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OPERATIONAL MODAL ANALYSIS OF A FOOTBRIDGE

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Abstract. *The article describes the use of an automatic modal analysis system applied to a footbridge. The objective is to use the continuous monitoring data to perform an automatic analysis of the modal properties of the structure with the least possible human influence. In this work, the method chosen was the Data-Driven Stochastic Subspace Identification method. In order to clean the stabilization diagram, the Modal Phase Collinearity and Modal Assurance Criterion parameters applied to a MATLAB hierarchical clustering routine were used. The results show a good agreement of the first ten modes of the structure identified by the monitoring system and the finite element model for a 24-hour analysis of data, separated in 1-hour duration series.*

Keywords: *operational modal analysis, dynamics, vibrations, signal processing*

1. INTRODUCTION

According to Brincker and Ventura (2015), Operational Modal Analysis (OMA) can be defined as the engineering field that studies the modal properties of systems under ambient vibrations or normal operating conditions. It also provides useful methods for modal analysis of many areas of structural engineering. Identification of modal properties of a structural system is the process of correlating the dynamic characteristics of a mathematical model with the physical properties of the system derived from experimental measurements.

Rainieri and Fabbrocino (2014) report that Experimental Modal Analysis (EMA) has been applied in different fields, such as automotive engineering, aerospace engineering, industrial machinery, and civil engineering. The identification of the modal parameters by EMA techniques becomes more challenging in the case of civil engineering structures because of their large size and low frequency range. For this reason, the community of civil engineers has more recently focused the attention on the opportunities provided by Operational Modal Analysis. Since OMA requires only measurements of the dynamic response of the structure in operational conditions, when it is subjected to the ambient excitation, it is also known under different names, such as ambient vibration modal identification or output-only modal analysis.

The remarkable technological progress that recently occurred in the field of data acquisition systems and information transmission through the Internet made it feasible a continuous dynamic monitoring of the structural behavior. These systems can presently play a very important role in the understanding of the structural behavior either during the bridge construction or during the service lifetime (Cunha et al., 2013).

2. DYNAMIC MONITORING

OMA methods assumes that the excitation input can be idealized through a zero-mean Gaussian white noise, comprehending two main groups: nonparametric methods, essentially developed in the frequency domain, and parametric methods, most of them in the time domain (Cunha et al., 2018). One time domain method that allows direct application to the response time series is the data-driven stochastic subspace identification (SSI-DATA), whose detailed process can be found in Van Overschee and DeMoor (1996).

The structure analyzed in this work is a stress-ribbon footbridge (Figure 1) located at the engineering college of the University of Porto, in the city of Porto, Portugal. The bridge is formed by two continuous spans 28m and 30m long, rising 2m from the abutments to the intermediate pier. A continuous concrete cast-in-situ slab embedding four pre-stressing cables takes a catenary shape over the two spans, with a circular transition over the intermediate support, which is made of four steel pipes and forms an inverted pyramid hinged at the base. The constant cross-section of the deck is approximately rectangular with external design dimensions of 3.80 m x 0.15 m (Caetano et al., 2015). The monitoring system is detailed in Caetano et al. (2015).

