Continuous Fatigue Assessment of an Offshore Wind Turbine Using a Limited Number of Vibration Sensors

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ABSTRACT

Offshore Wind turbines are exposed to continuous wind and wave excitation that leads to high periodic stresses and strains at critical locations. This makes the structures prone to structural failure due to possible crack initiations and propagations. The continuous monitoring of the Wind Turbine is of utmost importance in order to assess the remaining lifetime and accumulative fatigue damage of the structure. Health monitoring of wind turbines is usually performed by collecting real-time operating data on a limited number of accessible locations using traditional sensors such as accelerometers and strain-gauges. When dealing with Offshore Wind Turbine though, most of the fatigue sensitive spots are inaccessible for direct measurements, e.g. at the muddline 30 meters below the water level. Response estimation techniques can then be used to estimate the response at unmeasured locations from a limited set of response measurements and a Finite Element Model. This paper makes use of a modal decomposition and expansion algorithm that allows for successful response prediction. The algorithm is validated using data obtained from a monitoring campaign on an offshore Vestas V90 3 MW wind turbine on a monopile foundation.

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

INTRODUCTION

Offshore wind turbines are exposed to a variety of dynamic loading scenarios for which fatigue accumulation needs to be monitored and tracked over the course of the life of the structure. Generally, the loadings are of a level and occurrence to be considered normal routine loads and the design of the structure is built to accommodate these conditions. However, there are often other loadings which are more severe and more important to the overall load and fatigue accumulation for the structure. Therefore, a remote monitoring application with the ability to predict failures before they actually occur allowing for continuous fatigue assessment of the wind turbine is of utmost importance. 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 monitoring of 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 limited sets of monitoring transducers (accelerometers and strain gauges) are insufficient to accurately depict the true stress-strain imposed on the structure. In order to assess the actual dynamic behavior and response of the structure, more sophisticated utilization of the limited data available needs to be performed. Towards this direction, 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[4]. The relation between the modal coordinate and the acceleration in an arbitrary point is established by making use of the numerically obtained mode shapes [4]. 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 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.

1 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 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 follows:

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

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:

$$\varepsilon(x,t) = -N''_e(x)(u_{ey}(t)h_y + u_{ez}(t)h_z) \quad (6)$$

Using modal decomposition [5], [6], [7] the vector $u_e(t)$ can be expressed in terms of mode shapes Φ_e and modal coordinates $q(t)$ as follows:

$$u_{ey}(t) = \Phi_{ey} q(t)$$
$$u_{ez}(t) = \Phi_{ez} q(t) \quad (7)$$

Where Φ_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:

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

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

$$\sigma(x,t) = -EN''_e(x)[\Phi_{ey}h_y + \Phi_{ez}h_z]q(t) \quad (9)$$

2 OFFSHORE MEASUREMENTS AND IDENTIFICATION OF DYNAMIC PARAMETERS

The structure under consideration is a Vestas V90 3MW wind turbine on a monopile foundation with an average height of 72m above sea level located in the Belwind wind farm, 46km off the Belgian coast. The actual water depth at the location of the examined wind turbine is 24.03m and the penetration depth of the monopile is 20.97m. The soil is considered stiff and mainly consists of sand. Measurements are taken at 4 levels on 9 locations using a total of 10 sensors along the height of the tower of the Wind turbine. A schematic representation of the wind turbine as well as the measurement locations are indicated in Figure 1.

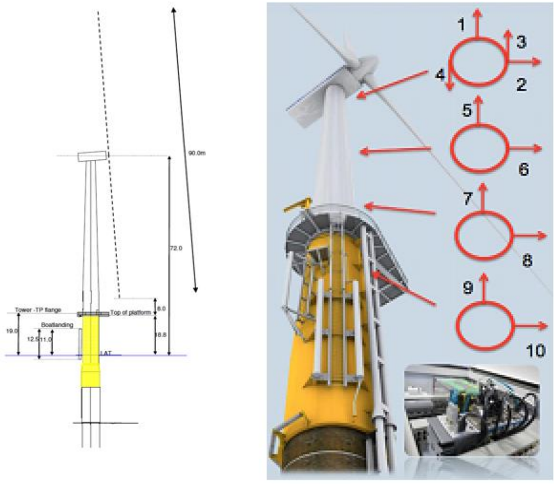

Figure 1: Schematic representation of the wind turbine (left) and measurement locations (right)

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 [8]

In the present work, a state of the art operational modal analysis technique called pLSCF, that has been automated [9], [10], [11] is used to identify the modal parameters (natural frequencies, modeshapes and damping ratios) from 2- week operational data of the wind turbine [12]. The frequencies of the 6 fundamental tower/foundation modes as well as the mode shapes and mode shape components at the specified measured levels are presented in figure 2 and summarized in table 1.

