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ONE YEAR OF CONTINUOUS DYNAMIC MONITORING OF A WIND TURBINE. STRUCTURAL INTEGRITY AND FATIGUE ASSESSMENT

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Abstract. *The paper presents recent results from a research project based on a continuous dynamic monitoring of a wind turbine. The monitoring system was developed with the capacity to detect structural abnormalities based on the continuous tracking of the modal properties of wind turbines (natural frequencies, modal damping ratios and mode shapes). In addition, the system is also capable to estimate the dynamic stress levels of the tower structure, in order to assess the damage condition and evaluate its remaining fatigue life.*
In the first part of the present paper, preliminary results from one year of continuous tracking of the modal properties of the wind turbine vibration modes are introduced. The main characteristics of the tracked modes are shown and the evolution of these modes with rotor rotation speed is characterized.
In a second part, the methodology followed to evaluate the stress condition of the wind turbine tower is introduced. This procedure is illustrated and validated with the help of a numerical analysis of a wind turbine, developed in the HAWC2 aeroelastic code.

1 INTRODUCTION

Wind power exploitation has shown a consistent growth both in onshore [1] and offshore installations [2], with increasingly competitive costs. This growth has been reflected in the installation of wind turbines composed by very flexible support structures and with large rotors. Due to these characteristics, wind turbines became very susceptible to vibration problems and, consequently, to fatigue damage problems.

This paper presents a continuous dynamic monitoring system, under development by the Laboratory of Vibrations and Structural Monitoring (ViBest, www.fe.up.pt/vibest) of FEUP, with the purpose of identifying structural changes (i.e. damage) and estimating the fatigue damage condition of a wind turbine. The system is based on the continuous tracking of modal properties of the structure (frequency values, modal damping ratios and mode shapes), identified during the different operating conditions of a wind turbine. The strategy adopted for the monitoring system has already proved to be suitable to be installed both in onshore and offshore wind turbines [3].

The modal identification of large structures excited by operational conditions, an approach usually named as Operational Modal Analysis (OMA), is a technique widely used in several applications [4]. Some examples of implementation of monitoring systems based on OMA in wind turbines are presented in [5, 6].

The assessment of fatigue condition through acceleration data records was already investigated by some researchers [7, 8]. However, in these works, the authors used the results from modal identification tests to tune a finite element model in order to estimate the stress condition of the structure.

This paper presents some results already achieved with the developed dynamic monitoring. Initially, the results obtained with the continuous tracking of the modal properties of the wind turbine during one year are presented. In the second part, an improved methodology to estimate the stress time history of the tower structure is presented, where only the acceleration data, alongside with a simple stiffness matrix of the tower, is used. This methodology is applied to a numerical example using the HAWC2 aeroelastic code [9].

2 DESCRIPTION OF THE STRUCTURE

The wind turbine under analysis is a 2.0 MW system with a variable-speed generator located at the north of Portugal. It has a hub height of 80 m and an up-wind rotor with a diameter of 80 m. Its support structure is composed by a concrete slab foundation and a steel tower. As usual, the tower is constituted by individual cylindrical segments which are connected to each other by flanged bolted connections.

The implemented dynamic monitoring system is composed by 9 uni-axial force-balanced accelerometers which are linked to a 24-bit digitizer and acquisition system. The sensors are located along the tower height according to Figure 1. Sensors S1 and S2 are not used in the modal identification and fatigue assessment process, since they are only used to evaluate the vibration levels at the foundation.

The monitoring system is configured to record acceleration time series of 10 minutes sampled at a rate of 50 Hz, and then decimated to 25 Hz. Alongside, the systems also uses the data recorded by the SCADA system. This system records the 10 minutes averaged values of several parameters such as rotor speed, yaw angle, wind speed and direction, temperature, among others.

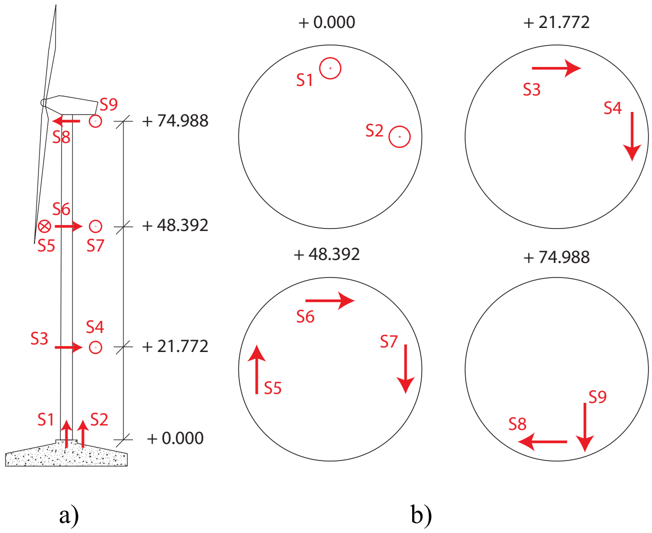


Figure 1: Position of the accelerometers at the different levels of the wind turbine: a) front view; b) top view at different sections

3 CONTINUOUS MODAL TRACKING

The results presented in this section are referred to the modal tracking of the wind turbine vibration modes during a period of analysis of one year. During this period, the wind turbine operated under several conditions. In order to cope with this variability of conditions, a strategy to automate the identification process was developed.