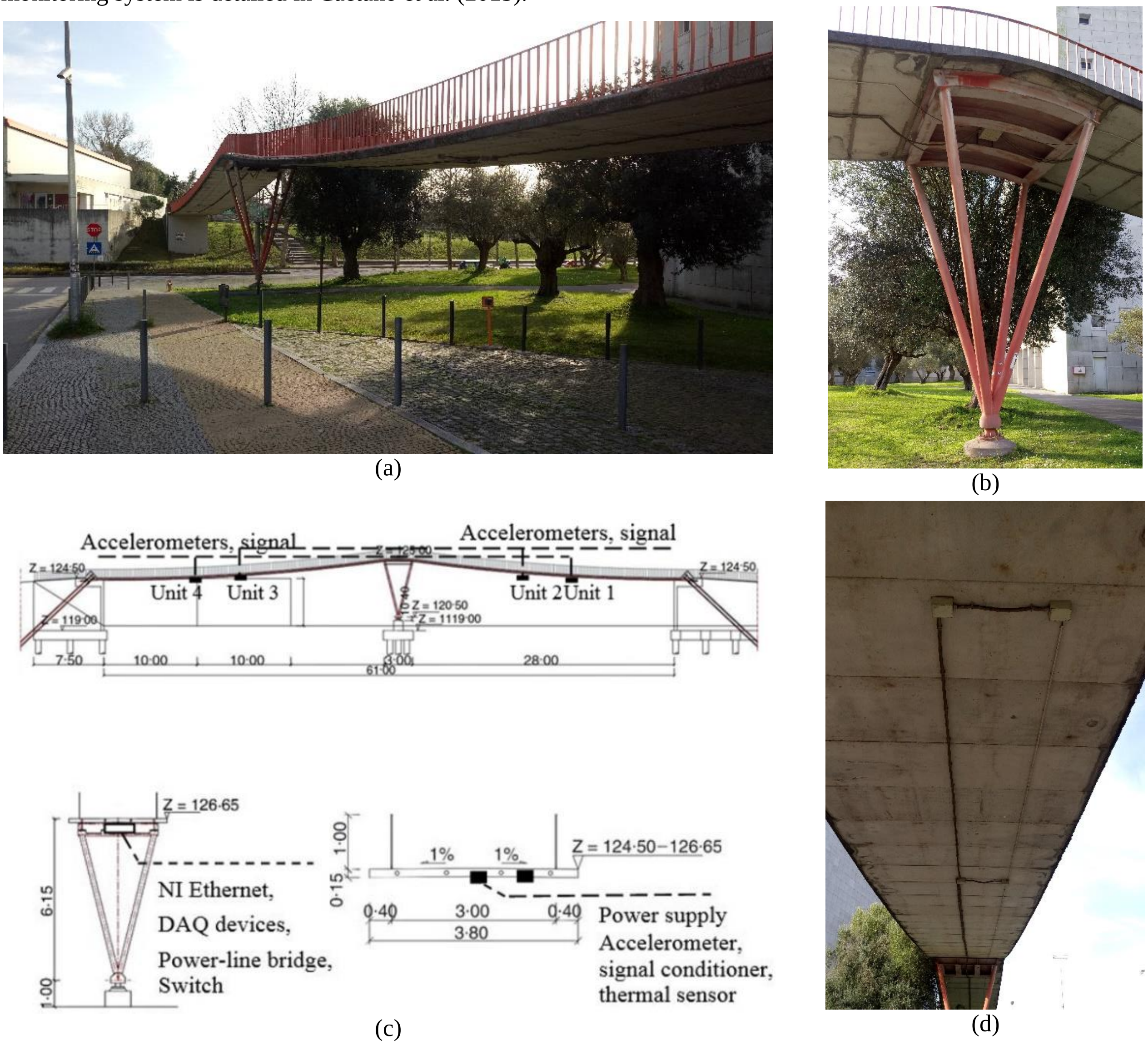

Figure 1 - Footbridge (a) overview of the structure; (b) intermediate support detail; (c) monitoring system layout; (d) monitoring system

The SSI DATA results are the modal properties of the structure (natural frequencies, damping ratios and vibration shapes). These properties are organized into stabilization diagrams, which contain the poles with the necessary information. In order to perform continuous monitoring, these diagrams must be interpreted automatically, and for this, some statistical resources were used.

•The first step of the process adopted was the application of the SSI DATA method in the matrix of signals obtained from the accelerometers, for the modal parameter identification. In this step, the parameters must be calibrated, varying the order of the system and the number of blocks of the matrix. The maximum order adopted was 300 and the minimum order was 150, the number of blocks was 100 (Figure 2).

•The second step was to carry out a cleaning of the stabilization diagram, for the removal of instable and irregular poles. In this work, the cleaning of the diagram was performed using damping ratio limits and Modal Phase Collinearity index. The damping ratio was limited to 5% and the negative coefficient poles were eliminated. Subsequently, because in modal testing the identified structural mode shapes are generally complex vectors, one modal validation criteria was used to evaluate the degree of complexity of the estimated mode shapes related to the identified poles, the Modal Phase Collinearity (MPC). The MPC is a correlation index that evaluates the linear relation between the real (Re) and imaginary (Im) part of the identified modal vector φr. If the imaginary part is strongly correlated to the real part, the MPC value is close to 1 indicating a mono-phase behaviour that is usually related to real normal modes (Cabboi et al., 2017). The minimum MPC adopted was 0.85. (Figure 3).

