AUTOMATED MODAL TRACKING IN A 2 MW ONSHORE WIND TURBINE

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ABSTRACT

This paper presents the strategy adopted to automatically track the variation of the modal parameters of an onshore wind turbine equipped with a dynamic monitoring system in operation for more than one year. The processing is based on state-of-the-art parametric operational modal analysis algorithms, such as SSI-COV, SSI-DATA and p-LSCF, that are combined with a cluster analysis that permits an automated interpretation of stabilization diagrams. The continuous tracking of natural frequencies and modal damping ratios of the wind turbine main vibration modes under distinct operating conditions permitted an accurate characterization of the influence of the wind velocity, yaw angle and rotor rotation speed on the dynamic behavior of the instrumented structure.

Keywords: Wind turbine, Automated Modal Analysis.

1. INTRODUCTION

Portugal’s electricity demand is covered in 24% by wind energy [1]. Therefore, the wind parks, essentially concentrate in the country mountainous regions, constitute an important infrastructure that should be carefully monitored and maintained. The installation of wind turbines in Portugal started 18 years ago and these structures were designed for a life time of 20 years. Therefore, in a near future it will be necessary to evaluate the need of replacement of wind turbine components. Furthermore, repowering operations are also being studied to better explore previous installations. In both cases structural monitoring is essential to take well-founded decisions.

Since wind turbines are flexible structures, whose structural performance is highly dependent on their dynamic behavior, monitoring should be focused on the dynamic response. This can be accomplished through the use of Operational Modal Analysis – OMA. As ambient excitation is always freely available and since the dynamic behavior is affected in the presence of structural anomalies, it is a technique that is suitable for continuous performance assessment.
Therefore, in the Laboratory of Vibration and Structural Monitoring, about two years ago, it was initiated a research project that aims the development of innovative experimental techniques and processing tools adequate for dynamic testing and continuous monitoring of the main structural components of a wind turbine: tower, foundation and blades.

At the present stage, one wind turbine is equipped with a dynamic monitoring system just based on accelerometers distributed along the tower height. In a second stage, a more complete dynamic monitoring system will be implemented. This will include also fiber optic strain gages in the blades roots [2] and sensors to permit the characterization of the tower static displacements and loads.

This experimental setup designed to be in continuous operation aims the:
- improvement of the knowledge on the dynamic behaviour of WT, especially focused on identification of the forces acting on the blades and tower and on the dynamic interaction between blades, tower and foundation;
- development of innovative monitoring software adequate to permanently check the structural health of the tower, blades and foundation, taking into account the automatic tracking of their modal parameters evolution;
- evaluation of the remaining life of the main structural components based on fatigue analysis supported by direct measurement of the curvatures with strain gages (in the blades) and by a virtual sensors approach, which takes profit from the results of the routines implemented for automated OMA;
- definition of the architecture of an optimized monitoring system.

The present paper briefly describes the present installation and some of the already obtained results, focusing on a very import feature of the monitoring system: the automatic tracking of the natural frequencies and modal damping ratios of the wind turbine most relevant modes.

2. WIND TURBINE AND MONITORING SYSTEM

The instrumented structure is a 2.0 MW onshore wind turbine located at the north of Portugal, with a variable-speed generator, a hub height of 80 m and an up-wind rotor with a diameter of 80 m. The rotor is supported by a steel tower, with a diameter that varies from 4.300 m (tower base) to 2.955 m (tower top), founded in a concrete slab.

![Figure 1. Position of the accelerometers at the different levels of the wind turbine:](image)
a) front view; b) zoom of a top view of the instrumented sections.

Before the installation of the monitoring system, it was performed an ambient vibration test in order to characterize the mains vibration modes of the structure and subsequently make a more founded selection of the sections to be instrumented. The results of this test are described in the proceedings of the previous IOMAC [3].
The installed monitoring system is composed by 9 uni-axial force-balanced accelerometers connected with a 24-bit digitizer that continuously produces data packages, which are then organized in text files by the local data acquisition software. The sensors are distributed along the tower height and at the foundation level, according to Figure 1.

The monitoring system is configured to record acceleration time series of 10 minutes with a sampling rate of 50 Hz. The system is complemented by the wind turbine SCADA system that characterizes the operational and environmental conditions, recording 10 minutes averaged values.

