Continuous fatigue assessment of offshore wind turbines using a stress prediction technique

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ABSTRACT

Fatigue assessment includes estimation of the expected damage accumulation and the remaining life-time of the structure. This work is based on output-only vibration measurements at a limited number of locations provided by a sensor network installed on the structure. For the fatigue damage assessment, the stress time responses are obtained by using the vibration sensor data and a modal expansion approach enabling predictions of stresses at positions where sensor installation is not possible. A methodology for the prediction of stresses based on the combination of a finite element numerical model and the accelerations recorded at measurement locations is presented in this paper.

Keywords: Stress prediction, Fatigue assessment, Modal decomposition and expansion, Finite Element Model

1. INTRODUCTION

Offshore wind turbines exhibit high periodic stresses and strains at critical locations, due to their continuous subjection to cyclic loading caused by wind and wave excitation. These fluctuating loads might cause crack initiations and propagations that can lead to structural failure. Therefore, continuous fatigue assessment is of utmost importance. Fatigue assessment includes estimation of the expected damage accumulation and the remaining life-time of the structure. Accurate estimation of fatigue damage is based on stress response time histories[1]. Experimentally determined stresses are normally obtained from strains measured with strain gauges at accessible locations along the structure. This is not the case though in monopile offshore wind turbines, where fatigue sensitive spots are located in sections where mounting of strain gauges is impossible or practically unfeasible (e.g. the muddline 30 meters below the water level, Figure 1). Thus, an important issue when performing continuous fatigue assessment on an offshore wind turbine is the limited availability of operational measurement data due to the limited set of physical sensors distributed over the turbine components. The set of physical sensors consists mainly of accelerometers and strain gauges mounted on a few easily accessible points of the structure that allow for identification of modal parameters (i.e. natural frequencies, modeshapes). The issue of limited information due to limited availability of operational data can be overcome by making use of an updated and properly calibrated finite element model. The calibration is performed by comparison of the experimentally obtained mode shapes and the corresponding numerical mode shapes in terms of the Modal Assurance Criteria (MAC)[1, 2]. As long as the finite element model is calibrated, the combined use of operational acceleration data and mode shape components derived from the finite element model can provide sufficient information for the prediction of accelerations at different levels along the height of the structure as well as stress predictions in any arbitrary point of the structure[3]. The prediction is based upon a modal decomposition of the measured accelerations that results in the estimation of the modal coordinates. The relation between the modal coordinate and the acceleration in an arbitrary point is established by making use of the numerically obtained mode shapes.

The full monitoring process cycle for the continuous fatigue assessment of the offshore wind turbine is summarized in Figure 2. This paper will demonstrate and validate the proposed approach for the continuous fatigue assessment of offshore wind turbines using real data. The experimental data have been obtained during a long-term monitoring

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campaign on an offshore wind turbine in the Belgian North Sea. State-of-the art operational modal analysis techniques and the use of appropriate vibration measurement equipment allowed obtaining high quality acceleration data and accurate estimates of the natural frequencies, damping ratios and mode shapes.

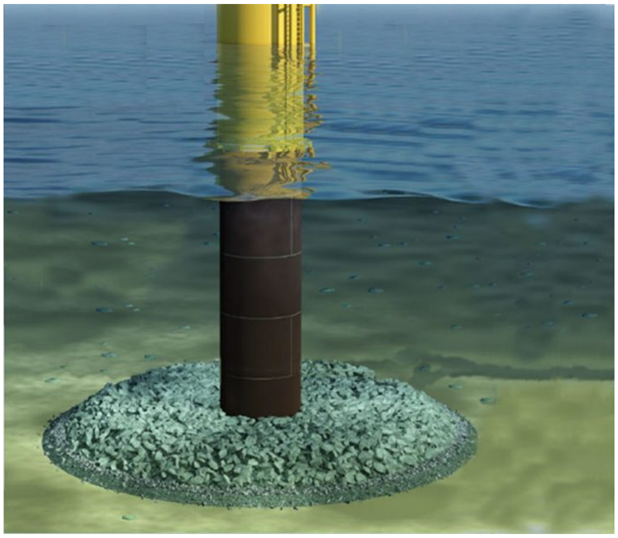


Figure 1. Muddline, fatigue critical location

Figure 2. Full monitoring process cycle of an offshore wind turbine

2. THEORY

The Euler-Bernoulli beam theory is used to describe the proposed methodology in this paper. The formula that relates the bending moments and the corresponding curvatures in an Euler-Bernoulli beam (figure 3) is given by the equations:

$$EI_z \frac{\partial^2 u_y}{\partial x^2} = M_z \tag{1}$$

$$-EI_y \frac{\partial^2 u_z}{\partial x^2} = M_y \tag{2}$$

where E is the Young's modulus, I_z and I_y are the second moment of inertia of the cross section about z and y axes (principal axis of inertia), respectively, u_y and u_z are the deflections in the y and z direction and M_z and M_y are the bending moments.

