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Prediction of dynamic strains on a monopile offshore wind turbine using virtual sensors

A N Iliopoulos[1], W Weijtjens[2], D Van Hemelrijck[1] and C Devriendt[2]

[1]Vrije Universiteit Brussel, Department of Mechanics of Materials and Constructions, Pleinlaan 2, B-1050,Brussels, Belgium
[2]Vrije Universiteit Brussel, Acoustic and Vibration Research Group, Pleinlaan 2, B-1050,Brussels, Belgium

Alexandros.Iliopoulos@vub.ac.be

Abstract. The monitoring of the condition of the offshore wind turbine during its operational states offers the possibility of performing accurate assessments of the remaining life-time as well as supporting maintenance decisions during its entire life. The efficacy of structural monitoring in the case of the offshore wind turbine, though, is undermined by the practical limitations connected to the measurement system in terms of cost, weight and feasibility of sensor mounting (e.g. at muddline level 30m below the water level). This limitation is overcome by reconstructing the full-field response of the structure based on the limited number of measured accelerations and a calibrated Finite Element Model of the system. A modal decomposition and expansion approach is used for reconstructing the responses at all degrees of freedom of the finite element model. The paper will demonstrate the possibility to predict dynamic strains from acceleration measurements based on the aforementioned methodology. These virtual dynamic strains will then be evaluated and validated based on actual strain measurements obtained from a monitoring campaign on an offshore Vestas V90 3 MW wind turbine on a monopile foundation.

1. Introduction

Many large-scale offshore wind farm projects use monopile foundation to obtain a cost effective design. The complexity of the offshore wind turbine (OWT) due to the added support structure as well as the unknowns in the soil-structure interaction encourage a thorough investigation of the dynamics of the structure. Furthermore, the harsh offshore conditions including combined wind and wave excitations, a corrosive environment, currents and shifts in the sea bed or soil conditions such as scour, i.e. erosion of the sea bed near the monopile, pose a threat to the structural integrity of the offshore wind turbine. Therefore, the monitoring of the condition of the OWT during its operational states offers the possibility of improving the safety of a mission. Fatigue deterioration, affecting the wind turbine, represents, in fact, one of the major issues regarding mission safety that needs to be addressed during its entire life. To assure the dynamic and fatigue strength of the structure, it is necessary to measure its dynamic strain distribution. However, strain measurements with conventional strain gauges are not always possible since the gauges are not reusable and cannot be moved from point to point when they have been attached. Moreover, to accurately assess the fatigue life consumption the strains at the mudline need to be measured. However, this implies installing sensors 30m beneath water level which is unfeasible for installation and maintenance. By contrast, a method that allows to estimate the strains at fatigue sensitive spots using accelerometers in the tower is cheaper and far more reliable.

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Different response estimation techniques have been investigated by researchers to predict response time histories at various locations within structural components using the measurements available at a limited number of locations. A common approach is based on the use of Kalman filter [1] methods [2-4]. All these applications, though, are restricted to the study of linear structures and make the assumptions that the input-forces are either known or broadband, so that they can be modeled as zero mean stationary white process. Moreover, the iterative algorithm makes these approaches time consuming and computationally expensive.

Another approach includes response estimation based on the concept of modal expansion. These methods intelligently extrapolate measured data to generate virtual strain measurements. Non-contact methods like Digital Image Correlation and Dynamic Photogrammetry are known techniques used to measure sets of limited surface data that can be used in conjunction with an expansion algorithm for full field information [5-8]. However, all the aforementioned surveys correspond to laboratory scale applications and the excitation is exactly known or/and the responses can be measured in a sufficient large number of points.

This paper deals with real scale offshore wind turbine instrumented with a limited number of sensors (accelerometers, strain gauges) and demonstrates the possibility to predict dynamic strains from acceleration measurements. The full field response of the structure is reconstructed based on a calibrated finite element model and a limited number of measured accelerations. The prediction is based on a modal decomposition of the measured accelerations that results in the estimation of the modal coordinates [9, 10]. The relation between the modal coordinate and the acceleration/strain in an arbitrary point is established by making use of the corresponding numerically obtained mode shapes [9, 10].