3. MONITORING SOFTWARE

The processing of the continuously collected data comprehends the following tasks: filtering and resampling to a reduce the sampling frequency to 25Hz, coordinate transformation to obtain the acceleration signals in the fore-after (perpendicular to the rotor plane) and side-side directions, characterization of the vibrations amplitude, automatic identification and tracking of the modal parameters, evaluation of the modal contribution of each mode to the observed structural response [4] and evaluation of stresses time series (from the acceleration time series) in critical sections to estimate remaining fatigue life time [5]. The present paper is essentially focused on the automatic identification and tracking of the modal parameters.

Pre-processing and characterisation of vibration amplitude

With the aim of minimizing the effects of the variation of the wind turbine geometry motivated the nacelle rotation (variation of the yaw angle), it is current practice to apply a coordinate transformation to the time series measured at the tower in order to obtain signals that are always aligned with two orthogonal horizontal directions: one perpendicular to rotor plane (FA) and another in the rotor plane (SS). This implies the use of the yaw angle provided by the SCADA system.

After this first step, it is possible to characterize the vibration amplitude along these principal directions. Figure 2 a) characterizes the variation of the RMS (root mean squared values) of the FA accelerations at three levels of the tower height with the wind speed. It is interesting to observe that the higher values do not occur at the tower top (+74.998 FA). Firstly, it should be stated that the acceleration measured at the tower height of 48.392m are highly influenced by the tower second bending mode (2FA in Figure 5), whereas the ones measured at the tower top are essentially influenced by the first mode, with a much lower natural frequency. Consequently, if dynamic displacements were measured, the highest values would most likely occur at the tower top. Anyway, the highest accelerations at the intermediate level are certainty due to the excitation introduced by the blade rotation, since the sensor at level +48.392 m is located in a position where the second bending mode of the tower presents its maximum ordinate and this mode is significantly excited by the rotor rotation.

Figure 2 b) presents the variation of the vibration amplitude at the tower top with the yaw angle, demonstrating that the vibration level is highly dependent on the rotor orientation which is conditioned by the wind direction. Two peaks are observed around 120º and 200-240º. These are motivated by higher wind speeds in these directions (justified by the terrain orography) but also by a not axisymmetric behaviour of the foundation, as can be concluded by the observation of Figure 2c), where the wind speed was limited to a narrow interval. It seems that the foundation is less stiff along the directions that are more excited by the wind.

Automated Operational Modal Analysis

The automatic identification of the wind turbine modal parameters is performed with three alternative algorithms: SSI-COV, SSI-DATA and p-LSCF [6], which are combined with a cluster algorithm to perform an automatic interpretation of the produced stabilization diagrams. A detailed description of this approach and of its theoretical background can be found in reference [7]. In the following paragraphs, its application is illustrated with some intermediate results of the processing of two representative datasets collected during very distinct operation conditions: one associated with parked
Figure 2. a) RMS values of acceleration in the for after direction vs rotor speed; b) RMS values of the acceleration in the top along the for-after direction vs yaw angle; c) RMS values of the acceleration in the top along the for-after direction vs yaw angle for wind speeds between 6 and 7 m/s.

Figure 3 shows the stabilization diagrams associated with the selected datasets provided by the SSI-COV method, including an averaged spectrum at the background. As expected, the spectrum and the stabilization diagram associated with the parked condition are clearer. Still, in the other stabilization diagram several vertical alignments of stable poles can be easily identified.

The automatic processing of the stabilization diagrams generated by the identification algorithms (the three tested methods produce similar stabilization diagrams) is accomplished with an algorithm based on the hierarchical clustering of the stabilization diagram poles, which groups the poles with similar natural frequencies and mode shapes [7]. For the setups under analysis, Figure 4 characterizes the created clusters by the average frequency of the poles included in each cluster and by the number of poles of each cluster. In the present application, at this stage, it was decided to exclude just the clusters with a very low number of poles (less than 6, as marked by the red dashed line). In the case of wind turbines, unlike in the case of bridges, due to the appearance of harmonics it is impossible to define a fixed number of clusters to be retained.

**Modal tracking**

In order to track the evolution of the modal properties of a particular mode and eliminate the clusters that do not represent modes with physical meaning, the representative properties of the selected clusters are compared with reference modal properties to select the cluster that represents the mode
under analysis. Since wind turbines are time-varying structures, with slightly different structural configurations according to the alternative operating situation, 6 operating regimes were considered when defining the reference properties of the vibration modes. These regimes are characterized in Table 1.

