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ABSTRACT

The research developed in this article, aimed to the structural monitoring of a telecommunication pole with a recently developed monitoring system, using radar IBIS-FS. This system comprises a radar which uses as working principle the interferometry technique. The main purpose of this work is to validate the results obtained from the radar and its comparison with numerical model of the corresponding telecommunication pole.

The present work describes a dynamic analysis of the structure under ambient vibration conditions, with the main goal of obtaining the natural frequencies and structural mode shapes. As a complement was still made a numerical structural computational model with the necessarily data for the geometric and mechanical characterization of the structure. With this model it was possible to carry out a modal analysis, in order to obtain a comparison of the frequencies of the vibration modes between the numerical model and the analysis performed using the radar IBIS-FS.

Keywords: Monitoring, structural dynamics, radar interferometry, telecommunication pole.

INTRODUCTION

The Structural Health Monitoring assumes an important and necessary task for the knowledge of real structures behaviour, which results in evaluation of safety and structural integrity, using monitoring systems that allow the detection of damage or degradation in monitored structures. Structural monitoring like other areas has been developed over the years, and recent developments allowed creation of a new monitoring technology that makes possible a non-intrusive and non-contact structural monitoring. This technology is based in radar principles, more specifically on reflection of electromagnetic waves and interferometric techniques, and its application is directed mainly to tower and bridge structures (but not only) as specified in the work and developments of previous authors and researchers, namely: (Pieraccini, 2007), (Pieraccini & Atzeni, 2009), (Gikas, 2012) and (Silva, 2015), among a few others.

This new radar system present many advantages over other monitoring systems, such as no need of placing sensors on the structure to be analysed, and the possibility of measuring static and dynamic deflections with sub-millimetric accuracy. These and other advantages that have been presented in detail (Silva, 2015) and outlined by works of his co-authors (Silva et al.; 2015-a , 2015-b) indicate that the interferometry radar IBIS-FS is a viable bet for the future of non-intrusive Structural Health Monitoring.
CHARACTERIZATION OF THE STRUCTURE

The present structure represented in Figure 1 is a steel tubular pole, also known as tubular mast, which has the functionality to support telecommunications antennas. This pole is located in the grounds of Metalogalva group company, and is located in Trofa (north of Portugal).

Fig. 1 - Telecommunication tubular pole

The tubular pole in steel class S275 is made up of 4 prismatic polygonal faceted trunks joined together by overlapping, with a gushing of approximately 16.5 mm/m (that induces such small inclination of the geometric generator side) and with a total height of 33.11 m. Figure 2 shows a schematic representation of the pole, with the 4 sections and overlapping joint links (A-B-C) and with a complementarity summary table of the characteristics of each section and link.

<table>
<thead>
<tr>
<th>Section</th>
<th>Lenght (m)</th>
<th>Thickness (mm)</th>
<th>First Diameter (mm)</th>
<th>Final Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.11</td>
<td>5</td>
<td>594,00</td>
<td>593,39</td>
</tr>
<tr>
<td>2</td>
<td>9.00</td>
<td>4</td>
<td>514,80</td>
<td>466,60</td>
</tr>
<tr>
<td>3</td>
<td>9.00</td>
<td>4</td>
<td>483,72</td>
<td>335,52</td>
</tr>
<tr>
<td>4</td>
<td>9.00</td>
<td>4</td>
<td>548,20</td>
<td>200,00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Link</th>
<th>Lenght (m)</th>
<th>Thickness (mm)</th>
<th>First Diameter (mm)</th>
<th>Final Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.30</td>
<td>5+4</td>
<td>514,80</td>
<td>593,39</td>
</tr>
<tr>
<td>B</td>
<td>1.04</td>
<td>4+4</td>
<td>483,72</td>
<td>466,60</td>
</tr>
<tr>
<td>C</td>
<td>0.77</td>
<td>4+4</td>
<td>348,20</td>
<td>335,52</td>
</tr>
</tbody>
</table>

Fig. 2 - Pole representation and characterization
The monitored pole still comprises auxiliary elements, such as an access ladder to the top, where exists a set of telecommunications antennas which together account for 90 kgf of additional weight. The ladder is fixed to the pole side and Figure 3 depicts the ladder detail and link elements.