Using the Navier's Law equation, the stress can be determined as folows:

$$\sigma(x) = -\frac{M_z}{I_z} h_y + \frac{M_y}{I_y} h_z \tag{3}$$

Where h_y and h_z are the distances from the neutral axis to the point of interest.

The strain is then related to the curvature according to the following equation:

$$\varepsilon(x) = \frac{\sigma(x)}{E} \Rightarrow \varepsilon(x) = -h_y \frac{\partial^2 u_y}{\partial x^2} - h_z \frac{\partial^2 u_z}{\partial x^2} \tag{4}$$

The displacements u_y, u_z in any arbitrary point can be calculated by the nodal displacements u_{ey}, u_{ez} and the shape functions $N_e(x)$ that approximates the displacement within each element of a finite element model by the following equation:

$$\begin{aligned} u_y(x) &= \boldsymbol{N}_e(x)\boldsymbol{u}_{ey} \\ u_z(x) &= \boldsymbol{N}_e(x)\boldsymbol{u}_{ez} \end{aligned} \tag{5}$$

Substituting equation 5 to equation 4, the following formula for the strain is obtained:

$$\varepsilon(x,t) = -\boldsymbol{N''}_e(x)(\boldsymbol{u}_{ey}(t)h_y + \boldsymbol{u}_{ez}(t)h_z) \tag{6}$$

Using modal decomposition[4, 5, 6] the vector $\boldsymbol{u}_e(t)$ can be expressed in terms of mode shapes $\boldsymbol{\Phi}_e$ and modal coordinates $\boldsymbol{q}(t)$ as follows:

$$\begin{aligned} \boldsymbol{u}_{ey}(t) &= \boldsymbol{\Phi}_{ey}\boldsymbol{q}(t) \\ \boldsymbol{u}_{ez}(t) &= \boldsymbol{\Phi}_{ez}\boldsymbol{q}(t) \end{aligned} \tag{7}$$

Where $\boldsymbol{\Phi}_e$ is a matrix containing the components of mode shapes at the DOF's of the element

If equation 7 is substituted to equation 6 then the strains at any point of a beam element can be calculated by means of the expression:

$$\varepsilon(x,t) = -\boldsymbol{N''}_e(x)[\boldsymbol{\Phi}_{ey}h_y + \boldsymbol{\Phi}_{ez}h_z]\boldsymbol{q}(t) \tag{8}$$

Finally multiplying equation 8 with Young's modulus (E) the expression for the stresses is obtained as follows:

$$\sigma(x,t) = -E\boldsymbol{N''}_e(x)[\boldsymbol{\Phi}_{ey}h_y + \boldsymbol{\Phi}_{ez}h_z]\boldsymbol{q}(t) \tag{9}$$

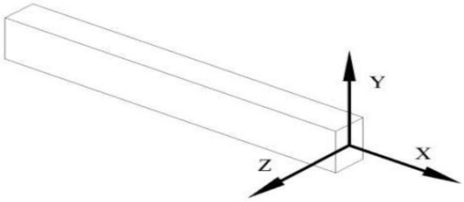


Figure 3. Example of Euler-Bernoulli beam

3. OFFSHORE MEASUREMENTS

The measurement campaigns are performed at the Belwind wind farm, which consists of 55 Vestas V90 3MW wind turbines. The wind farm is located in the North Sea on the Bligh Bank, 46km off the Belgian coast. The hub-height of the wind turbine is on average 72m above sea level. Each transition piece is 25m high and has a weight of 167ton. The tests are performed on the BBCO1-turbine that is located in the north of the wind farm directly next to the offshore high voltage substation (OHVS). The wind turbine is placed on a monopile foundation structure with a diameter of 5m and a wall-thickness of 7cm. The actual water depth at the location of BBCO1 is 24.03m and the monopile has a penetration depth of 20.97m. The soil is considered stiff and mainly consists of sand. The structures instrumented in this campaign are the tower and transition piece. Measurements are taken at 4 levels on 9 locations using a total of 10 sensors. A schematic representation of the wind turbine as well as the measurement locations are indicated in Figure 4.