The proposed algorithm and the virtual dynamic strains will be evaluated and validated based on actual measurements obtained from a monitoring campaign on an offshore Vestas V90 3 MW wind turbine on a monopile foundation.

2. Theory

Herein the theoretical background of the modal decomposition and expansion approach used to predict the dynamic responses is discussed in detail. The quality indicators used as correlation tools are presented too.

2.1. Modal decomposition

The displacement vector can be written as a linear combination of the mode shape vectors by making use of the modal decomposition approach [11-13]:

$$\begin{aligned} \boldsymbol{x}(\mathrm{t}) &= \Phi \boldsymbol{q}(t) \\ \Phi &= [\boldsymbol{\varphi_1} \quad \boldsymbol{\varphi_2} \quad \dots \quad \boldsymbol{\varphi_n}] \\ \boldsymbol{q}(t) &= [q_1(t) \quad q_2(t) \quad \dots \quad q_n(t)]^T \end{aligned} \tag{1}$$

where $\boldsymbol{q}\,(t)$ is the vector of the modal coordinates for each time instant t, Φ is the mode shape matrix, n is the total number of modes and $[.]^{\mathrm{T}}$ denotes the transpose of a matrix. Since our interest lies within the lower frequency range, the first two or three tower modes in the Fore-Aft (FA) or Side-Side (SS) direction are the considered subset of modes.

2.2. Modal expansion

If we consider a subset of a active DOF's corresponding to the measured locations of the real experimental model and d remaining DOF's corresponding to predicted locations, then the relationship for only the measured DOF's is written as:

$$\boldsymbol{x_m} = \Phi_m \boldsymbol{q_m} \tag{2}$$

where subscript m corresponds to the measured DOF's.

Assuming that the number of modes, n_m , is less than the number of active DOF's, a, the modal coordinates $\boldsymbol{q_m}$ are calculated by using the pseudo inverse as follows:

$$\boldsymbol{q_m} = (\Phi_m^T \Phi_m)^{-1} \, \Phi_m^T \, \boldsymbol{x_m} = \Phi_m{}^{\dagger} \, \boldsymbol{x_m} \tag{3}$$

This result can be expanded to the predicted locations (d remaining DOF's) with the following expression:

$$\boldsymbol{x_p} = \Phi_p \boldsymbol{q_m} = \Phi_p \, \Phi_m{}^{\dagger} \, \boldsymbol{x_m} \tag{4}$$

where subscript p corresponds to the predicted DOF's.

A schematic representation of the modal decomposition and expansion approach for the case of the offshore wind turbine is presented in figure 1.

