from turbulence. Furthermore, because of the changing wind speed, the rotor speed is fluctuating. Due to the varying rotor speed, each harmonic is characterized by a band of frequencies, instead of only one clearly distinguishable frequency. For higher harmonics, these frequency bands get wider. In this section, results for stochastic wind of 12 m/s are shown. For this case, more severe resonance is expected. At $V_r$, the rotor speed changes much less compared to the partial loading region, as the controller tries to keep it constant through blade pitching and generator-torque control. On the other hand, in the partial loading region, the rotor speed increases linearly with wind speed to maintain constant tip-speed ratio and optimal wind-power conversion efficiency, as described in Jonkman et al. (2009). Thus, any variation of the wind speed due to its stochastic nature below $V_r$ would cause considerable change in the rotor speed (see Fig. 7), therefore resulting in more smeared and less intense excitation regions. The standard deviation of the rotor speed at stochastic wind of 8 m/s is 0.68 rpm, whereas at 12 m/s it is 0.14 rpm.

Figure 8 shows the PSD of out-of-plane displacement at the X4E sensor located in the middle of the lowest brace, for the load case where an OWT is excited with the stochastic wind of 12 m/s. The peaks are not that clearly pronounced like in the deterministic case shown before. Here, the excitation frequency is slightly smeared due to fluctuations of the rotor speed and turbulent wind loading. Nevertheless, there is an observed increase of energy.
in the frequency region between 3.2 Hz–5.0 Hz, where local out-of-plane vibrations are present. Such pronounced increase in energy is not observed for the load case with the stochastic wind of 8 m/s, where harmonic frequencies are much more smeared.

Other good indicators of the out-of-plane vibration in the braces are bending moments. Figure 9 compares PSD of the in-plane and out-of-plane bending moments at a member of brace X4N (see Fig. 1). The energy of out-of-plane $M_y$ is 3 to 4 orders higher than the energy of in-plane $M_x$ in the frequency region between 3.2 Hz and 5 Hz. For lower frequencies between 0 Hz and 2 Hz, the opposite behavior is observed – in-plane $M_y$ tends to have higher energy.

In Fig. 10, the PSD of bending moments $M_x$ and $M_y$ of the rotor shaft are presented for the same load case with stochastic wind speed of 12 m/s. Peaks that are visible in the PSD of $M_y$ and $M_x$ bending moments indicate edgewise and flapwise rotor modes, respectively. Edgewise vibrations have more energy than flapwise and are better pronounced in the frequency regions where the out-of-plane local vibrations of the braces are induced at around 3.6 Hz and 4.8 Hz. This suggests a direct relation between higher rotor harmonics and vibrations induced in the lower part of the jacket.

To sum up, there is a higher chance of occurrence of local out-of-plane vibrations at $V_r$ and above, where rotor speed is relatively constant. In the partial loading region, harmonic frequencies are much more smeared due to higher variation of the rotor speed.

### Influence of Hydrodynamics on Local Vibration Phenomena

The frequencies where vibrations of the lowest jacket braces are coupled to other structural modes are higher than the usual wave excitation, which is below 0.25 Hz. Therefore, the additional consideration of wave kinematics does not affect the local vibration phenomena, which are observed in the frequency range above 3.0 Hz. The exemplary results of PSD of the out-of-plane displacement at X4E are shown in Fig. 11. The spectral energy at frequencies above 0.5 Hz is very comparable for load cases with only stochastic wind load (LC group III) and for those with stochastic wind and irregular wave (LC group IV). The only visible drop in the spectral content for LC III (only stochastic wind) is observed at around 0.25 Hz due to lack of hydrodynamic excitation. It has to be emphasized that the water-added mass is included in both LC groups and only hydrodynamic load is enabled or disabled. The influence of the water-added mass is analyzed in the next section.

### Fatigue Analysis

This section presents results of the fatigue analysis of the out-of-plane bending moments of the braces located in the lowest bay of the jacket (see Fig. 1). The results are presented in terms of DEL, which are calculated as the peak-to-peak amplitudes of sinusoidal load effects with $2E+8$ cycles for the S-N curve slope of 4. These loads produce the same equivalent fatigue damage as the original loads. DEL are calculated for LC IV group, where DLC 1.2 and DLC 6.4 from IEC (2005) are simulated.