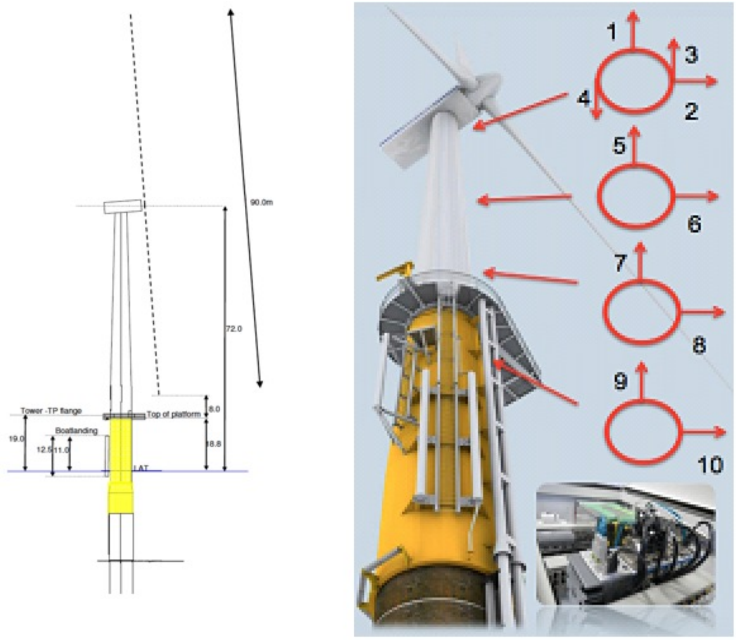


Figure 4. Schematic representation of the wind turbine (left) and measurement locations (right)

The locations are chosen based on the convenience of sensor mounting, such as the vicinity of platforms. The chosen levels are 69m, 41m, 27m and 19m above Lower Astronomical Tidal level (LAT). The data acquisition software allows for the continuous monitoring of the accelerations. The software measures continuously and sends data every 10 minutes to the server that is installed onshore using a dedicated fiber that is running over the seabed. All data receives a time-stamp from a NTP timeserver in order to be able to correlate them with the SCADA and Meteo data. For more details about the measurements, the reader is referred to [7]. Figure 5 gives an example of the measured acceleration time domain signals in respectively rotating and parked conditions at the four levels in the fore aft direction.

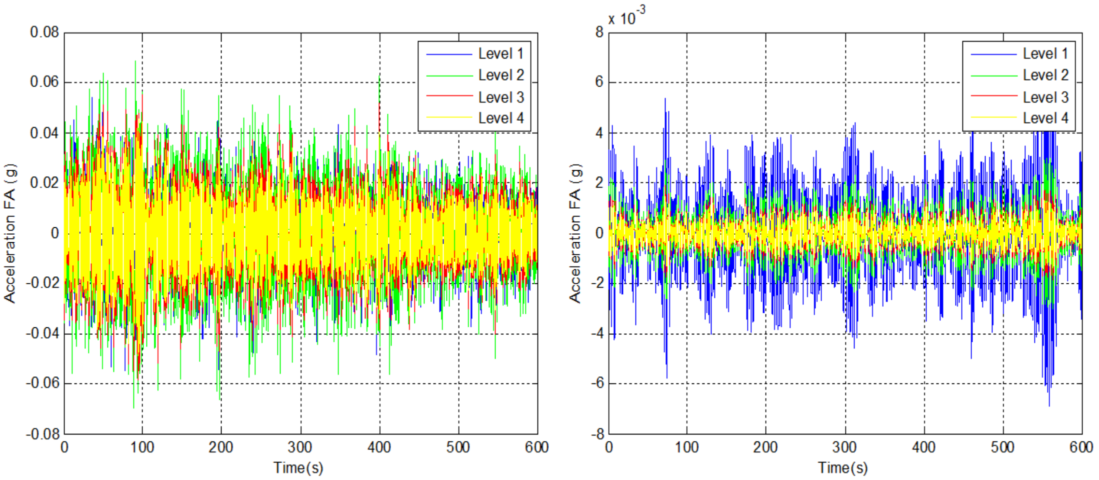


Figure 5. Example of time domain acceleration signals in Fore-Aft direction for the 4 measured levels in respectively rotating and parked conditions of the wind turbine.