DESCRIPTON OF THE MONITORING PLAN

The development of the monitoring plan took into account several factors, but the major one focused on the position of IBIS-FS radar. Due to the ladder position, the pole is not fully symmetric; on this account there are two principal structural vibration directions which affect the main vibration modes. In this plan were considered different monitoring directions for analysis to evaluate vibrations, which are represented in Figure 4 as Direction 1 and Direction 2. In the same figure are also represented the front views of the respective monitoring directions.
Figure 5 shows a schematic position (geometry) of the radar positioning towards the pole in direction 1 and direction 2. The geometry which characterizes this monitoring is set according to the parameters shown in (Silva, 2015) and (Silva et al. & Barros, 2015-a). The parameters values are shown in Table 1, for both directions.

![Fig. 5 - Schematic monitoring geometry for both directions](image_url)

Table 1 - Monitoring geometrical parameters for direction 1 and for direction 2

<table>
<thead>
<tr>
<th>Direction</th>
<th>x (m)</th>
<th>z (m)</th>
<th>c (m)</th>
<th>z (m) - c (m)</th>
<th>( \varphi ) (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.45</td>
<td>1.53</td>
<td>1.40</td>
<td>0.13</td>
<td>60°</td>
</tr>
<tr>
<td>2</td>
<td>29.30</td>
<td>1.53</td>
<td>1.40</td>
<td>0.13</td>
<td>45°</td>
</tr>
</tbody>
</table>

After defining the geometric parameters of the structure it is necessary to define the analysis parameters that influence the acquisition of data in the radar software system IBISDV (Silva, 2015). The analysis parameters to consider are:

- Maximum monitoring distance to consider (for large structures should be considered additional 20 m of the structure size);
- Range resolution (width of radial cells);
- Antenna type;
- Sampling Frequency;

The Table 2 shows the values of the analysis parameters (Silva, 2015) used in each of the monitoring directions.
With the definition of the parameters described above, data acquisition is only dependent on one factor: the monitoring acquisition time (Silva, 2015). As a rule-of-thumb for good use of IBIS-FS interferometry radar, each structural monitoring direction should have a measurement time from 1000 to 2000 times the structure fundamental period. In the beginning, the first period of the telecommunication pole was not known. So it was necessary to build previously a simplified numerical model; according to such model the first vibration mode was about 0.7 Hz, therefore the time of each monitoring should be at least 23 minutes 49 seconds. Were performed measurements in both directions, with approximately 30 minutes of monitoring period in each direction. However, for the day of observation, only the measurements during the second monitoring period were taken into account for data analysis. The exclusion of the measurements during the first monitoring period was justified with a great movement of vehicles inside the antenna beam-width during such measurements, causing major interferences in the acquired data which meant that they were not acceptable structural monitoring data for post-processing analysis of the structural reality.

EXPERIMENTAL RESULTS

The post-processing of the data obtained from monitoring was conducted by IBISDV program. The first step of post-processing is the selection of range bins (radial cells) that have better results (Silva, 2015).

Direction 1

The bins selection was performed according to the Peak-Picking Method and based in three factors (Silva, 2015) which are:

1. SNR<sub>e</sub> (Estimated Signal Noise Ratio) – select range bins with better signal results (corresponding to largest energy peaks), as shown in Figure 6;

2. Discrete phase of the complex signal of the radial cells – select and use the polar representation, according to the details in (Silva et al. & Barros, 2015-a);

3. Analysis of range bins displacement-time graph, as shown in Figure 7.

Figure 6 shows graph of range bin selection in direction 1, with a representation of the SNR<sub>e</sub> (dB) along the height of the structure (m).
The displacement graph shown in Figure 7 has the primary objective to demonstrate an in-phase displacement of all range bins selected and therefore correspond to the same structure (the same happens for all the cases presented afterwards). The time graph only corresponds to a time interval of the total temporal series. According to the selection factors of range bins, between the 107 bins created by IBIS-FS, only range bins 25, 28, 31, 34, 36, 40, 44, 45, 47 and 48 present acceptable data to characterize the structural behaviour.

**Direction 2**

The bins selection was performed according to the Peak-Picking Method and based on the three factors used for direction 1 and which are represented by Figures 8 and 9.
According to the selection factors of range bins, between the 107 bins created by IBIS-FS, only range bins 50, 52, 56, 57 and 58 present acceptable data to characterize the structural behaviour.
DATA ANALYSIS

The range bins selection in direction 1 proved to be easy and satisfactory because with a 20 minutes of observations it was possible to select ten bins with good data results. All selected range bins have a good signal (see energy peaks in Figure 6). In addition to these good results, the range bins show in-phase displacements as shown in Figure 7.