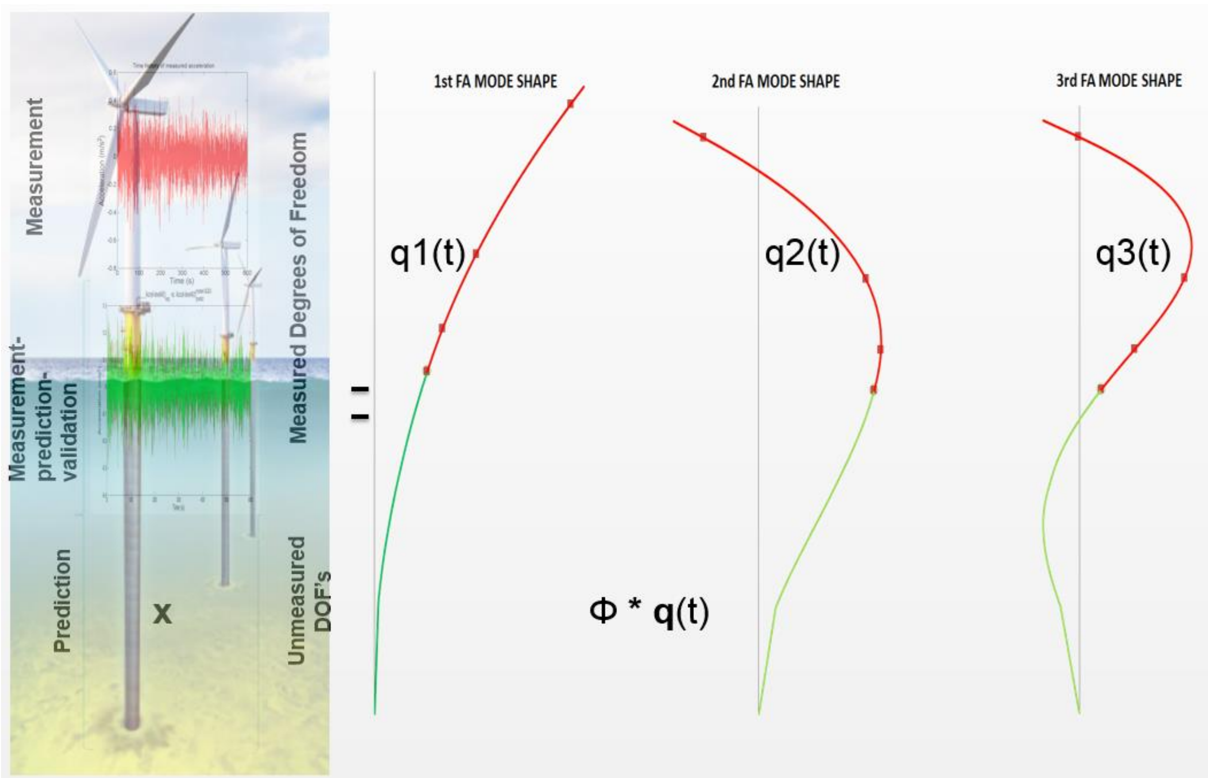

Figure 1. Modal decomposition and expansion in a schematic representation for the case of OWT. In red is the accessible area of the OWT with the corresponding measured locations and in green is the critical and inaccessible part of the OWT.

2.3. *Prediction of vibrational accelerations*

In order to be able to predict the acceleration signal [9, 10, 14], the acceleration mode shape matrix first needs to be constructed. This is done by making use of the numerically obtained displacement mode shape components as follows:

$$\omega_j = 2\pi f_j \tag{5}$$

$$\Phi_{a,ij} = \omega_j^2 . \Phi_{ij} \tag{6}$$

where ω_j is the angular frequency of the j[th] mode calculated from the corresponding natural frequency f_j derived from the Finite Element Model, Φ_{ij} is the numerically (FEM) obtained absolute displacement mode shape component of the i[th] degree of freedom that corresponds to the j[th] mode and $\Phi_{a,ij}$ is the resulting acceleration mode shape component of the i[th] degree of freedom that corresponds to the j[th] mode. The modal coordinates $\boldsymbol{q_m}(t)$ are calculated from the limited number of experimentally known acceleration time signals at measured locations $\boldsymbol{a_m}(t)$ with the following expression:

$$\boldsymbol{a_m}(t) = \Phi_{\alpha_m}\boldsymbol{q_m}(t)$$
$$\boldsymbol{q_m}(t) = (\Phi_{\alpha_m})^{-1}\boldsymbol{a_m}(t) \tag{7}$$

where superscript m indicates measured degrees of freedom (DOF's). Then, the acceleration can be predicted at any inaccessible point of the structure as follows:

$$\boldsymbol{a_p}(t) = \Phi_{\alpha_p}\boldsymbol{q_m}(t) \tag{8}$$

where superscript p indicates predicted degrees of freedom (DOF's).