4. IDENTIFICATION OF MODAL PARAMETERS

Operational Modal Analysis (OMA) is a technique with many potential applications in civil structures[8, 9] and mechanical systems[10]. In OMA the structures are excited using natural or operating loads and the modal tests can be performed with the structure in operation subject to natural or operational loads In the present work, a state of the art operational modal analysis technique called pLSCF, that has been automated[11, 12, 13] is used to identify the modal parameters (natural frequencies, modeshapes and damping ratios) from 2- week operational data of the wind turbine. The frequencies of the 6 fundamental tower/foundation modes as well as the mode shapes and mode shape components at the specified measured levels (69m, 41m, 27 and 19m above LAT) are presented in figure 6 and summarized in table 1.

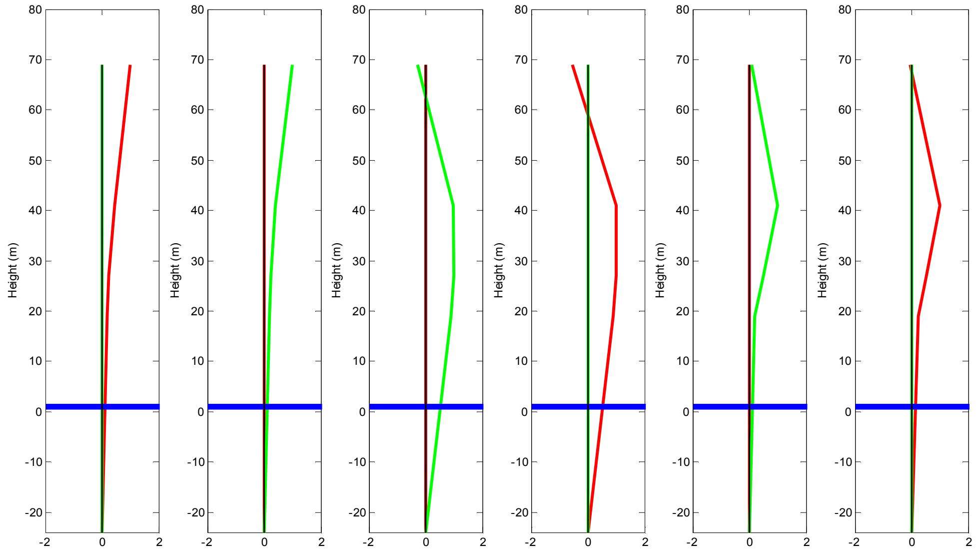


Figure 6. The mode shapes of the 6 fundamental tower/foundation modes: FA-direction (red lines), SS-direction (green lines), and water level (blue lines). From left to right: FA1, SS1, SS2, FA2, SS3, FA3

	Freq.
FA1	0.361
SS1	0.365
SS2	1.448
FA2	1.560
SS3	3.610
FA3	3.910

FA1	**SS1**	**SS2**	**FA2**	**SS3**	**FA3**
1	0	0	-0,538	0	-0,041
0,433	0	0	0,991	0	1
0,247	0	0	1	0	0,523
0,184	0	0	0,885	0	0,246
0	1	-0,274	0	0,068	0
0	0,389	0,974	0	1	0
0	0,243	1	0	0,485	0
0	0,184	0,882	0	0,185	0

Table 1. Natural frequencies of the six fundamental tower/foundation modes (left) and mode shape components of the 6 fundamental tower/foundation modes at the specified measured locations (4 height levels).

5. NUMERICAL SIMULATIONS

At this stage a numerical model that represents the real wind tower/foundation system of the examined monopile offshore wind turbine is assembled. A 3d model has been set up using the commercial Finite Element Analysis (FEA) software ANSYS. Figure 7 shows the 3-D representation of the structure built up as a sequence of pipe elements. "Pipe 288" elements are used in order to take advantage of the special features allowed by this type of element (e.g. hydrodynamic loading, hydraulic added mass, nonlinear material models). Pipe elements are geometrically defined by 3 parameters: height, diameter and thickness. In order to account for conical shapes, a sequence of pipes with a 'step by step' diminishing cross section is used.