3.1 Strategy for automated processing

The strategy implemented for the continuous modal tracking of the turbine modal properties is composed by an initial pre-processing, where the signals are filtered and re-sampled. After this step, the modal properties of the structure are identified through the application of output-only system identification algorithms: SSI-COV [10] and SSI-DATA [11] (both in time domain); and p-LSCF [12] (in frequency domain). Usually, the results obtained with these algorithms are presented in the form of stabilization diagrams. These diagrams show the obtained poles with different model orders at the frequencies of suspected resonance peaks. Thus, if the properties of a pole (modal parameters) are kept constant, it is considered a stable pole and it is very likely to represent a physical pole, in opposition to a spurious one.

Lastly, a methodology for automatic identification of the modal parameters is used. This method is based on a hierarquical clustering algorithm, which tend to cluster poles that are related to the same physical mode [13]. The properties of the cluster are then compared to reference properties of the vibration modes intended to be tracked, in order to classify the cluster as the correct vibration mode.

Due to different operating conditions and, consequently, different structural configurations (e.g. pitch angle variations), 6 operating regimes were considered when defining the reference properties of the vibration modes. These regimes are presented in Table 1.

Operating regime	Wind turbine condition
1	Parked or idling (with high pitch angle)
2	Parked or idling (with lower pitch angle, in conditions to start operating)
3	Transition situation from non-operation to operation (mean value of rotor speed between 0 and the lowest operating rotor speed)
4	Operating situation, defined by the lowest operating rotor speed and the point where the pitch angle starts to increase to avoid excessive rotor torque values
5	Operating situation, between regime 4 and highest operating rotor speed
6	Wind speed higher than cut-out speed

Table 1: Operating regimes considered for reference modal properties of the vibration modes

3.2 Identified vibration modes

The analysis of the collected data clearly evidenced different vibration scenarios of the wind turbine support structure due to the different operating regimes. As an example, Figures 2 and 3 present the results from the modal identification obtained with two different situations. In Figure 2, the stabilization diagram from a non-operating situation, where the wind turbine is idling and the wind speed is low, is shown. In this case, the assumptions for application of OMA are practically fulfilled and the identification of the vibration modes is straightforward. On the other hand, in operating situations, these assumptions are not present [14] and the modal identification is considerably hindered. Figure 3 presents the results from an operating situation (regime 4), where the rotor is rotating at a mean velocity of 14 rpm. As can be seen, there are several resonance peaks that are not present in Figure 2. These peaks, identified as 1, 3, 6, 9 and 12P, are due to the harmonic excitation of the structure from the rotor rotation (where the rotation frequency is denoted as 1P). Although these resonance peaks are indicated as vibration modes from a raw analysis of the results from the modal identification algorithms, they should not be confused as such.