2.4. Prediction of dynamic strains

The combined use of operational acceleration data and strain mode shape components derived from a well-tuned FEM [9, 10, 14] allows for successful prediction of the dynamic strain responses at different levels along the height of the structure. The prediction is based upon a modal decomposition of the measured accelerations, $\boldsymbol{a_m}(t)$, that results in the estimation of the modal coordinates, $\boldsymbol{q_m}(t)$, according to (7). The relation between the modal coordinate and the strain in any arbitrary point is established by making use of the corresponding numerically obtained strain mode shapes with the following formula:

$$\boldsymbol{\varepsilon_p}(t) = \Phi_{\varepsilon_p}\boldsymbol{q_m}(t) \tag{9}$$

where superscript p indicates predicted degrees of freedom (DOF's), Φ_{ε_p} is the strain mode shape matrix that consists of the strain mode shape components of each acting mode at the inaccessible DOF of interest.

2.5. Quality indicators

The quality indicators utilized to compare the results of the predicted and the measured signals are discussed here. First is the Time Response Assurance Criterion (TRAC) [5] which is the correlation for one DOF over all time of the predicted response time domain signal ($\boldsymbol{g_p}(t)$) with the corresponding measured response time domain signal ($\boldsymbol{g_m}(t)$).

$$TRAC = \frac{\left[\boldsymbol{g_m}(t)^T\boldsymbol{g_p}(t)\right]^2}{\left[\boldsymbol{g_m}(t)^T\boldsymbol{g_m}(t)\right]\left[\boldsymbol{g_p}(t)^T\boldsymbol{g_p}(t)\right]} \tag{10}$$

Additionally, the frequency domain equivalent to the Time Response Assurance Criterion called the Frequency Response Assurance Criterion (FRAC) [14] is introduced. This is the correlation for one DOF over all frequencies of the predicted complex frequency domain signal ($\boldsymbol{g_p}(f)$) with the measured complex frequency domain signal ($\boldsymbol{g_m}(f)$).

$$FRAC = \frac{\left[|\boldsymbol{g_m}(f)^H \boldsymbol{g_p}(f)|\right]^2}{\left[\boldsymbol{g_m}(f)^H \boldsymbol{g_m}(f)\right]\left[\boldsymbol{g_p}(f)^H \boldsymbol{g_p}(f)\right]} \tag{11}$$

where $(.)^H$ denotes the Hermitian conjugate and $(.)^T$ denotes the transpose of the vector and $\boldsymbol{g_m}$ is the generalised measured response (acceleration $\boldsymbol{a_m}$ or strain $\boldsymbol{\varepsilon_m}$**)** and $\boldsymbol{g_p}$ is the generalised predicted response (acceleration $\boldsymbol{a_p}$ or strain $\boldsymbol{\varepsilon_p}$**)** respectively. The Mean Absolute Error in the time domain and the Mean Absolute Error of the Spectral Densities in the frequency domain are utilised too.

3. Offshore field measurements

The measurement campaign is 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. Measurements are taken at 4 levels on 9 locations using a total of 10 accelerometers. Eight accelerometers capture the vibrations in the X-Y direction and the two additional accelerometers are utilised to identify torsional vibrations in the tower. The locations are chosen based on the convenience of sensor mounting, such as the vicinity of platforms. The chosen levels are 69 m, 41 m, 27 m and 19 m above Lowest Astronomical Tide Level (LAT). On the level 19m LAT, 4 optical fiber Bragg strain sensors have been installed. On the level 41m LAT, 2 fiber brag strain sensors have been installed. Figure 2 gives an overview of the instrumented OWT with the corresponding measurement locations. For more information the reader is referred to [9, 10].