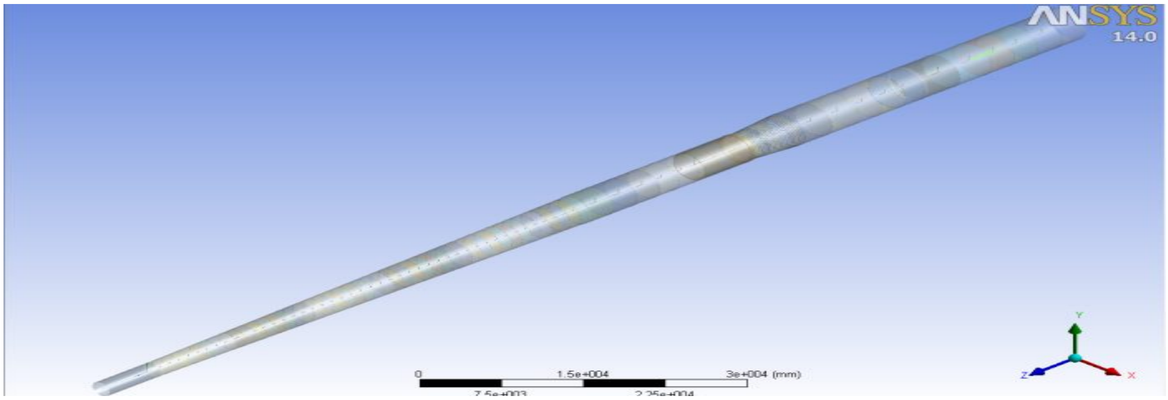


Figure 7. 3-D representation of the monopile wind turbine

As the tower-foundation system is a complex system that consists not only of stainless steel parts but also from special high resistance grout filling the space between the smaller diameter monopile and the larger diameter transition piece, two different material types are taken into account in the material definition of the structure. A fine mesh is used to capture the geometry and provide results with great accuracy.

The monopile foundation is driven into the sea-bed and thus it experiences a certain stiffness constraint by the surrounding soil. This soil-pile interaction is modeled by use of the "Distributed springs" approach[14]. The soil material properties are specified on a layer by layer basis. Making use of these soil properties, the non-linear lateral force-displacement curve (P-Y curve) as well as the non- linear skin friction force-displacement curve (T-Z curve) is generated for each stratum.

Finally, in order to be able to consider the hydraulic added mass, the ocean environment and the sea current were implemented in the software. Figure 8 shows the results of the modal analysis conducted with ANSYS and the corresponding values are summarized in table 2. In the aforementioned figure only the 3 fundamental modes in the Fore-Aft (FA) direction are presented whereas the Side-Side (SS) modes are omitted as they are identical with the FA due to symmetry in the design of the finite element model.

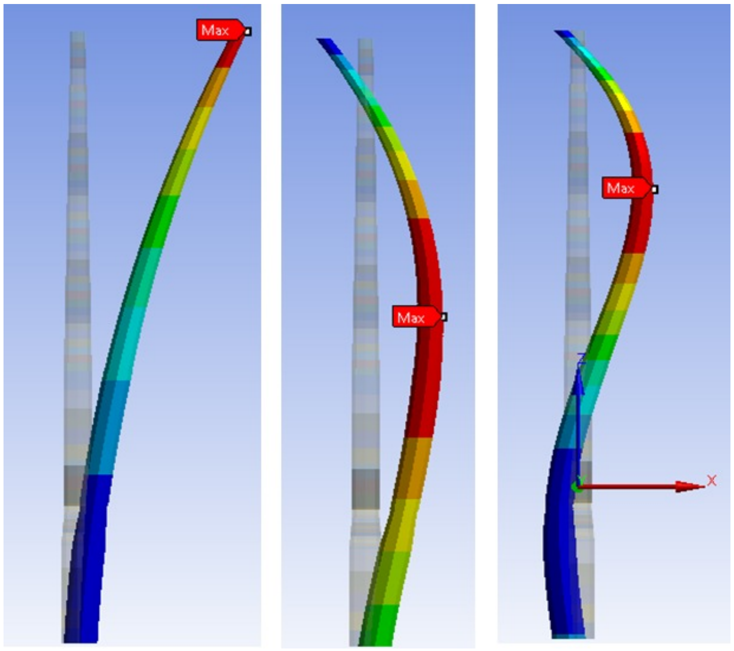


Figure 8. Fundamental fore-aft tower/foundation modes obtained through modal analysis in ANSYS

