Evaluation of low cost vibration based damage detection systems

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Abstract. This paper evaluates the results that can be obtained with different strategies of instrumentation for an utility-scale wind turbine, considering variations on the number of sensors, on their distribution in the wind turbine tower and on their noise level. With the goal of reducing the investment in monitoring equipment, layouts based on a reduced number of low cost sensors are tested. The data processing strategy is based on the continuous tracking of the wind turbine main vibration modes using Operational Modal Analysis techniques combined with algorithms that deal with the particularities of operation of the wind turbines and that permit an online automated identification. After the mitigation of the influence of the environmental and operation factors on the tracked natural frequencies, it is possible to detect abnormal variations of the natural frequencies, which might flag the appearance of damage. The alternative monitoring scenarios are recreated using a database of acceleration time series collected during one year in an onshore 2MW wind turbine, by a quite extensive monitoring system, using low noise accelerometers.

1. Introduction

This work is focused on the analysis of the results provided by vibration-based monitoring systems, suited for both onshore and offshore wind turbines, designed considering different budgets, which essentially depend on the numbers of sensors and on their noise levels. The implemented and applied data processing is based on Operational Modal Analysis (OMA) techniques and aims the identification of structural changes (i.e. damage) at an early stage. Within this system, the modal properties of the structure (natural frequencies, modal damping ratios and mode shapes) are evaluated throughout the different operating conditions of the wind turbine. By tracking abnormal variations of these properties, the occurrence of structural changes can be flagged.

This work uses a database collected by an extensive one-year monitoring campaign, based on 9 low noise and quite expensive accelerometers. The collected data is manipulated in order to recreate alternative less expensive monitoring systems, selecting a subset of sensors and adding noise to the measured acceleration time series, to simulate low cost MEMs type accelerometers. Four alternative layouts for the distribution of a varying number of accelerometers along the tower height are tested together with four noise levels for the sensors.

One of the goals of this contribution is to compare two alternatives for reduction of the monitoring system cost: one based on the reduction of the number of sensors and another based on the reduction of
the quality of the sensors. Another goal is to define the maximum level of noise that permits adequate results for current utility-scale wind turbines.

2. Instrumented Wind Turbine

The case study adopted for the illustration of alternative monitoring strategies is a 2.0 MW onshore wind turbine, with a rotor diameter of 82m and a tower height of 75m, located at the north of Portugal (Figure 1). Still, most of the conclusions should be valid for any modern utility-scale wind turbine.

The database used in the present study was collected by a dynamic monitoring system composed by 9 uni-axial force balance accelerometers, 7 distributed along 3 sections of the tower, as presented in Figure 1 and 2 placed in the tower foundation. It comprises acceleration time series of 10 minutes, continuously recorded during about one year with a sampling rate of 50 Hz [1]. This data is complemented with the information collected by the SCADA system of the wind turbine regarding the operational and environmental conditions: rotor speed, yaw angle, pitch of the blades, wind direction, wind speed and temperature.

![Figure 1. Wind turbine and distribution of the installed accelerometers.](image)

3. Methodology for data simulation and data processing

The data collected by the monitoring system described in the previous section is manipulated to recreate the four alternative layouts for the acceleration sensors summarized in Fig. 2, considering 4 levels of noise for each layout. Layouts 1 and 2 are just based on one bi-axial sensor, Layout 3 is based on two bi-axial sensors and Layout 4 is the most complete layout based on the original 7 acceleration channels installed in the tower.

The sensors adopted in the monitoring system installed in the wind turbine are force balance accelerometers, with prices typically higher than 1000€ and very low noise floors. As can be observed in the first power spectra of Figure 3, the spectral noise presents values lower than 1E-5 m/s^2/\sqrt{Hz}.

In order to replicate the records that would be produced by low cost MEM sensors four levels of noise were tested: the original noise level of the adopted sensors, and spectral noise levels N1 = 1E-3 m/s^2/\sqrt{Hz}, N2 = 1E-2 m/s^2/\sqrt{Hz} and N3 = 1E-1 m/s^2/\sqrt{Hz}. The higher level of simulated noise is a quite conservative upper bound, whereas the intermediate noise levels are representative of MEM sensors with costs around 100€ [2]. The noise was simulated adding band-limited white noise time series with different amplitudes (tuned according to the simulated spectral noise level) to the originally measured acceleration time series. Therefore, it is assumed that the spectral noise is constant in the frequency range under analysis.