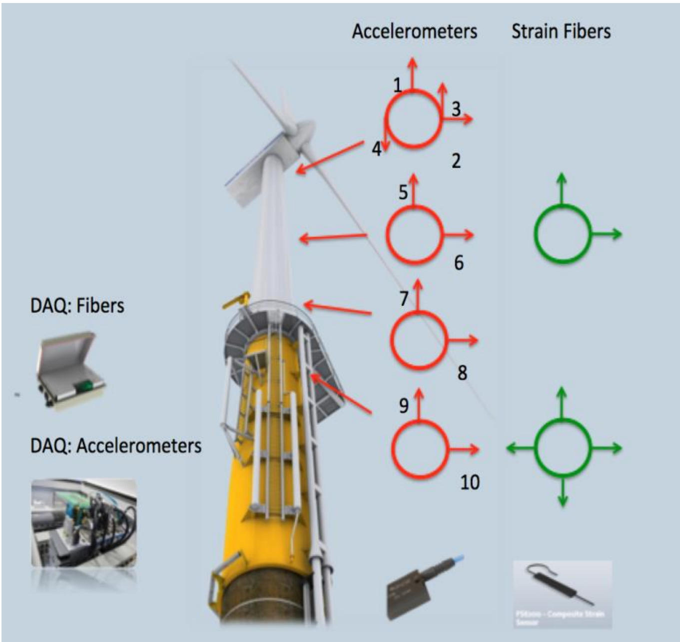

Figure 2. BBC01 OWT at Belwind farm with the instrumentation and the measurement locations.

4. Results

The acceleration time histories recorded at several locations of the structure are used in conjunction with a modal decomposition and expansion algorithm in order to compose a complete methodology for the prediction of vibrational accelerations and subsequently prediction of dynamic strains, as discussed in section 2. The results of the prediction of the dynamic strains in the time domain as well as in the frequency domain accompanied with the corresponding quality indicators are presented herein. As shown in figures 3-4, there is a great agreement between the measured and predicted dynamic strain time domain signal at both levels (+19m LAT and +41m LAT) under parked conditions of the OWT.

Journal of Physics: Conference Series **628** (2015) 012108 doi:10.1088/1742-6596/628/1/012108

Moreover there is high spectral coherence between the two signals. The qualitative good match indicated in the figures is quantified through the quality indicators (figure 6) which prove the high correlation in terms of amplitude, temporal evolution and frequency content between the measured and predicted signals (very high TRAC and FRAC indexes exceeding 0.975 for both cases and simultaneously low mean absolute errors).

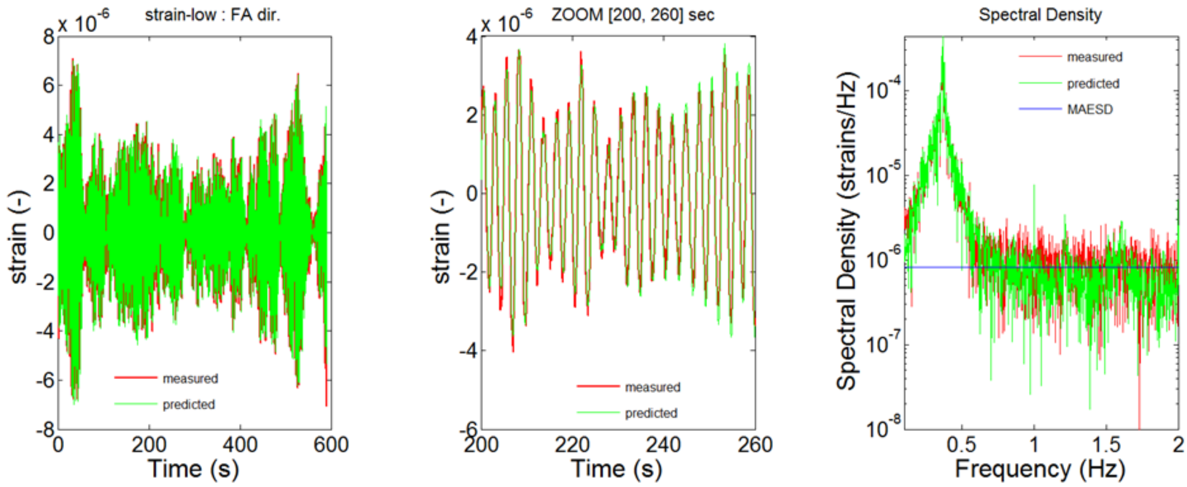

Figure 3. Comparison of the measured dynamic strain (red) at **19m LAT** and the predicted dynamic strain (green) in the FA direction under **parked** conditions of the OWT.