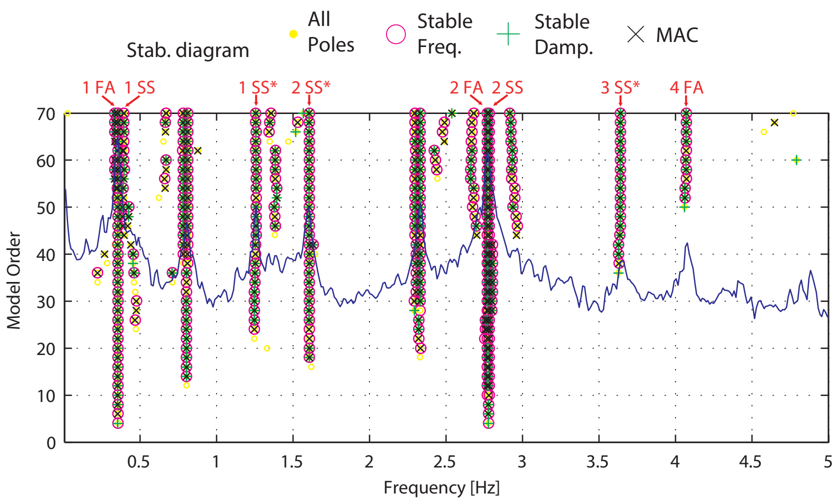


Figure 2: Stabilization diagram from a non-operating situation

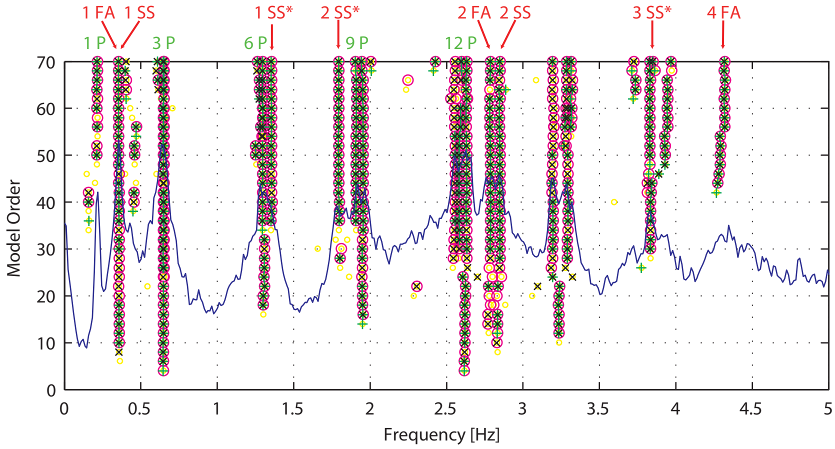


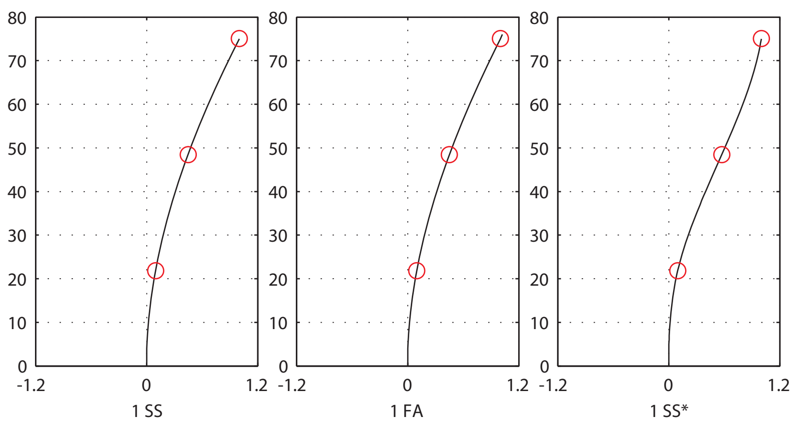
Figure 3: Stabilization diagram from a power production situation

From initial analysis of the data, some vibration modes were selected to be tracked. For this decision, the modes with the higher contribution to the vibration of the structure and with little interference from harmonics excitation were selected. From this analysis, it was decided to track 9 vibration modes within a frequency range of 0 – 4.5 Hz. The mean value of frequency of these modes is presented in Table 2. Although these modes include a support structure component in their mode shape, the modes identified with an asterisk ("*") have a significant rotor motion.

Vibration mode	*f* [Hz]
1 SS	0.355
1 FA	0.362
1 SS*	1.363
2 SS*	1.796
2 FA	2.801
2 SS	2.843
3 SS	3.700
3 SS*	3.813
4 FA	4.300

Table 2: Mean frequency value of the of the tracked vibration modes

The configurations of the modes are presented in Figure 4.



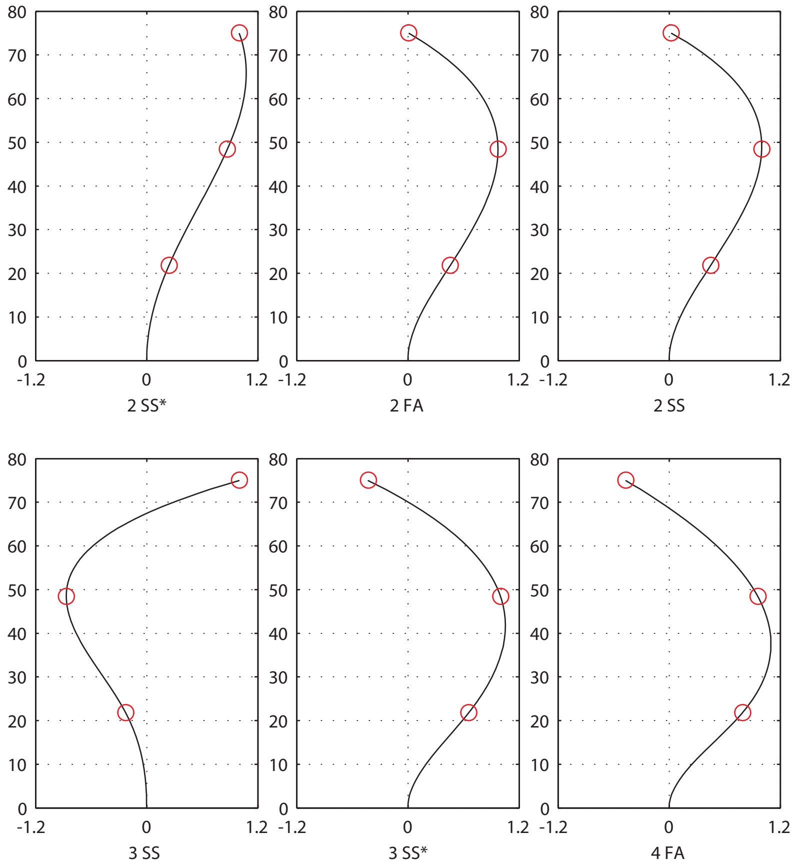


Figure 4: Mode shapes of the selected vibration modes

3.3 First monitoring results

The automated analysis of the data was processed according to the presented strategy. During the period of one year, the 9 selected vibration modes were successfully identified under various operating conditions of the wind turbine.

In order to illustrate the influence of the harmonic excitation in the identification of the vibration modes, Figure 5 shows a Campbell diagram of all identified clusters of stable poles, plotted according to the direction of vibration (FA or SS), where the diagonal dashed lines represents the harmonic frequencies of rotor rotation (multiples of 3P). The vertical dashed lines indicate the non-production situation, a transition state and the operating regimes from the wind turbine. As can be seen, the influence of the harmonics is clearly noticed, particularly from the 3P and 6P, with a large number of clusters around the diagonal dashed lines.