Fig. 3 shows, for different wind velocities, the spectra of the acceleration time series associated with the tower top already contaminated with the previously described noise levels. It can be seen that for very low wind velocities, all the simulated noise levels are superior to the measured accelerations, but as soon as the wind velocity reaches values around 2.5 m/s the accelerations are already above the two first noise levels. The higher noise level is only overcame by the acceleration signal for quite high wind velocities (higher than 15 m/s).
The monitoring strategy is based on the continuous tracking of the modal parameters of the wind turbine structure (natural frequencies, damping ratios and mode shapes) over time. As damages are normally associated with stiffness reductions, abnormal reductions of the natural frequencies (evaluated in a statistical sense) are assumed as being motivated by damage. The monitoring system uses 10 min. acceleration signals and SCADA data (10 minutes averages) as inputs of the data processing algorithms.

Having in mind the early detection of damage, the following steps are performed: pre-processing of the acceleration times with application of filters, resampling and coordinate transformation to obtain signals that are always aligned to the fore-aft and side-side directions; automated modal analysis and modal tracking to obtain time series of the most relevant natural frequencies of the system foundation-tower-blades; minimization of the operational and environmental effects on the natural frequencies of the identified vibration modes, using the SCADA data; detection of damage using $T^2$ multivariate control charts, which are able to flag abnormal variations of the natural frequencies.
The quality of the results is very dependent on the accuracy of the routines used for automated modal analysis. The present paper adopts state-of-the-art routines developed in ViBest-FEUP [1]. In order to increase the success rates of the identification, each dataset is processed by three alternative identification algorithms: SSI-COV, SSI-DATA and p-LSCF [3]. The main results of these routines are presented in the following section.

4. Automated modal analysis results

The full instrumentation layout allowed the tracking of 9 vibration modes, including tower bending modes and rotor blades modes. Their mode shapes are represented in Figure 4. Since the blades were not instrumented, the classification of the modes as rotor modes is done considering their behaviour in different operation regimes of the turbine, as detailed in the following paragraph. These 9 modes were selected from a larger group of identified modes considering their importance on the dynamic response of the wind turbine and also the accuracy of the estimates provided by the identification algorithms in the different operating regimes of the wind turbine.

The evolution of vibration modes throughout the different operating regimes is usually presented in Campbell diagrams, where the identified natural frequencies are plotted against the rotor speed. Since the monitoring period covered about one year, the recorded database contains a significant number of datasets for all the relevant operation regimes of the instrumented wind turbine. Figure 5 shows some examples of Campbell diagrams associated with two of the tested layouts and noise levels. Other results can be found in [4, 5]. In the diagram associated with layout 4 without added noise it is clear that the modes labelled as rotor modes present relevant variations of the natural frequencies with the rotor speed. It was this behaviour that determined their classification as rotor modes. The first and second pair of the tower bending modes (1SS-1FA and 2SS-2FA) present very close natural frequencies, so in the presented Campbell diagrams they appear mixed in the same horizontal line.

![Mode shapes of the tracked vibration modes: SS - side-side; FA - for-after; SS* or FA* - modes where the contribution of the blades is important.]

Figure 4. Mode shapes of the tracked vibration modes: SS - side-side; FA - for-after; SS* or FA* - modes where the contribution of the blades is important.
The analysis of the plots in the first column of Figure 5 shows that even considering the more complete layout (Layout 4), for noise level N3, only the second pair of the tower bending modes can be reasonably tracked. So for the subsequent analyses this noise level is not considered. The analysis of the plots in the first row of the Figure shows that even with just one bi-axial sensor (Layout 2) it is possible to obtain a Campbell diagram with reasonable quality. If the quality of this sensor is decreased (Layout 2 N2), then the number of identified natural frequencies for lower RPM (lower wind and so lower vibration levels) significantly reduces.

![Figure 5. Campbell diagrams for Layouts 4 and 2 considering 2 noise levels. The vertical lines separate the non-production region, a transition region and two operating regimes. The diagonal dashed lines represent the harmonics associated with the rotor rotation. FA – mode perpendicular to the rotor plane; SS – mode in the rotor plane. The labels with the * represent blade modes.](image)

5. Simulated damage
In order to evaluate the ability of each alternative monitoring solution to detect the appearance of damage in the wind turbine structure at an early stage, three different damage scenarios are tested: one damage with more impact on the second pair of the tower bending modes (D1), another with more impact on the first pair of the tower bending modes (D2) and a third one affecting the blades (D3).

Damage scenario D1 can be associated with scour problems at the foundation of an offshore monopile wind turbine (the present case study is an onshore wind turbine but the natural frequencies present values that are similar to the ones found in offshore wind turbines [6]). A small scour depth around 0.075 times the base diameter of the monopole is considered. Taking into account references [7, 8], this damage corresponds to the frequency variations presented in Table 1. Damage scenario D2 can be explained by foundation problems in onshore wind turbines, related to the connection between the steel tower and the concrete foundation. It reproduces frequency variations in the tower bending modes that are 5 times smaller than the ones reported in the experimental study presented in [9]. The last damage scenario (D3) is related to a blade damage. The monitored wind turbine was modelled in the HAWC2 software [10] to assess the sensitivity of the natural frequencies of modes 1 SS* and 2 SS* to structural damage at the blades. The stiffness of the three blades was decreased 15 % over a length of 2 m (5 % of the total length of the blade) around 33 % of the chord length from the blade root. The imposed stiffness reductions led to the variations of the rotor mode frequencies reported in Table 1.