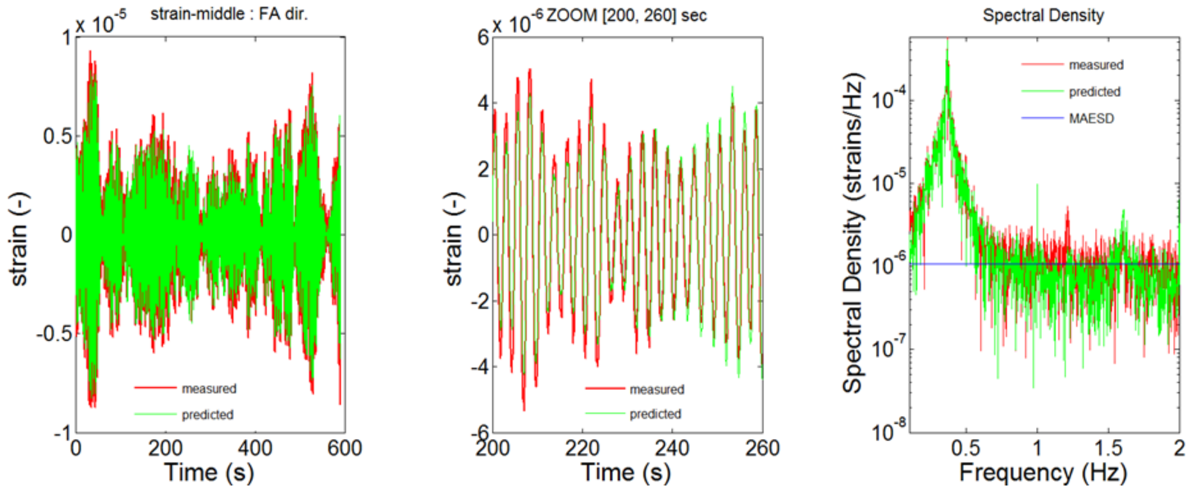

Figure 4. Comparison of the measured dynamic strain (red) at **41m LAT** and the predicted dynamic strain (green) in the FA direction under **parked** conditions of the OWT.

The prediction of dynamic strains is also shown for the case that the OWT is under normal rotating conditions in figure 5. According to this figure and the indicators in figure 6, it is worth stating that the prediction of dynamic strains under this type of loading remains a challenge with a good potential for further improvement of the quality indicators used to describe the correlation between the measured and predicted signals. The observed differences can be attributed to the non-optimally tuned Finite element model resulting in a mismatch between the experimentally obtained modal characteristics and the corresponding numerical used for the analysis. Moreover, changing operational and/or ambient conditions might be a possible source of difference.