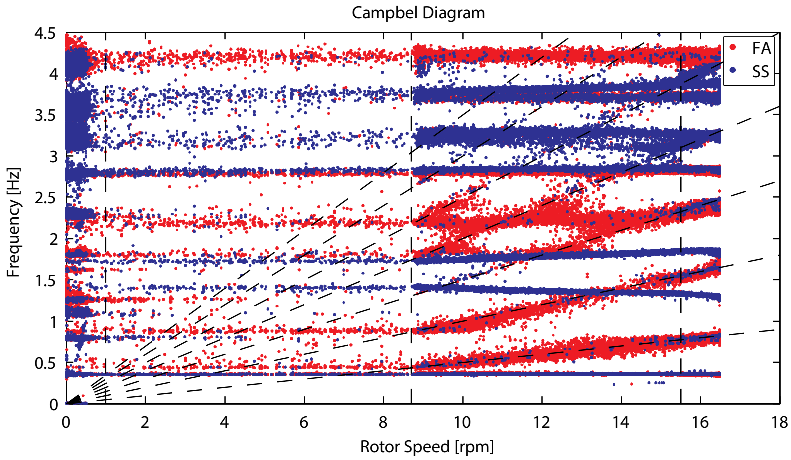


Figure 5: Campbell diagram of identified clusters of stable poles (including vibration modes and external sources of excitation)

Since the aim of the monitoring system is the identification of the modal properties of the wind turbine, an accurate definition of the reference properties from the selected vibration modes was performed. Figure 6 presents the results of the modal identification after comparison of the clusters properties with the reference values of each vibration mode. It is possible to attest the almost inexistence influence of the harmonic excitation.

One interesting phenomenon is observed in Figure 6. It is clearly visible that the frequency value of modes 1 SS*, 2 SS* and 3 SS* presents a clear dependency on the rotor rotation speed. This is a characteristic of rotor vibration modes that, when in operation, develops two whirl modes: one forward and one backward mode. From a non-rotating reference (like the one from the installed sensors on the tower), the frequency values of these modes tend to increase and decrease, respectively for the forward and backward mode, with the increase of the rotor speed.

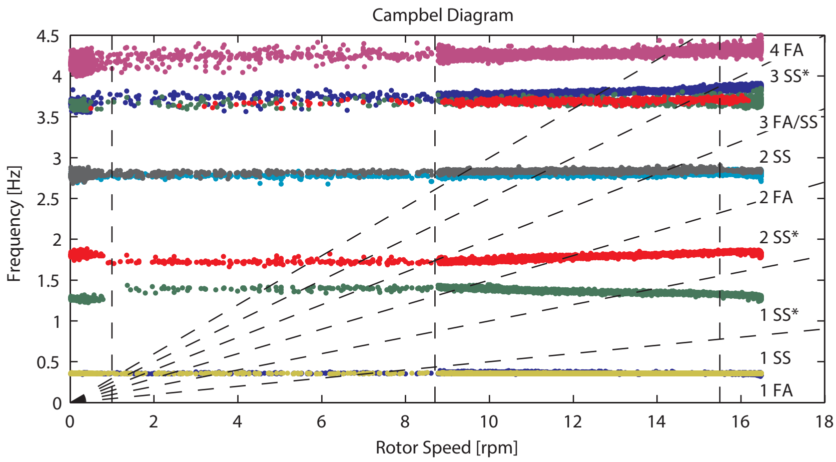


Figure 6: Campbell diagram of the tracked vibration modes

4 FATIGUE ASSESSMENT

The methodology adopted in this paper to assess the fatigue condition of the wind turbine tower is based on the decomposition of the acceleration data records in modal acceleration responses. After this step, the fatigue stress due to each vibration mode or stationary responses to harmonic excitations is computed. Finally, the real dynamic component of stress of the structure is obtained as the sum of every individual contribution.

The presented methodology is illustrated and validated with the help of a numerical example developed with the HAWC2 code.

4.1 Decomposition of the acceleration time series in modal acceleration responses

The decomposition of the acceleration time series into modal responses is based on the approach present in [10]. This starts with the computation of the state-space matrix A and the output-matrix C from the state-space model of the wind turbine (both obtained from the modal identification algorithms), and with the process and measurement noise covariance matrices Q, R and S (obtained as a post-process of the modal identification algorithms).