Figure 12 compares DEL of the out-of-plane bending moments at two members in the jacket, which are located at the very bottom of Leg 2 and at the brace X4N (see Fig 1). These two locations are indicators of the global and local dynamics of the structure, respectively. Both DEL are normalized for easier comparison of the trends. For the qualitative comparison of DEL, it is decided not to accumulate them over the turbine lifetime with the Weibull
distribution, which describes probability of occurrence of wind speeds in a year.

There is a relatively high change of the brace DEL between wind speed bins 2 m/s and 4 m/s, respectively. Such dramatic change is not observed for DEL at the very bottom of Leg 2. At \( V_{\text{cut-in}} \) of 4 m/s, the rotor starts to spin and the wind turbine starts to produce power. Harmonic excitations resulting from the spinning rotor induce vibrations in the lowest brace, which are pronounced as a high increase of DEL. On the other hand, the relatively small change in DEL of bending moment at Leg 2 is mostly driven by an increase of the rotor thrust force. In the partial loading region described by wind speed bins in the range from 4 m/s to 8 m/s, there is a relatively small increase in DEL at the brace and at Leg 2, as well.

Constant increases of DEL for both jacket members are observed for wind speeds from and above 10 m/s, where the rotor reaches around 99% of its rated speed (Jonkman et al., 2009). This is most likely caused by increasing variance of the stochastic wind field for higher wind speeds and, therefore, larger fluctuations of the excitation signal. This results in larger amplitudes of the structural response and, finally, in higher DEL. The only exception from this increasing trend is at the wind speed bin of 30 m/s, where the rotor idles. This sudden drop in DEL is caused by much lower aerodynamic loads due to feathering of the blades and lack of harmonic excitation from the idling rotor.

Linear fits (dashed and dotted lines) are applied to DEL located in the wind speed bins range of 10 m/s to 24 m/s. In this range, both the rotor speed and the harmonic excitations are relatively constant. Two lines with different inclination angles describe the relative increase of DEL when going from one wind speed bin to another. For the out-of-plane bending moment DEL at the brace, the slope is steeper than for DEL at the very bottom of Leg 2. This indicates a relatively higher increase of fatigue load at braces when changing from one wind speed to another. This proves a direct influence of local vibration phenomena on fatigue loads of the lowest braces in the jacket.

In Fig. 13, the effect of the wind loading directionality on DEL of out-of-plane bending moment of brace X4N is studied. The results for DLC 1.2 and DLC 6.4 are shown in Fig. 14. Loading data are accumulated over the turbine lifetime with occurrence, according to the Weibull distribution from Fischer et al. (2010a). The wind direction of 210° is the prevailing one at the site where measurements were collected. This is reflected in DEL that are the highest at 210° along most of the wind speed bins. The maximum DEL value of the out-of-plane bending moment is identified for the wind speed bin of 22 m/s.

In order to investigate the influence of marine growth on the local vibration phenomena, a marine growth sensitivity analysis is performed. The presence of marine growth increases the diameter of an element, resulting in greater hydrodynamic loads. Furthermore, it also increases mass of the jacket sub-structure, by which the dynamics of an entire OWT are affected. In order to assess the effect of marine growth on the vibration of the braces, DEL from three different scenarios of marine growth are calculated. In the first scenario, a jacket model with marine growth of 100-mm thickness is used with the corresponding wave loads. In the second scenario, an OWT with the jacket sub-structure without marine growth is simulated with the corresponding wave loads. Finally, in the third scenario, an OWT with the jacket sub-structure is simulated without marine growth, but loaded with hydrodynamic loads that come from the first scenario. The simulation of this unrealistic combined scenario is performed in order to study the influence of the increased hydrodynamic loads on the jacket model without marine growth.
In Fig. 15, results of the marine growth sensitivity analysis for the brace X4N are presented as normalized DEL. There is a very small difference in terms of DEL between the combined scenario and the no-marine-growth scenario, proving that the increased hydrodynamic load would have a small impact on the lowest braces DEL. A much bigger impact on DEL would have change in the jacket mass that directly affects its dynamics. The DEL results from the marine growth scenario are around 35% greater than those from the no-marine and combined scenarios. These results become more interesting when compared with an influence of marine growth on OWT eigenfrequencies shown in Fig. 16. Eigenmodes No. 24 and No. 35 are fully dominated by local vibrations of the lowest braces (no deformation of blades or tower is visible). Eigenfrequencies of these modes are increased by around 26% for the jacket model without marine growth. Eigenmodes Nos. 25–27 and 29–34 have a significant contribution of local out-of-plane displacements that occur jointly with rotor vibrations and global swaying of an entire OWT. For these modes, the frequency increase is from around 6% up to 22%. These shifts in eigenfrequencies result in less excitation of the out-of-plane vibration, since the local vibration eigenmodes are now excited by even higher-order harmonics, which carry even less energy.