As a conclusion resulting from using the Fourier Transform, the velocity spectrum (Figure 10) was obtained in which it is possible to clearly identify the first two frequencies of structural modes in direction 1.

The first peak frequency value was 0.7 Hz, corresponding to the structure first vibration mode; the second peak frequency value was 2.64 Hz, corresponding to the structure third vibration mode.

The range bins selection in direction 2 proved to be more complex than in direction 1, because of monitoring external interference of several non-structural reflections from the movement of vehicles inside the monitoring area (an environment factor abnormal behavior). Due to this fact we only could identify five range bins with acceptable results, however only the top three (56, 57, 58) have good data results in terms of energy level and at the level of the range-bin complex discrete signal.

Figure 9 graph showed in-phase displacements of all selected range bins. Again using the Fourier Transform, the velocity spectrum (Figure 11) was obtained in which it is possible to clearly identify the first two frequencies of structural modes in direction 2. The first peak frequency value was 0.78 Hz, corresponding to the structure second vibration mode; the second peak frequency value was 3.2 Hz, corresponding to the structure fourth vibration mode.
NUMERICAL MODELING

The numerical model of the pole was made using the finite element software Robot Millennium Structural Analysis. The 4 prismatic polygonal faceted trunks were modeled with shell elements, the lateral ladder was modelled with standard beam elements, while the flange connection at the pole-foundation link was modelled also with shell elements. The telecommunication antennas were here considered as point masses at the top of the pole. Finally, Figure 12 shows the numerical model of the pole.

With such a numerical model of the pole was performed a modal analysis using Jacobi’s algorithm, without geometric non-linearity effects of axial forces (weights) of structural elements, where the first 4 frequencies of the structure and the respective modes were numerically and properly identified.

COMPARISON OF EXPERIMENTAL RESULTS WITH THE NUMERICAL MODEL

Table 3 shows the values of the monitored frequencies and frequencies obtained by the numerical model. Through a comparison between frequency groups was calculated the percentual error.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Experimental (Hz)</th>
<th>Numerical Model (Hz)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,70</td>
<td>0,69</td>
<td>1,4 %</td>
</tr>
<tr>
<td>2</td>
<td>0,78</td>
<td>0,79</td>
<td>1,3 %</td>
</tr>
<tr>
<td>3</td>
<td>2,64</td>
<td>2,64</td>
<td>0,1 %</td>
</tr>
<tr>
<td>4</td>
<td>3,20</td>
<td>3,12</td>
<td>2,5 %</td>
</tr>
</tbody>
</table>
Figure 12 - Numerical model of the pole used in Robot Millennium

Figure 13 shows the comparison between experimental and numerical vibration modes, done for the 1st and 3rd vibration modes which are the two main modes of direction 1. The 2nd and 4th vibration modes have not been compared graphically because there were no sufficient range bins (Silva, 2015) to allow accurate post-processing to perform comparisons between modes.
According to Table  and Fig. , it can be concluded that exists a very small (negligible) percentage error between the numerical model and the monitoring results by radar interferometry; more pronounced in the 1st vibration mode (1.4 % error) because the 3rd vibration mode has a value of percentage error around zero (which can also be seen in the 3rd mode shape graph, as shown in Fig. 3). In this study case the monitoring results obtained in different directions have different accuracies. The quality of results in direction 1 was better than in direction 2 because of the lower interference inside the structure surrounding scenario. Even with hard conditions in direction 2 surrounding scenario, it was possible to clearly identify the first 4 structure frequencies. However, it was only possible to clearly identify the structural deformed shapes along direction 1 and so clearly obtain the vibration modes (1st and 3rd).

As regards the comparison of the experimental results with the numerical model, the maximum error obtained was 2.5% in the 4th vibration mode. This error source is due to the difficulties presented in direction 2 of pole monitoring; but in general it is also necessary to take into account that a numerical model is only an approximation of the reality, both as regards to geometric and mechanical modeling and even to nonlinear behavior that the numerical model might not detect (if it would be considered as linear).

CONCLUSIONS
As stated in (Silva, 2015) and (Silva et al. & Barros, 2015-a, 2015-b) the Interferometric Radar IBIS-FS presents numerous advantages compared to current structural monitoring systems. Its main advantage is the possibility of structural monitoring without contact (non-intrusive) with the structure, and that resulted in a great advantage in this study case. It is also noted the great monitoring precision obtained with this type of technology, because the maximum error obtained was reduced (often negligible) when compared to a numerical model.
REFERENCES