After the computation of these matrices, the Lyapunov equation is used to obtain Σ:

$$\Sigma = A\Sigma A^{T} + Q \tag{1}$$

where ^{T} represents the transpose operation. Then, the correlation and next-state output correlation matrices (R_0 and G) are computed:

$$R_0 = C\Sigma C^{T} + R \tag{2}$$

$$G = A\Sigma C^{T} + S \tag{3}$$

in order to solve the Riccati equation for P:

$$P = APA^{T} + (G - APC)^{T}(R_0 - CPC^{T})^{-1}(G - APC^{T})^{T} \tag{4}$$

Lastly, the Kalman gain (K) is calculated according to:

$$K = (G - APC^{T})(R_0 - CPC^{T})^{-1} \tag{5}$$

After the Kalman gain is computed, it is possible to define the identified model in a forward innovation model:

$$\begin{aligned} z_{k+1} &= A\, z_k + K\, e_k \\ \ddot{y}_k &= C\, z_k + e_k \end{aligned} \tag{6}$$

where e_k represents the white noise innovation sequence and $\ddot{y}_k$ is the acceleration recorded at k time step. Transforming equations (6) into modal basis equations:

$$\begin{aligned} z_{m,k+1} &= \Lambda_d\, z_{m,k} + K_m\, e_k \\ \ddot{y}_k &= V\, z_{m,k} + e_k \end{aligned} \tag{7}$$

where Ψ and Λ_d represents a matrix with the eigenvectors and a diagonal matrix with the eigenvalues of the state-space matrix and:

$$z_{m,k} = \Psi^{-1}\, z_k \tag{8}$$

$$K_m = \Psi^{-1}\, K \tag{9}$$

With the model of the equation (7), an estimation of the acceleration data can be reconstructed with the contribution of n modal responses:

$$\hat{\ddot{y}}_k = \sum_{i=1}^{n} \hat{\ddot{y}}_{k,i} = \sum_{i=1}^{n} V_i\, z_{m,k,i} \tag{10}$$

Since Λ_d is a diagonal matrix, equation (7) allows to decompose the measured acceleration time series into several acceleration time series with the contribution of vibration modes or stationary responses to external harmonic loads.

4.2 Modal fatigue stress

Considering that a reasonable number of accelerometers is available, the resolution of each mode shape (eigenvector) along the tower height can be increased through a cubic spline interpolation. With this step, it is possible to estimate the modal acceleration response at any point of the tower with equation (10).

At this point, it is necessary to integrate the modal acceleration response signal obtained into modal displacements. In this paper, the double integration of the acceleration time series in the frequency domain was performed:

$$\hat{Y}_{k,i} = -\frac{\hat{\ddot{Y}}_{k,i}}{\omega^2} \tag{11}$$

where $\hat{Y}$ represents the estimated displacements of the structure in the frequency domain.

Since the modal displacement field of the wind turbine tower has a sufficient characterization (due to the performed interpolation), equivalent forces imposing the same deformation, for each vibration mode, are calculated according to:

$$F_{k,i}(z) = K\,\hat{y}_{k,i}(z) \tag{12}$$

where z indicates the height of the wind turbine tower and K represents the stiffness matrix of the wind turbine tower. Since the tower structure can be assumed as a simple cantilevered beam, the matrix K can be constructed through simple methods, once the structural characteristics (variation of the bending stiffness along the height) are known.

After obtaining the equivalent forces for each vibration mode, the total dynamic component of the force is obtained as the sum of all modal contributions. The stress at any height of the tower can then be evaluated. Figure 7 illustrates the presented methodology.

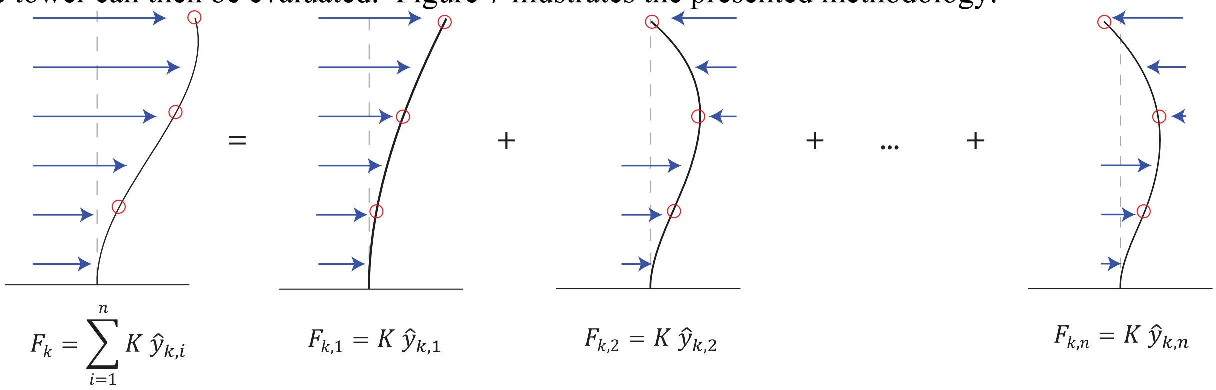


Figure 7: Illustration of the proposed methodology to estimate the dynamic forces along the tower height

4.3 Numerical model of the wind turbine

A numerical model of the studied 2.0 MW wind turbine has been developed using HAWC2 code [9]. HAWC2 is an aeroelastic code developed in Riso DTU, intended for calculating wind turbine response in time domain under aerodynamic loads. It uses the multibody formulation to model the wind turbine structure through beam elements with 6 degrees of freedom.

The aerodynamic model implemented in the HAWC2 code is based on the blade element theory. In the performed analysis, the effect of the tip loss and dynamic stall of the blades were included. Also, the tower shadow effect, due to disturbance of the flow created by the tower, was included.