The monitoring database was split into two different periods, consisting each one of data from intercalary days. With this strategy, both periods contain results within a period of one year, but from different days. Period 1 was then used to define a multivariate regression model to minimize the influence of the operational (rotor speed and pitch) and environmental factors (ambient temperature), while Period 2 was used to assess the quality of the model and for testing the algorithm for damage
detection. It is considered that the damage associated to each scenario occurred at the middle of Period 2. The damage is simulated introducing small frequency shifts (as quantified in Table 1) in the natural frequencies time series estimated either from the original acceleration times or from the same acceleration time series corrupted with artificial noise. In other words, after the date assumed for the appearance of damage, the experimentally identified frequencies were decreased according to the percentages presented in Table 1.

Table 1. Variation of the natural frequencies associated with the tested damage scenarios

| Modes | D1  | D2  | D3  |
|-------|-----|-----|-----|
| 1 SS  | -0.20 | -0.50 | 0.00 |
| 1 FA  | -0.20 | -0.50 | 0.00 |
| 1 SS* | 0.00  | 0.00  | 0.65 |
| 2 SS* | 0.00  | 0.00  | -0.65 |
| 2 FA  | -0.40 | -0.24 | 0.00 |
| 2 SS  | -0.40 | 0.24  | 0.00 |

6. Damage Detection Results

The methodology implemented to detect the presence of damage is based on the construction of $T^2$ control charts. The residual error between the natural frequencies identified from the acceleration time series and the natural frequencies forecasted by the regression models trained with the reference datasets (Period 1 referred in the previous section) was used as input of the control charts. The results obtained for some of the evaluated layouts and noise levels are presented in Figure 6. In order to have clearer plots (with lower scatter) each points of the control chart is calculated from 36 datasets (equivalent to 6 hours of data). An upper limit was defined by considering that 95% of the values from the training period (Period 1) are considered within the safety region. In the presented diagram only the points associated with Period 2 are represented. It should be noted that some points over the control limit does not mean a structural change, without any damage we should expect 5% of the points to be above the limit.

The analysis of the first row of plots in Figure 6 shows that Layout 1 is not adequate for the detection of damage D1. This is easily explained by the fact that the modes that are more affected by this type of damage, 2FA and 2SS, are not well characterized by this layout, since the modal ordinates of these modes in the instrumented point are quite low (see Figures 2 and 4).

In all the other tested layouts and noise levels (N3 was excluded in a first step) the 3 damages could be identified, after the introduction of damage the majority of the points are above the control limit. This observation is very important, since it is shown that even with just one low cost bi-axial sensor (Layout2), if well placed, it is possible to successfully flag very small structural changes.

However, the reduction of the sensor quality and the reduction of the sensor number has a cost. The density of the points in the control charts is reduced. This happens because the number of datasets with a successful identification of all the modes under analysis decreases when the noise increases or the number of sensor decreases. So, for the same time period there are less results. This implies that more time is need to confidently identify the structural change.

The comparison of the control charts associated with Layout 4 N2 and Layout 2 without noise shows that the control charts associated with the latter present globally more points and after the introduction of damage the points are more clearly above the control line. This means that it seems preferably to use a lower number of well positioned good sensors that to use a larger number of lower quality sensors.
7. Conclusions

In a first instance the paper describes a processing methodology for vibration based damage detection and shows that it permits to automatically identify small structural changes. Then, it presents the results obtained with the simulation of alternative monitoring systems: varying the number of adopted sensors and their quality.

As a first important result, it is quantified the sensor noise above which it is not possible to adequately track the relevant modes a common utility-scale wind turbine. Afterwards, it is shown that acceptable results can be obtained with just one low cost well design MEM bi-axial sensor, if this is placed in an
adequate tower section. Still, it is also demonstrated that the reduction of the number of sensors and/or the reduction of their quality implies that more time is need to confidently identify a structural change. Finally, the obtained results indicate that it seems preferably to use a lower number of well positioned good sensors that to use a larger number of lower quality sensors.

The achieved results and the developed tools are very relevant to promote the use of dynamic monitoring systems in wind turbines and for the optimization of dynamic monitoring systems to be installed in these structures, permitting a more wisdom choice of the type of sensors to be adopted and of their distribution along the tower height.

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