<table>
<thead>
<tr>
<th>Poles</th>
<th>Stab. freq</th>
<th>Stab. damp</th>
<th>Stab. MAC</th>
<th>ANPSD</th>
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</thead>
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<tr>
<td>0</td>
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<td>1</td>
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<td>2</td>
</tr>
<tr>
<td>2.5</td>
<td>3</td>
<td>3.5</td>
<td>4</td>
<td>4.5</td>
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</table>

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Model Order</th>
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<tr>
<td>0</td>
<td>0</td>
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<tr>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>1</td>
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![Stabilization diagrams](image1)

**Figure 3.** Stabilization diagrams.

![Characterization of the clusters](image2)

**Figure 4.** Characterization of the clusters: average frequency and number of poles included in each cluster.

A representative configuration of the vibration modes to be tracked is presented in Figure 5. Considering just the points instrumented in the tower, there are very similar configurations, but, as will be shown in the results section, some of the modes are significantly conditioned by the rotor behaviour (just indirectly characterized with the present monitoring system).

For each reference mode, from the clusters that present an average natural frequency that does not differ more than a predefined percentage value (from 10 to 20% depending on the mode type) from the reference natural frequency value, it is selected the one that presents the average mode shape with the highest correlation with the reference mode shape (evaluated with the MAC coefficient). Modes with MACs lower than 75% are not considered.
Table 1. Operating regimes considered for reference modal properties of the vibration modes

<table>
<thead>
<tr>
<th>Operating regime</th>
<th>Wind turbine condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Parked or idling (with high pitch angle)</td>
</tr>
<tr>
<td>2</td>
<td>Parked or idling (with lower pitch angle, in conditions to start operating)</td>
</tr>
<tr>
<td>3</td>
<td>Transition situation from non-operation to operation (mean value of rotor speed between 0 and the lowest operating rotor speed)</td>
</tr>
<tr>
<td>4</td>
<td>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</td>
</tr>
<tr>
<td>5</td>
<td>Operating situation, between regime 4 and the highest operating rotor speed</td>
</tr>
<tr>
<td>6</td>
<td>Wind speed higher than cut-out speed</td>
</tr>
</tbody>
</table>

Figure 5. 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.

4. MONITORING RESULTS

Figure 6 presents the selected clusters (before the tracking), in a Campbell diagram (frequency vs rotor rotation velocity in rpm), considering datasets collected during one year. In this figure, several alignments of clusters are clearly identified, corresponding to real vibration modes. However, it also shows some clusters located around the diagonal dashed lines (corresponding to the harmonics associated with the rotor rotation). These clusters, are only present when the turbine is in operation (rotor speed higher than 8.7 rpm), corresponding to poles motivated by the harmonic excitation.

After the tracking (comparison of the cluster properties with the reference properties of the vibration modes intended to be analysed), alignments of points associated with particular modes are obtained (Figure 7) and the influence of the harmonics is eliminated. In fact, in this particular application, this simple tracking procedure was adequate to eliminate the influence of the harmonics in the modes under analysis.
In Figure 7, some vibration modes present a clear dependency on the rotor rotation speed. These modes are identified with an asterisk (1 SS*, 2 SS* and 3 SS*). This behavior 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 8 characterizes the dependency of the modal damping ratios of the first bending modes in each direction (FA and SS) with the wind speed, presenting all the estimated values and boxplots with the evolution of the mean values and 25% and 75% quartiles. The observed values are in accordance with the results presented in [8]. It is clear that the damping values of the FA mode presents an important increase around a wind speed of 3 m/s. This situation corresponds to the cut-in wind speed of the turbine. Since this vibration mode has a large amplitude at the top of the tower and vibrates orthogonal to the rotor plane (and, consequently, in the direction of the wind when in operation), the aerodynamic damping has a large influence in this mode. It is also evident that, between 10 m/s and 13 m/s, the damping values present another steep increase. This fact is a consequence of the increase of the lift coefficient of the blades due to the start of the pitch angle mechanism around 10 m/s. At 13 m/s, the wind turbine reaches its rated power and its maximum thrust force at the tower top. From this wind speed, the aerodynamic damping tends to decrease as a consequence of the decreasing thrust force. The first SS mode presents much lower modal damping values and less dependent on the wind speed.
CONCLUSIONS

The paper describes the dynamic monitoring project of a 2.0 MW onshore wind turbine system, focusing the presentation on the automated tracking of the turbine modal properties. It is demonstrated that the implemented routines were able to automatically and accurately identify the modal properties of the most relevant vibration modes. Interesting patterns of variation of the frequency values and damping ratios of the relevant vibration modes throughout the various operating conditions are described and interpreted.

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REFERENCES