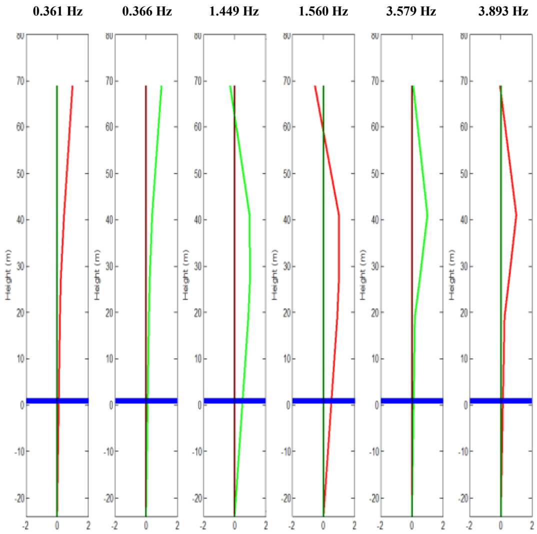

Table 1: Mode shape components of the 6 fundamental tower/foundation modes at the specified measured locations (4 sensor levels)

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

Figure 2: The mode shapes of the 6 fundamental tower/foundation modes with their corresponding natural frequencies: FA-direction (red lines), SS-direction (green lines), and water level (blue lines). From left to right: FA1, SS1, SS2, FA2, SS3, FA3

3 FINITE ELEMENT MODAL ANALYSIS

A 3-D numerical model of the tower foundation system of the examined monopile wind turbine is set up using a sequence of "pipe 288" elements supported by the commercial Finite Element Software ANSYS. In the material definition, the steel as well as the high resistance grout that is filling the gap between the smaller diameter monopile and the larger diameter transition piece are taken into account. The soil-pile interaction and the ocean environment could not be excluded from the model. For more information about the numerical model the reader is referred to [4]. Figure 3 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.

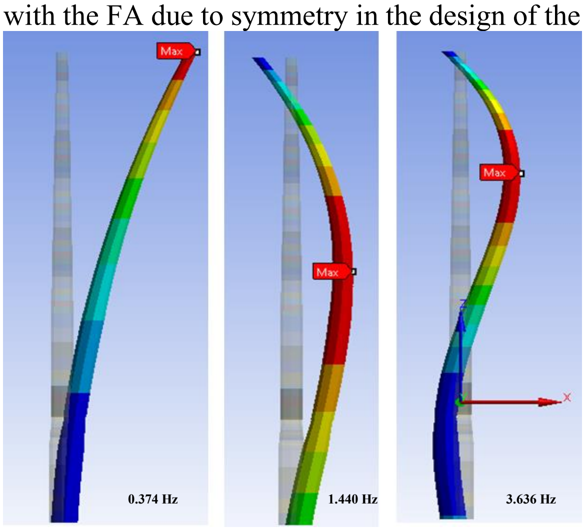

Table 2: Mode shape components of the 6 fundamental tower/foundation modes at the specified measured locations (4 sensor levels)

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

Figure 3: Fundamental fore-aft tower/foundation modes and their corresponding frequencies obtained through modal analysis in ANSYS

The accuracy of the numerical model is checked with the Modal Assurance Criterion (MAC) by comparison of the experimentally obtained mode shapes with the corresponding numerical as follows:

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

The MAC 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.

Table 3: MAC values for the 6 fundamental tower/foundation modes

	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**

4 RESPONSE ESTIMATION FROM LIMITED SET OF DATA

The prediction of the acceleration time histories is based on the modal decomposition and expansion approach similarly to equation 7. Thus, in order to be able to predict the acceleration signal, the acceleration mode shape matrix needs first to be constructed [4]. 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 ω_j is the angular frequency of the "j"-mode calculated from the corresponding natural frequency f_j derived from the Finite Element Software, 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 Φ_{accel}, ij is the resulting acceleration mode shape component of the "i"-degree of freedom that corresponds to the "j" mode. The modal coordinates $q^m(t)$ are calculated from the limited number of experimentally known acceleration time signals at measured locations $A^m(t)$ with the following expression:

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

$$q^m(t) = (\mathbf{\Phi}_{accel,FE}^m)^{-1} . A^m(t)\omega_j = 2\pi f_j \tag{15}$$