Influence of marine growth on OWT eigenfrequencies

CONCLUSION

It is confirmed that coupled local vibration phenomena of the jacket sub-structure exist. They are mainly present in the lower bays of the sub-structure, where the braces are longest. The results of the modal analysis show that local vibrations are the part of high-frequency (3.1–6.7 Hz) eigenmodes that also involve high-order rotor modes and global tower modes. This complies with earlier findings from Seidel and Foss (2006), Böker (2010) and Kjetså and Saaghus (2010).

There is a clear relation between rotor harmonic excitations and local vibration phenomena. This is verified by the examination of dynamic response of the OWT under the deterministic wind, at which various resonance regions with presence of local vibrations are identified. Higher-rotor harmonics are found in the vicinity of frequencies where local vibrations are present. In this region, there is an increase of energy in PSD of the out-of-plane displacements and bending moments of braces.

When an OWT is excited by the stochastic wind, there is a higher chance of occurrence of local out-of-plane vibrations at $V_r$ and above, where rotor speed is relatively constant. It is shown that, in the partial loading region, harmonic frequencies are much more smeared due to higher variation of the rotor speed.

These findings are further confirmed by analysis of DEL for individual wind speed bins. In the partial loading region, there is a marginal increase in DEL for subsequent wind speed bins. It is shown that, from around $V_r$, DEL start to increase with a constant slope. The slope for DEL of out-of-plane bending moment of braces is steeper than the slope for DEL of bending moment at the foundation of the jacket. This indicates a relatively higher increase in fatigue at braces when changing from one wind speed to another.

Directionality of loading has an impact on DEL of the lowest braces. DEL are the highest for those loading directions that are perpendicular to the braces.

Increase of the structural mass due to marine growth affects dynamics of the jacket, which directly translates to significantly higher DEL of the lowest braces. On the other hand, the influence of the increased hydrodynamic load on fatigue loads of the brace is marginal. Consideration of wave kinematics does not affect the local vibration phenomena, which is observed in the frequency range above 3.0 Hz. The frequencies where the lowest jacket braces are coupled to other structural modes are higher than the usual wave excitation, which is below 0.25 Hz.

Recommendations for Further Research

Further study on the relative importance of the out-of-plane vibrations of the braces on fatigue loads may be performed by filtering out higher frequencies where local vibrations are present. A low-pass filter can be applied to remove frequency peaks where local vibrations are expected. Then, a comparison of DEL generated from the original and filtered data may provide the relative impact of these phenomena on fatigue loads. However, it must be taken into account that the application of a simple low-pass filter would also remove structural frequencies where local vibrations are not present. Moreover, all filters introduce some phase shift to the processed signal. It is not certain how it will affect the physical meaning of the filtered time series and the accuracy of the fatigue loads calculation. Therefore, the in-depth study of different methods of filtration and their impact on the fatigue loads is recommended.
It is also suggested to study local vibration phenomena with a more detailed jacket model that includes local joint flexibility or more structure details, as described in Vorpahl and Reuter (2011). This would give a more realistic view on the local vibration phenomena and their impact on fatigue loads in the braces.

ACKNOWLEDGEMENTS

Professor Michael Muskulus from the Norwegian University of Science and Technology is acknowledged for sharing the Kjetså and Saaghus (2010) MSc thesis document.

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