The wind turbine tower structure was modelled according to the technical drawings made available by the manufacturer. However, since the characteristics of the nacelle and rotor were not provided, the characteristics from the NREL 5MW [15] reference wind turbine were scaled down to meet the characteristics of the desired wind turbine.

The model was then used to perform a 600 s time-domain analysis with a time resolution of 0.02 s. In the analysis, the wind turbine was subjected to a tridimensional turbulent wind flow field with a mean wind speed of 9 m/s. The time history of the wind speed at hub height is shown in Figure 8. During the analysis, the rotor speed varied between 16.2 and 17.8 rpm (Figure 9).

The same layout of sensors presented in Figure 1 was implemented to record the numerically simulated acceleration time series of the structure (although only the 3 sensors oriented in the FA direction were used in this work).

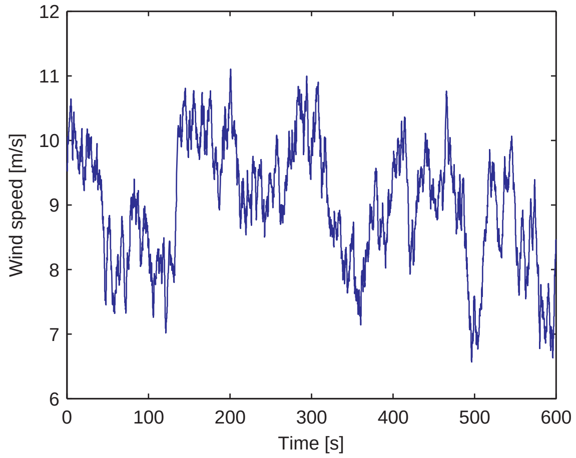


Figure 8: Wind speed at hub height

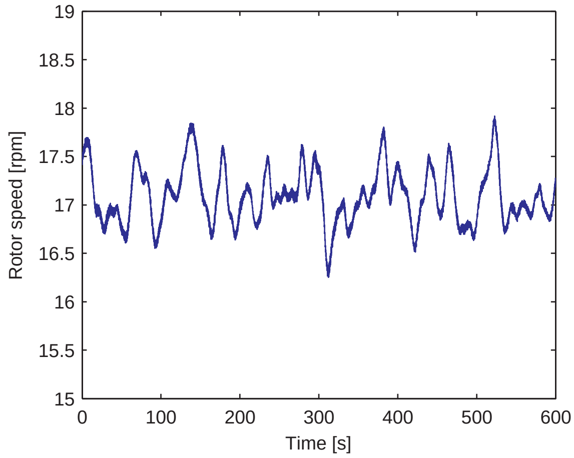
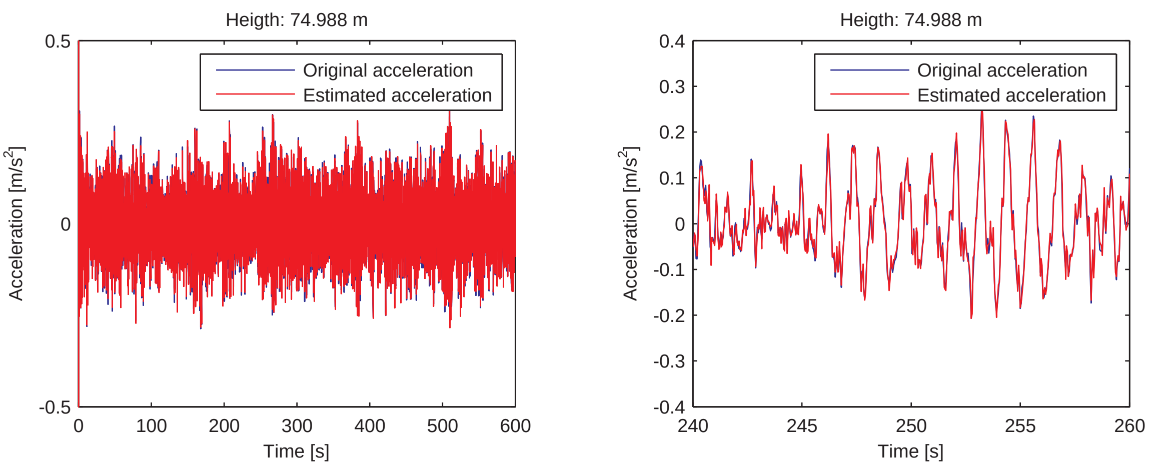