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 as follows:

$$\mathrm{A}^{um}(t) = \mathbf{\Phi}_{accel,FE}^{um} \cdot q^m(t) \tag{16}$$

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

Figure 4 shows the results of the acceleration prediction at the lowest sensor level (level 4) when the wind turbine is under rotating conditions. 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 is considered. Red color corresponds to accelerations derived from accelerometers whereas the accelerations estimated with the methodology proposed in this paper are shown in green. Two correlation tools are utilized to compare the results of the predicted and measured time domain signals. The first is the correlation coefficient which represents the normalized measure of the strength of linear relationship between variables and the second is the Time Response Assurance Criterion (TRAC) [13] which is the correlation for one DOF over all time of the predicted time domain signal with the measured time domain signal. These are expressed by the following equations and the results are given for the case of rotating conditions of the Wind turbine below figure 4.

$$\textbf{Corrcoef} = \frac{Cov\left(accel_{meas}(t)\,,\ accel_{pred}(t)\right)}{\sigma_{accel_{meas}}\sigma_{accel_{pred}}} \tag{17}$$

$$\textbf{TRAC} = \frac{\left[\{accel_{meas}(t)\}^T\{accel_{pred}(t)\}\right]^2}{\left[\{accel_{meas}(t)\}^T\{accel_{meas}(t)\}\right]\left[\{accel_{pred}(t)\}^T\{accel_{pred}(t)\}\right]} \tag{18}$$