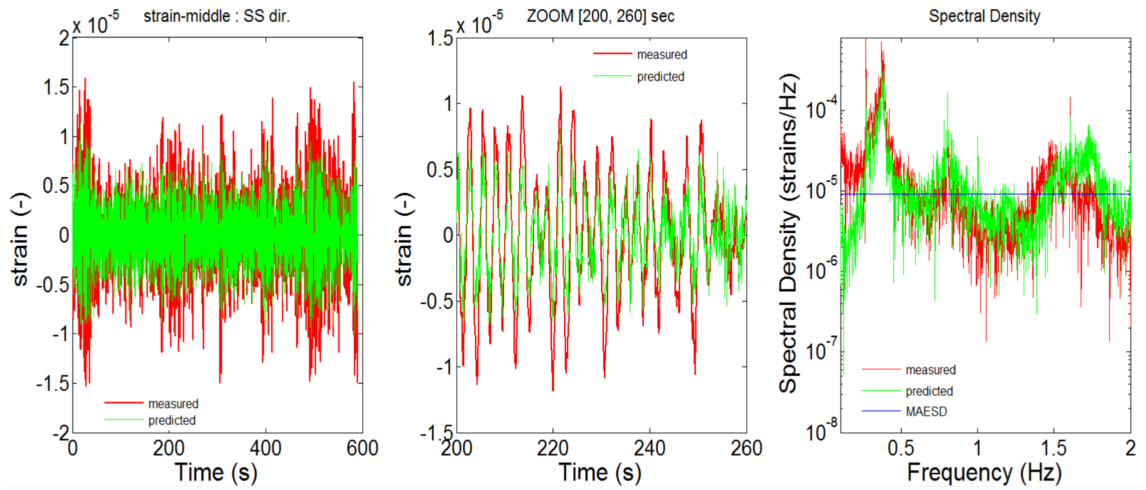

Figure 5. Comparison of the measured dynamic strain (red) at **41m LAT** and the predicted dynamic strain (green) in the SS direction under **rotating** conditions of the OWT.

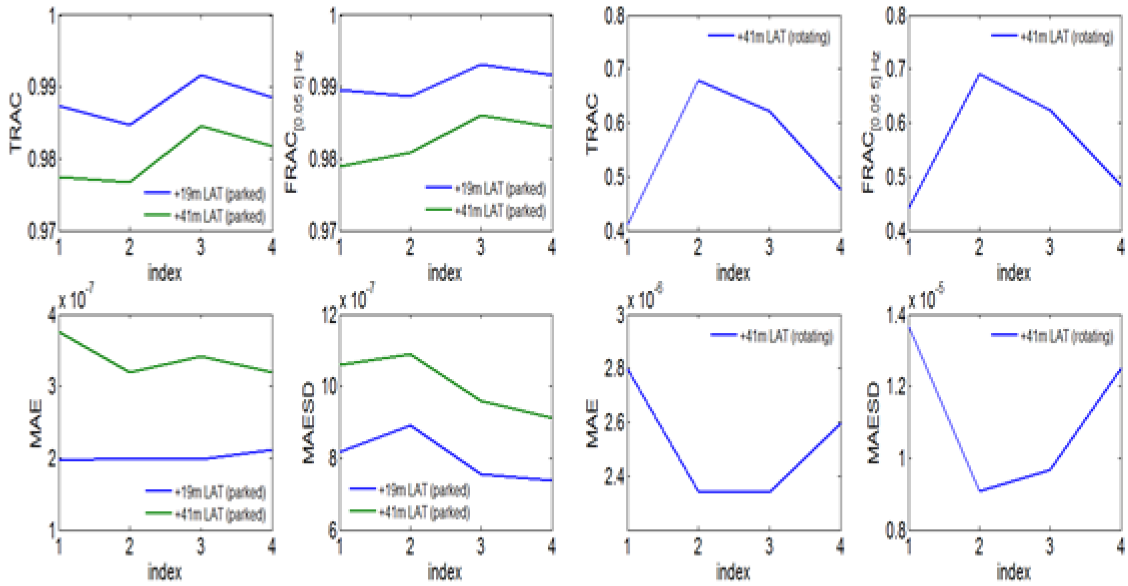

Figure 6. Quality indicators for 4 consecutive 10-min dynamic strain datasets (measured Vs predicted) for parked conditions (2 levels) and rotating conditions (1 level) of the OWT

5. Conclusion

This paper presents the results of a dynamic response prediction method applied on an offshore Vestas V90 3 MW wind turbine on a monopile foundation. The proposed method is based on a modal decomposition and expansion approach that is used to estimate the response at unmeasured locations by combining a limited set of acceleration response measurements and a Finite Element (FE) model. The method has proven to be fast, easy to implement, reliable and effective for the prediction of dynamic strain signals. The proposed algorithm and the virtual dynamic strains were evaluated and validated based on actual measurements obtained from a monitoring campaign on the examined OWT.

Acknowledgements
This research has been performed in the frame-work of the Offshore Wind Infrastructure Project (http://www.owi-lab.be) and the IWT SBO Project, OptiWind and the IWT O&O Parkwind project. The authors therefore acknowledge the financial support from the Agency for innovation by Science and Technology (IWT). The authors also gratefully thank the people of Belwind NV for their continuous support within this project.

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