	Freq.
FA1	0.374
SS1	0.374
SS2	1.440
FA2	1.440
SS3	3.636
FA3	3.636

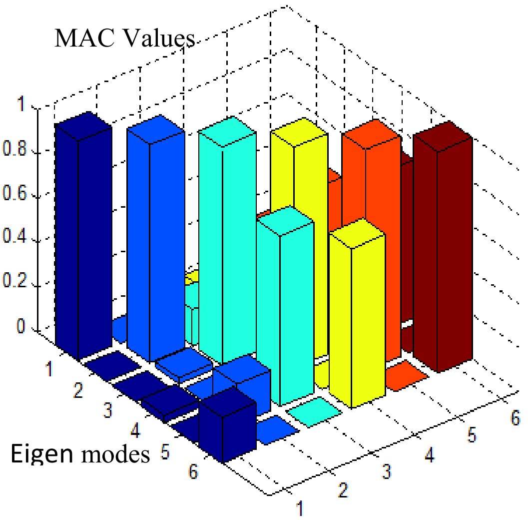
FA1	**SS1**	**SS2**	**FA2**	**SS3**	**FA3**
1	0	0	-0.454	0	-0.0106
0.518	0	0	0.876	0	1
0.346	0	0	1	0	0.527
0.268	0	0	0.944	0	0.207
0	1	-0.454	0	-0.0106	0
0	0.518	0.876	0	1	0
0	0.346	1	0	0.527	0
0	0.268	0.944	0	0.207	0

Table 2. Natural frequencies of the six fundamental tower/foundation modes (left) and mode shape components of the 6 fundamental tower/foundation modes at the specified measured locations (4 height levels).

In order to check for the accuracy of the numerically obtained mode shapes a comparison with the experimentally obtained mode shapes is done in terms of the Modal Assurance Criterion (MAC) as follows:

$$MAC\left(\phi_{exp,i}, \phi_{FE,i}\right) = \frac{\left|\phi_{exp,i}^{T}\phi_{FE,i}\right|^{2}}{(\phi_{exp,i}^{T}\phi_{exp,i})(\phi_{FE,i}^{T}\phi_{FE,i})} \tag{10}$$

The results depicted in figure 9 and their corresponding values summarized in table 3 indicate the good agreement between the modes obtained from the measurements and the modes obtained from the FEM analysis. The comparison is done at the reference sensor points.



	FA1	SS1	SS2	FA2	SS3	FA3
FA1	**0.987**	0	0	0.069	0	0.268
SS1	0	**0.981**	0.161	0	0.347	0
SS2	0	0.026	**0.984**	0	0.620	0
FA2	0.032	0	0	**0.993**	0	0.712
SS3	0	0.181	0.768	0	**0.993**	0
FA3	0.20	0	0	0.722	0	**0.998**

Figure 9. Graphical illustration of MAC values
Table 3. MAC values for the 6 fundamental tower/foundation modes

6. MODEL UP-DATING AND MODAL EXPANSION

As shown in the previous section, there is a great agreement between the experimentally and numerically obtained modes shapes and this is certified by the high MAC values. This pronounces a well updated and calibrated numerical model. After updating, a transformation matrix T is obtained from:

$$\phi_{exp}^{m} = \phi_{FE}^{m}.T \tag{11}$$

where subscripts 'exp' and 'FE' correspond to experimental and numerical mode shapes respectively and superscript 'm' indicates measured degrees of freedom (DOF's). Then, the experimental mode shapes are expanded to the unmeasured DOF's (superscript 'um') by the expression:

$$\phi_{exp}^{um} = \phi_{FE}^{um}.T \tag{12}$$

7. PREDICTION OF ACCELERATION

In order to predict the acceleration time histories, the acceleration mode shape matrix needs first to be constructed. This is done by making use of the numerically obtained displacement mode shape components as follows:

$$\omega_j = 2\pi f_j \tag{13}$$

$$\Phi_{accel}, ij = \omega_j^2 . X_{ij} \tag{14}$$

where $\boldsymbol{\omega_j}$ is the angular frequency of the "j"-mode calculated from the corresponding natural frequency f_j derived from the Finite Element Software, $\boldsymbol{X_{ij}}$ is the numerically (FEM) obtained absolute displacement mode shape component of the "i"-degree of freedom that corresponds to the "j" mode and $\boldsymbol{\Phi_{accel}, ij}$ is the resulting acceleration mode shape component of the "i"-degree of freedom that corresponds to the "j" mode.

Based on the modal decomposition, the modal coordinates $q^m(t)$ are calculated from experimentally known acceleration time signals at measured locations $A^m(t)$ as follows:

$$A^m(t) = \boldsymbol{\Phi}^{\boldsymbol{m}}_{\boldsymbol{accel,FE}} \cdot q^m(t)$$

$$q^m(t) = (\boldsymbol{\Phi}^{\boldsymbol{m}}_{\boldsymbol{accel,FE}})^{-\mathbf{1}} . A^m(t)$$

where subscripts 'FE' correspond to numerical acceleration mode shapes and superscript 'm' indicates measured degrees of freedom (DOF's). Then, the acceleration can be predicted at any inaccessible point of the structure by the following expression:

$$\mathrm{A}^{um}(t) = \boldsymbol{\Phi}^{\boldsymbol{um}}_{\boldsymbol{accel,FE}} \cdot q^m(t)$$

where superscript 'um' indicates unmeasured degrees of freedom (DOF's).