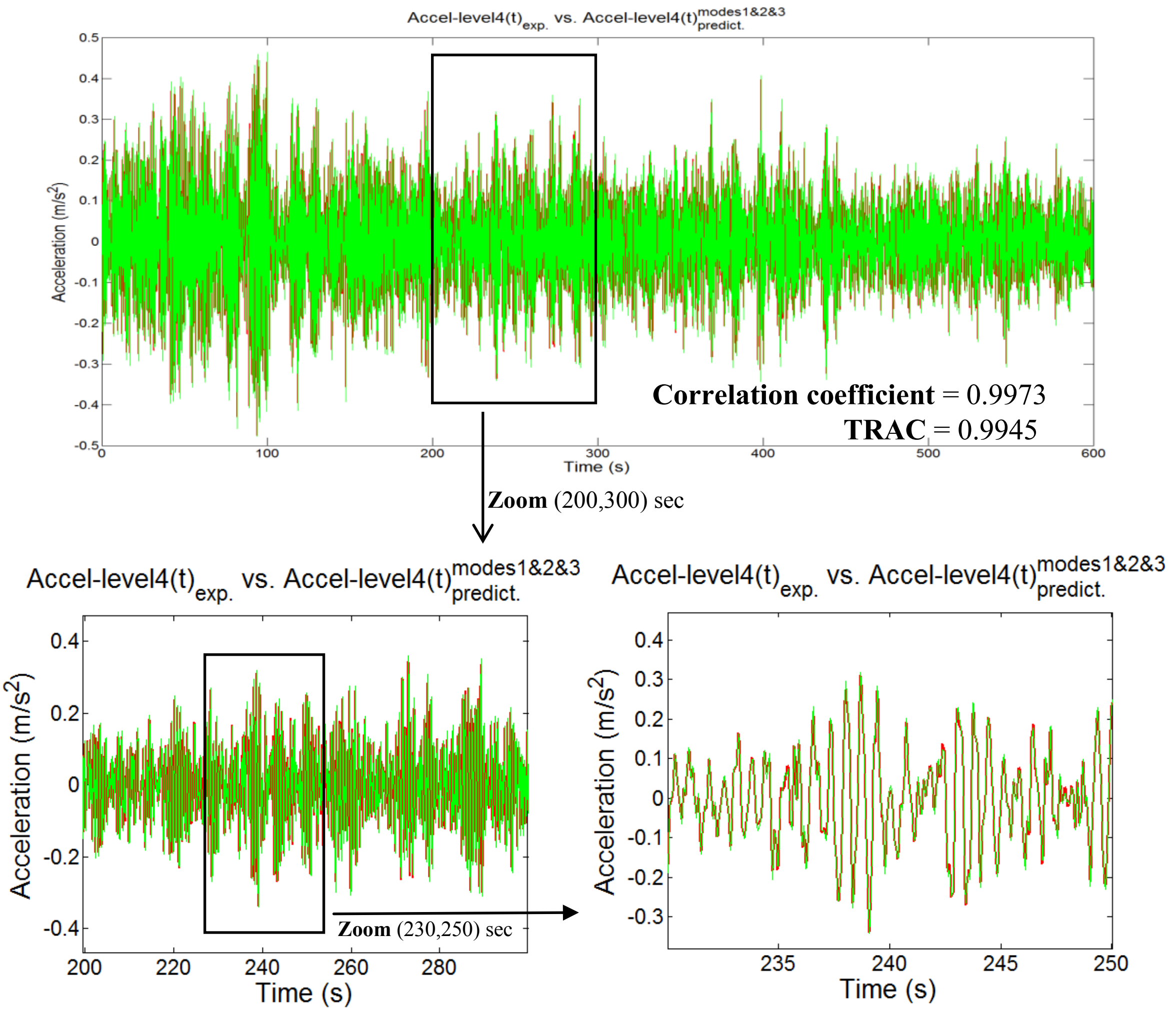

Figure 4: **Rotating conditions**: Acceleration time history prediction and comparison with real measured data at sensor level 4 (z=+19m above LAT).

As shown in the above figures and indicated by the high values of the correlation coefficient and the TRAC approaching the unity, 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. Considering now the 2 signals (measured, predicted) and their respective spectra the following plot is obtained, shown in figure 5:

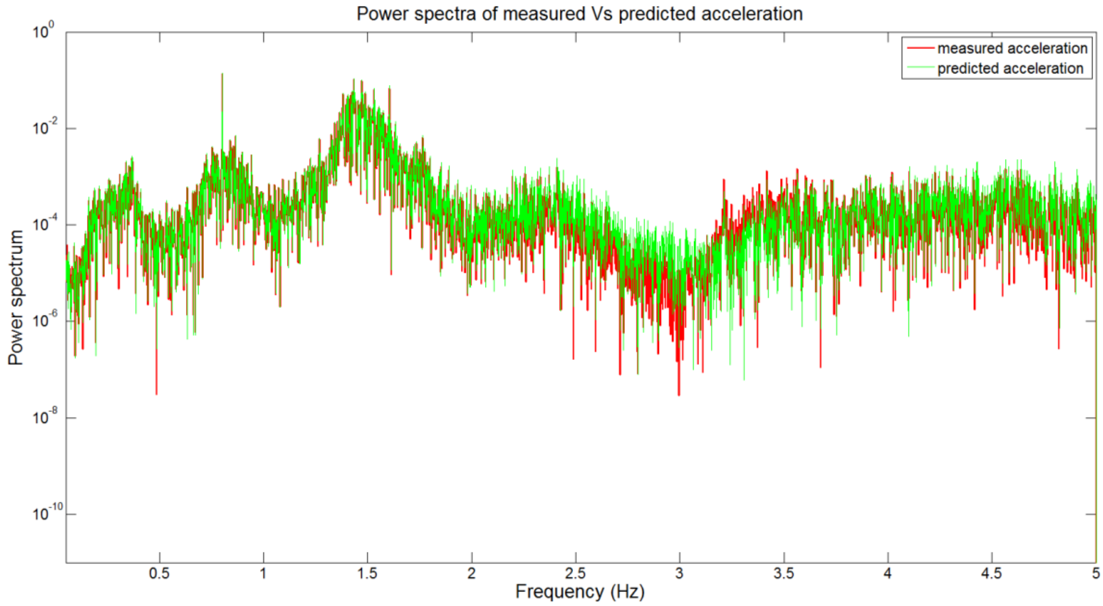

Figure 5: **Rotating conditions**: power spectra comparison of the measured and predicted acceleration signal at the lowest sensor level (z=+19m above LAT).

As shown above there is a high spectral coherence between the 2 signals giving more value to the time domain correlation indicated earlier. Finally, in figure 6 the Fourier Amplitude spectrum of the modal accelerations Qa derived by double differentiation of the modal displacements $q^m(t)$ in the frequency domain, clearly distinguishes the influence of each mode to the resulting acceleration output. Three regions are observed, which make clear that the resulting output could be decomposed in frequency regions where only one dominant frequency is present and then summed up again in order to give the final signal.