Figure 9: Rotor speed

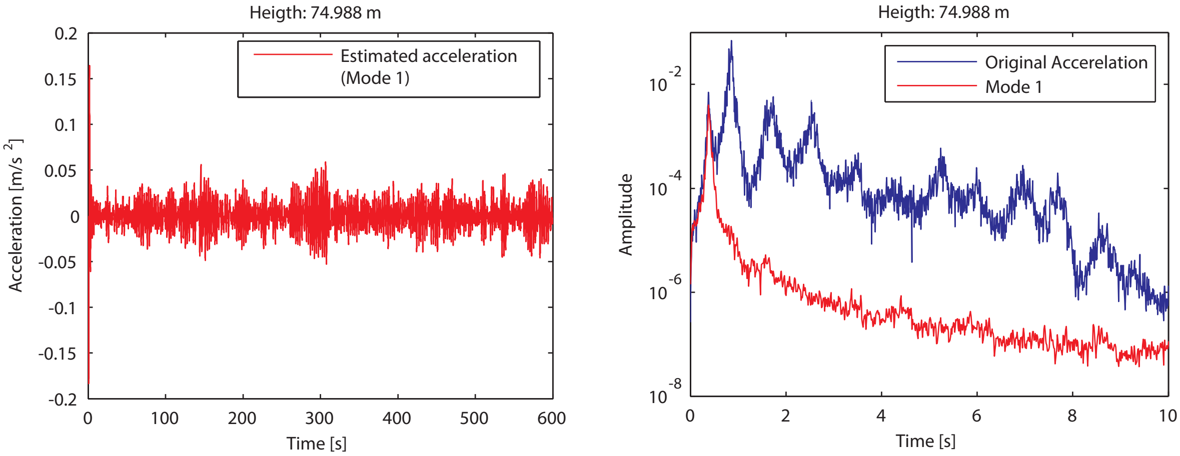
During the analysis, the SSI-DATA modal identification algorithm was used and the results obtained from the analysis were decimated to a sampling frequency of 25 Hz, to be consistent with the settings of the monitoring system. The acceleration time series "recorded" by the top sensor (height of 74.988 m) is presented in Figure 10 a), alongside with the estimated acceleration obtained as the contribution of all identified poles. Figure 11 b) shows a zoom for a period of 20 seconds where it is possible to attest the very good agreement between the two signals.



a) b)

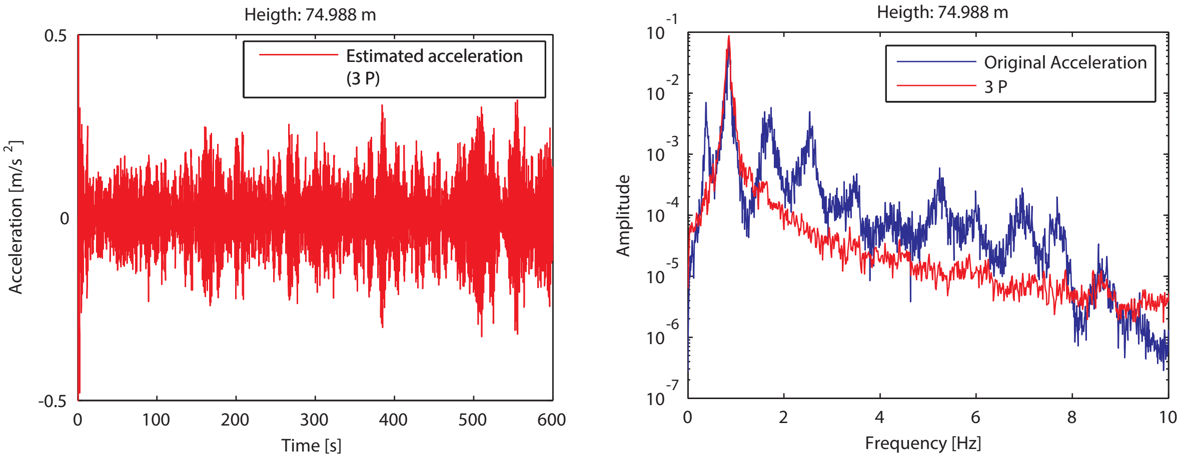
Figure 10: Estimated and recorded acceleration by the sensor: a) complete time series; and b) zoom of a period of 20 seconds

In order to illustrate the procedure presented in 4.1, the acceleration signal obtained for the first vibration mode of the wind turbine and due to the harmonic excitation of 3P is presented (in both time and frequency domain) in Figures 11 and 12, respectively.



a) b)

Figure 11: Estimated acceleration due to the 1st vibration mode in time domain a) and comparison with the recorded acceleration signal in frequency domain b)



a) b)

Figure 12: Estimated acceleration due to the harmonic excitation 3P in time domain a) and comparison with the recorded acceleration signal in frequency domain b)

After the estimation of the acceleration response time series for every vibration mode and harmonic excitation, it is possible to apply the procedure introduced in 4.2. Firstly, the displacement due to each mode and harmonic excitation is estimated. The displacements directly provided by the HAWC2 software (reference displacement) and estimated from simulated acceleration time series (estimated displacement) at the height of 74.988 m are shown in Figure 13. As can be seen, the agreement between the two signals is considerably good for the most important part of the spectrum. It is important to notice that, for very low frequencies (lower than 0.10 Hz), the signal coherence is not so good due to the frequency cut value chosen for the double integration process. However, this fact is not very important when trying to estimate the dynamic component of the displacements. Since standards, such as [16, 17], use an approach based on accumulated damage and S/N curves to estimate the fatigue damage of steel structural components, that does not consider the quasi-static component of the stresses, this fact has a very low influence in the estimation of the remaining fatigue life of the structure.