In figures 10 and 11 the results of the acceleration prediction at the lowest sensor level (level 4) are presented corresponding to parked and rotating conditions of the wind turbine respectively. The contribution of the first three modes in the Fore Aft direction as well as the acceleration information obtained from the three sensors installed in the upper levels of the tower are considered. Red color corresponds to accelerations derived from accelerometers whereas the accelerations estimated with the methodology proposed in this paper are shown in green.

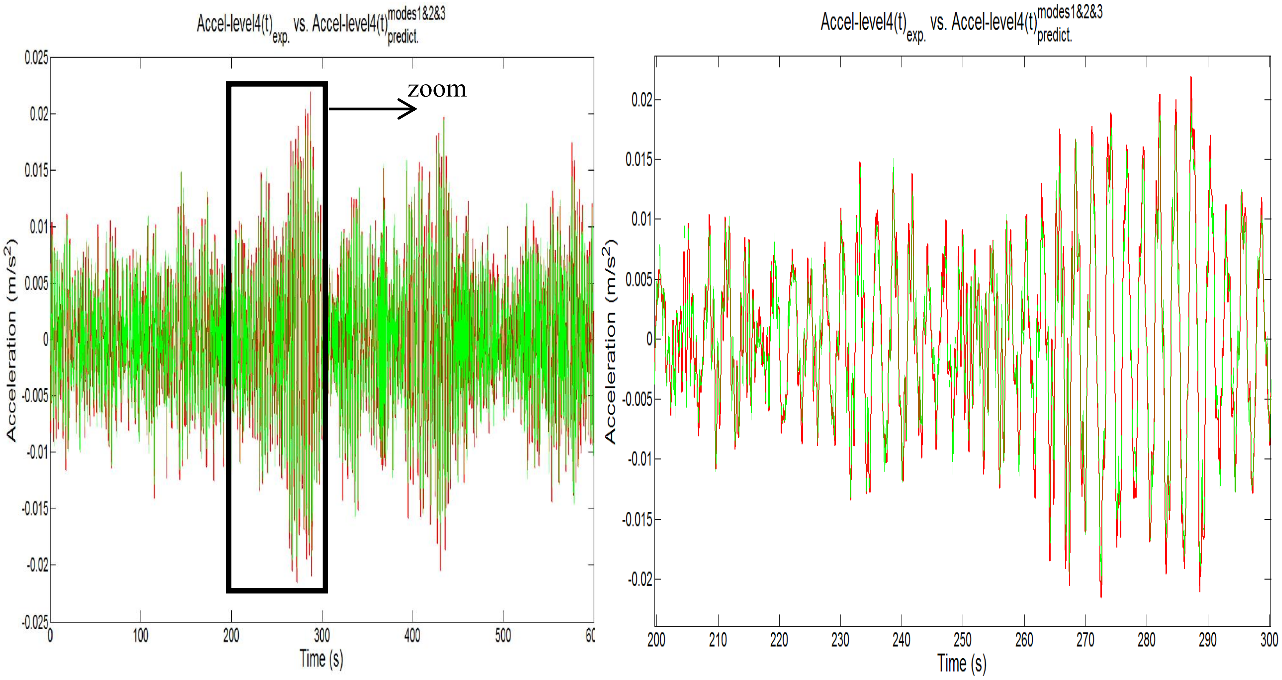


Figure 10. **Parked conditions**: Acceleration time history prediction and comparison with real measured data at sensor level 4 (z=+19m above LAT)