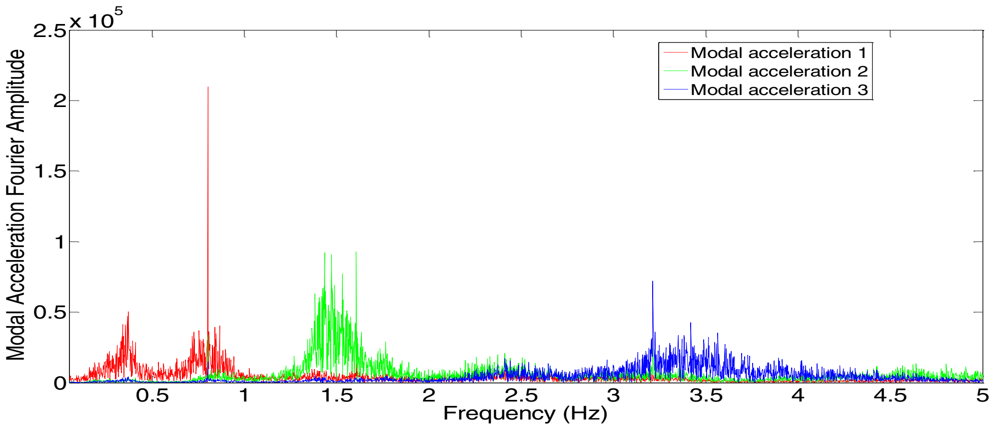

Figure 6: Modal acceleration Fourier Amplitude spectrum

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 monitoring 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 [14]

CONCLUSION

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 offshore 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 temporal evolution and frequency content.

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REFERENCES

[1] H.P. Hjelm, R. Brincker, J. Graugaard-Jensen and K. Munch. Determination of Stress Histories in Structures by Natural Input Modal Analysis. *Proceedings of 23rd Conference and Exposition on Structural Dynamics(IMAC-XXIII),*Orlando, Florida, USA, 2005

[2] M.L Aenlle, A.Skafte, P. Fernandez and R. Brincker. Strain Estimation in a glass Beam Using Operational Modal Analysis. *Proceedings of the Society for Experimental Mechanics,* 375-382, 2013

[3] M.L Aenlle, L. Hermanns, P. Fernandez and A. Fraile. Stress Estimation in a scale model of a symmetric two story building. *Proceedings of 5th International Operational Modal Analysis Conference,* Portugal, 2013

[4] A. Iliopoulos, C. Devriendt, S. Iliopoulos and D. Van Hemelrijck. Continuous fatigue assessment of offshore wind turbines using a stress prediction technique, In *Proceedings SPIE 9064, Health Monitoring of Structural and Biological Systems 2014, 90640S*, San Diego, CA, USA, March, 2014, doi:10.1117/12.2045576.

[5] W. Heylen, S. Lammens and P. Sas. [Modal Analysis: Theory and Testing], Katholieke Universiteit Leuven(1997)

[6] N. Maia, J. Silva, J. He, N. Lieven, R.-M. Lin, G. Skingle, W. To and Urgueira. [Theoretical and Experimental Modal Analysis], Research Studies Press Ltd(1997)

[7] D. Ewins. [Modal Testing 2, theory, practice and application], Research Studies Press Ltd, 2 edn,(2000)

[8] C. Devriendt, P. Jan Jordaens, Y. Van Ingelgem, G. De Sitter and P. Guillaume. Monitoring of resonant frequencies and damping values of an offshore wind turbine on a monopile foundation. In: *EWEA 2013 conference*, Vienna, Austria

[9] C. Devriendt, F. Magalhaes, W. Weijtjens, G. De Sitter, Á. Cunha and P. Guillaume. Structural health monitoring of offshore wind turbines using automated operational modal analysis. *Proceedings of IWSHM 2013*, Stanford, September 2013

[10] P. Guillaume, P. Verboven, S. Vanlanduit, H. Van der Auweraer and B. Peeters. A poly-reference implementation of the least-squares complex frequency domain-estimator. *Proceedings of the 21th International Modal Analysis Conference*, Kissimmee (Florida), February 2003

[11] M. El-Kafafy, P. Guillaume, B. Peeters. Modal parameter estimation by combining stochastic and deterministic frequency-domain approaches. *Mechanical Systems and Signal Processing*, vol 35(1-2), 52-68(2013)

[12] C. Devriendt, W. Weijtjens, M. ElKafafy and G. De Sitter. Monitoring resonant frequencies and damping values of an offshore wind turbine in parked conditions. *IET Renewable Power Generation (In Press)*, 2014

[13] P. Avitabile and P. Pingle. Prediction of full field dynamic strain from limited sets of measured data. *Shock and Vibration,* Vol. 19, 765-785(2012), doi:10.3233/SAV-2012-0686

[14] C. Papadimitriou, C.-P. Fritzen, P. Kraemer and E. Ntotsios. Fatigue predictions in entire body of metallic structures from a limited number of vibration sensors using Kalman filtering. *Struct. Control Health Monit.* Vol. 18, 554-573(2011)