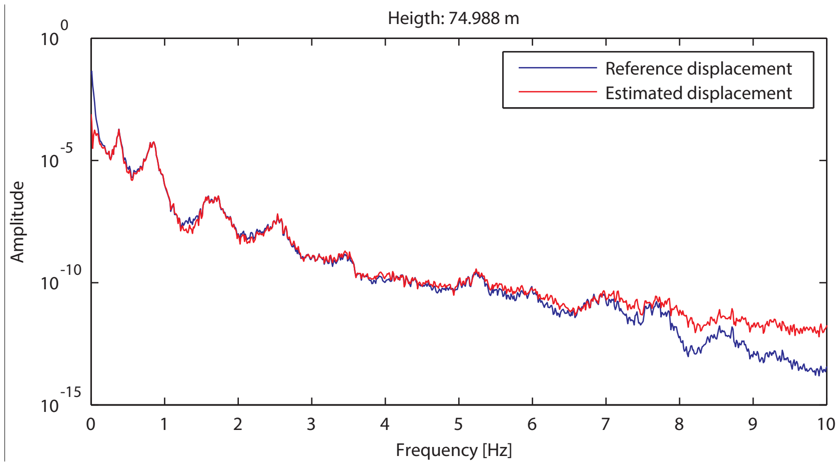


Figure 13: Comparison between reference and estimated displacement at height of 74.988 m

Lastly, after the equivalent forces are computed, it is possible to estimate the bending moment at the foundation level. The estimated bending moment at the foundation level is presented in Figure 14 and compared with the result directly obtained in the numerical analysis.

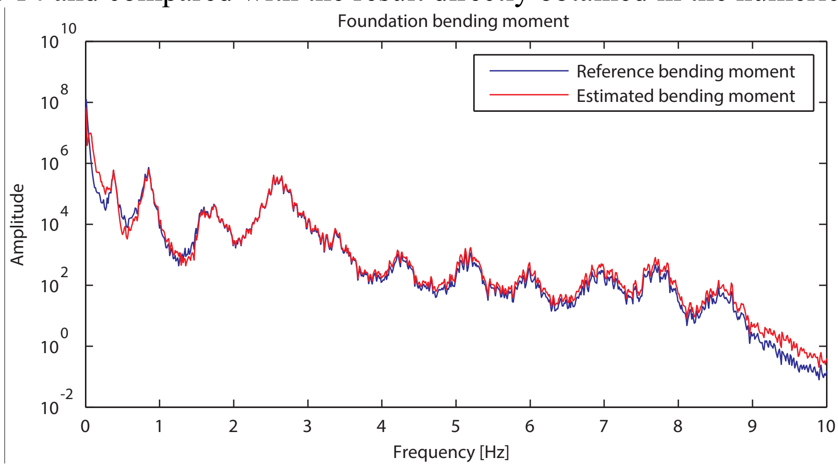


Figure 14: Comparison between the reference and estimated bending moment

In the context of the fatigue analysis, it is usual to use the Rainflow method to count the number of load cycles acting on the structure. This methodology followed in the standards despises the mean value of the stress (or bending moment) cycles for the fatigue analysis of steel towers. The comparison of the load cycles calculated using the bending moments directly obtained from the numerical analysis and the ones estimated from the simulated acceleration time series at the foundation level is presented in the histogram of the Figure 15. Once again, the histogram obtained with both signals is very similar, attesting the low influence of the simplifications adopted in the analysis.

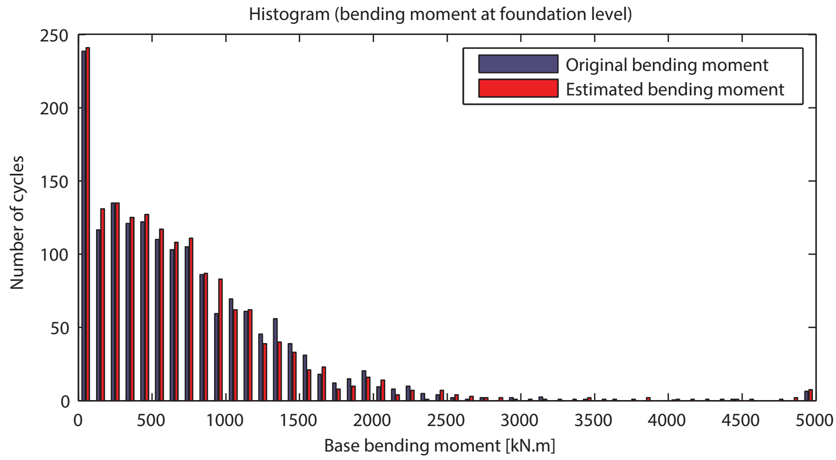


Figure 15: Histogram with the number of cycles from the original and estimated bending moment at the foundation level

5 CONCLUSIONS

The paper presents the work carried out up to the date in the development of a dynamic monitoring system for a 2.0 MW wind turbine system.

In the first part, the strategy for the automated continuous modal identification of the wind turbine is introduced and preliminary results are presented. In addition, the influence of the harmonic excitation in the vibration of the wind turbine is also illustrated.

The second part of the paper introduces a methodology to assess the fatigue stress of the wind turbine tower through the recorded acceleration data. In order to attest the suitability of the approach, a numerical analysis was used to illustrate the method. The good results achieved with the proposed methodology are a good indicator for the application of this approach in continuous processing of real acceleration time series.

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