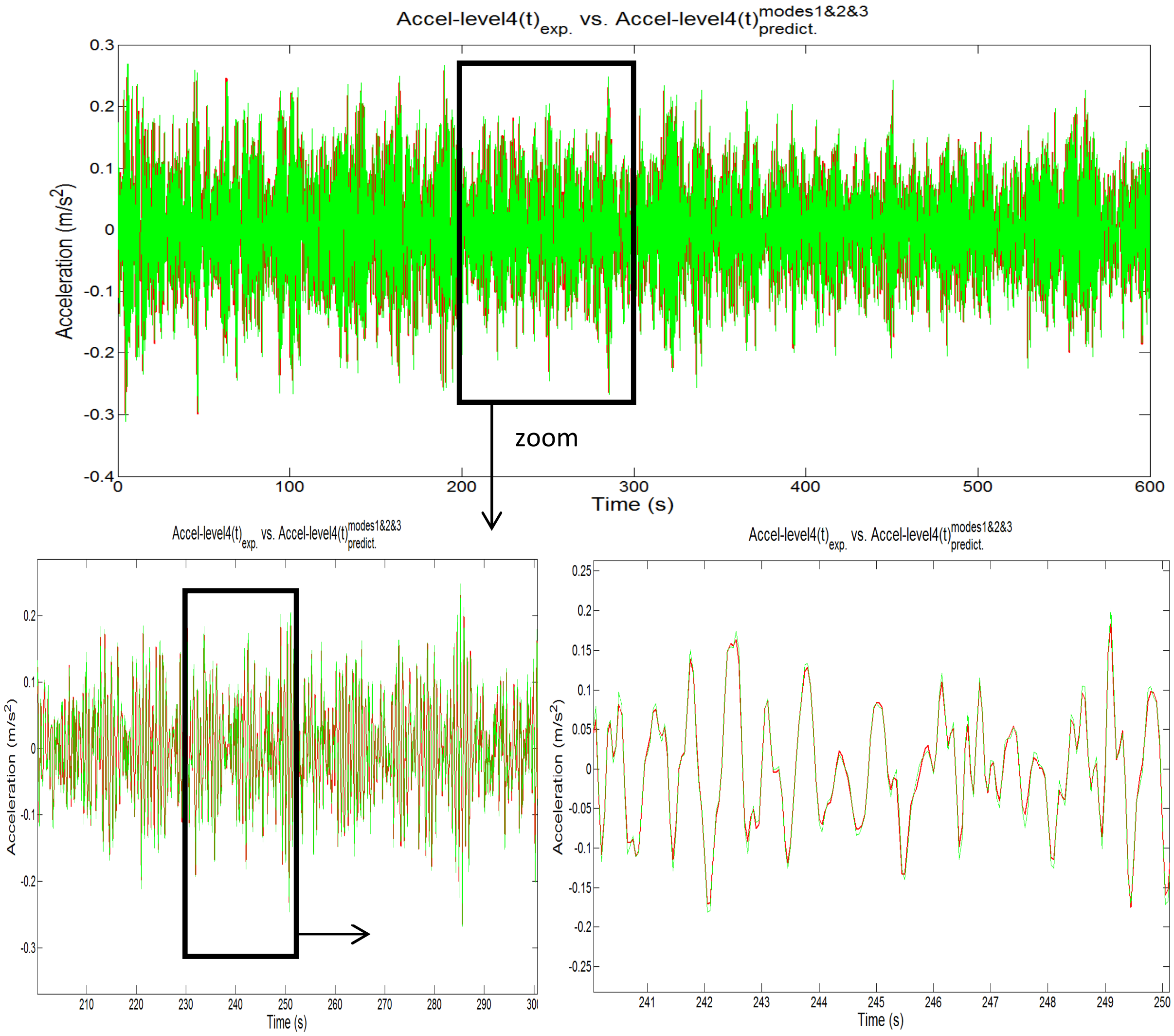


Figure 11. **Rotating conditions**: Acceleration time history prediction and comparison with real measured data at sensor level 4 (z=+19m above LAT)

As shown in the above figures, the predicted response is in great agreement with the operational measurement data. Small observed differences are mainly attributed to the slight difference between the experimentally and numerically obtained mode shapes.

The modal decomposition and expansion technique is thus validated and will be used further on for the prediction of stresses and strains at critical and inaccessible points of the structure. Once the stress response time histories are predicted, the last step in the continuous fatigue assessment includes the estimation of the expected damage accumulation and remaining life-time of the structure. Available frequency domain stochastic fatigue methods, based on the Palmgren-Miner damage rule and Dirlik's probability distribution of the stress range, will be used to predict the expected fatigue damage accumulation of the structure in terms of the power spectral density (PSD) of the predicted stresses[15]

8. CONCLUSIONS

A numerical model, the modal parameters identified by OMA, and the acceleration time histories recorded at several points of the structure are used in order to compose a complete methodology for the prediction of accelerations, stresses and strains at any arbitrary and inaccessible point of the monopile Wind turbine. The methodology has been validated by comparison of acceleration predictions with real accelerations provided by the accelerometers during the measurement campaign. The agreement between experimentally obtained and numerically predicted accelerations is very good both in terms of acceleration amplitudes and temporal evolution for both parked and rotating operating conditions of the wind turbine.

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