•In the third step was applied the statistical process of clustering, in which poles with similar properties are grouped into clusters. Clusters with more poles are considered as real modes and clusters with fewer poles are considered spurious and / or noisy. The user must define the cut line for the differentiation of these two types of clusters. In this process, was used the Modal Assurance Criterion, which is an index that compares two modal vectors (φ*1*, φ*2*) and ranges from 0 (orthogonal modes) to 1(when the modes only differ on a scale fator) (Magalhães, 2010). In this clustering was considered both frequency difference and MAC, and the sum of both indexes could not be greater than 0.05 for the poles to belong to the same cluster. The cut line used was 50 poles. (Figure 4 and Figure 5).

•In the last step this process was automated in a MATLAB routine and applied to 24-hour series of data (10.13.2018), to check if the developed system is able to identify the modes continuously. (Figure 6).

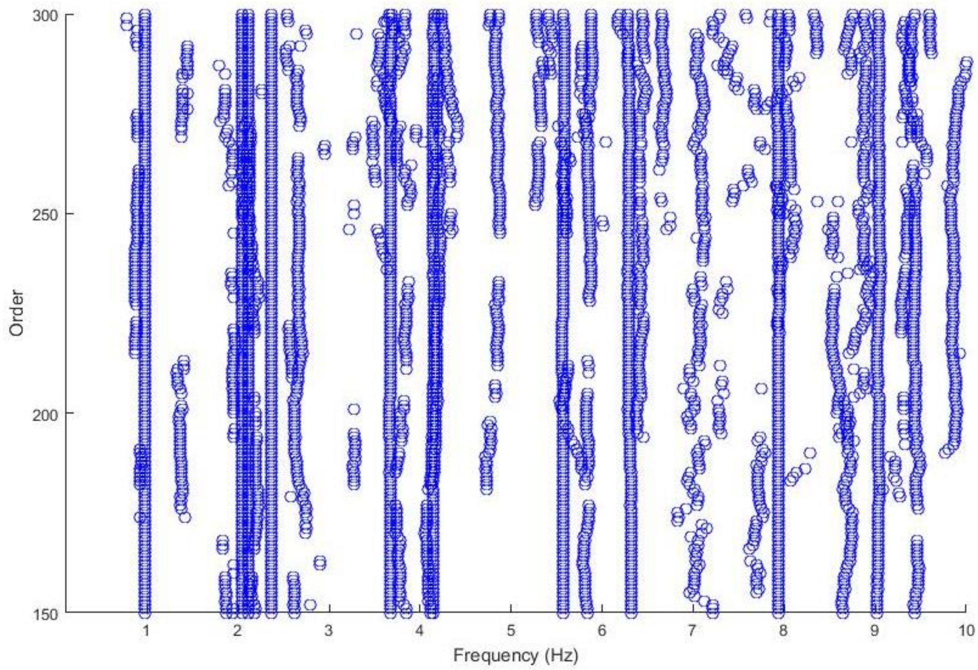

Figure 2 – Stabilization diagram in its original form

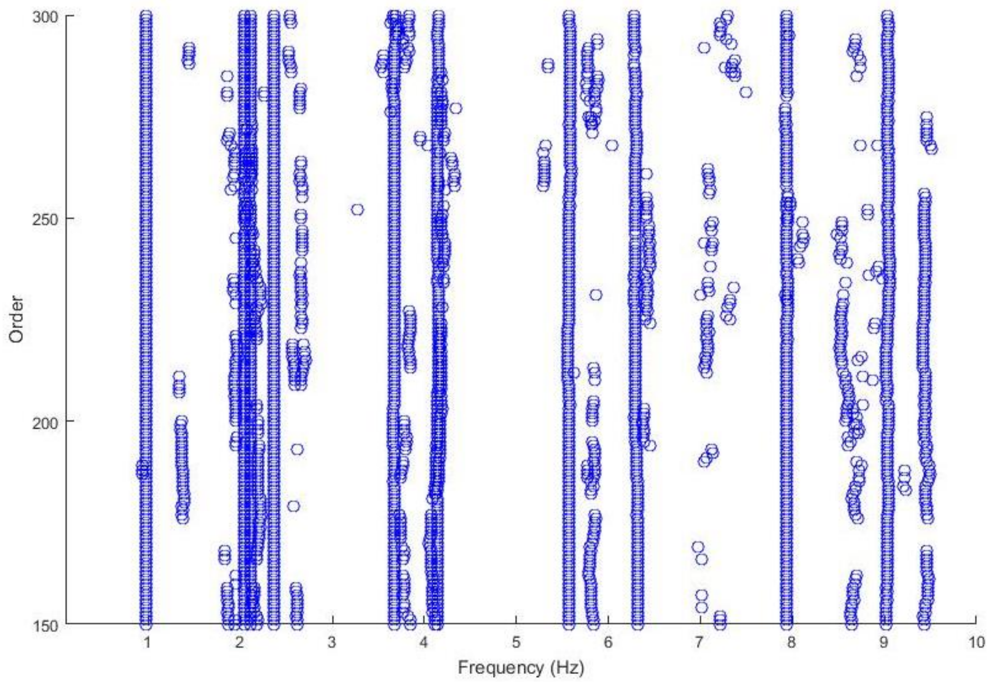

Figure 3 – Stabilization diagram after cleaning

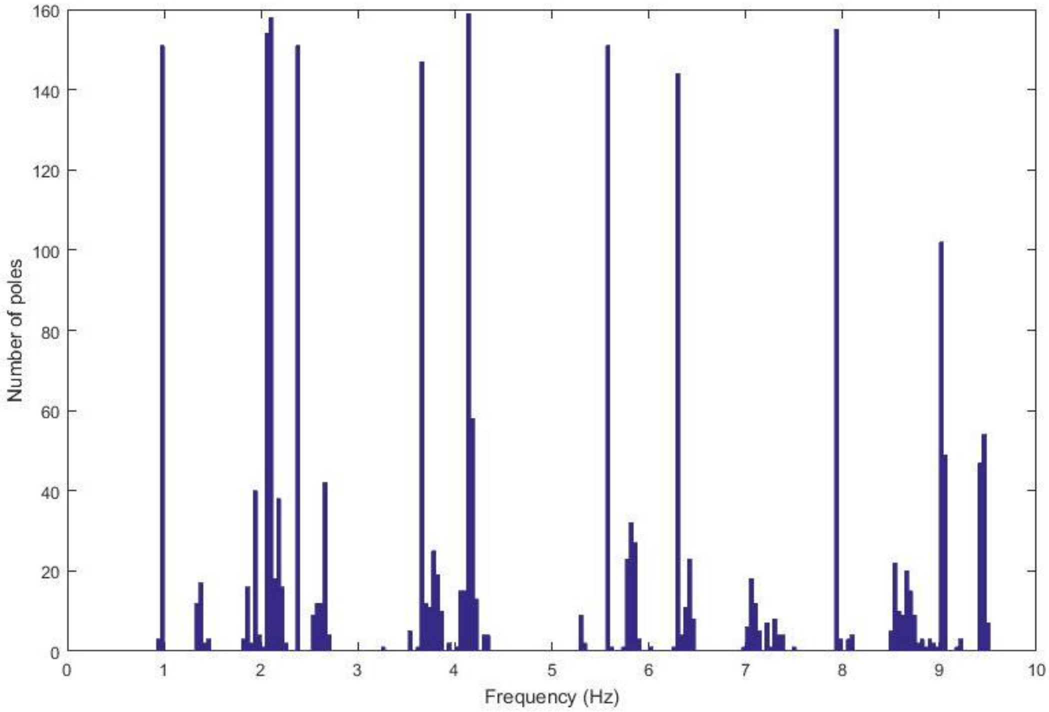

Figure 4 – Histogram with grouped poles;

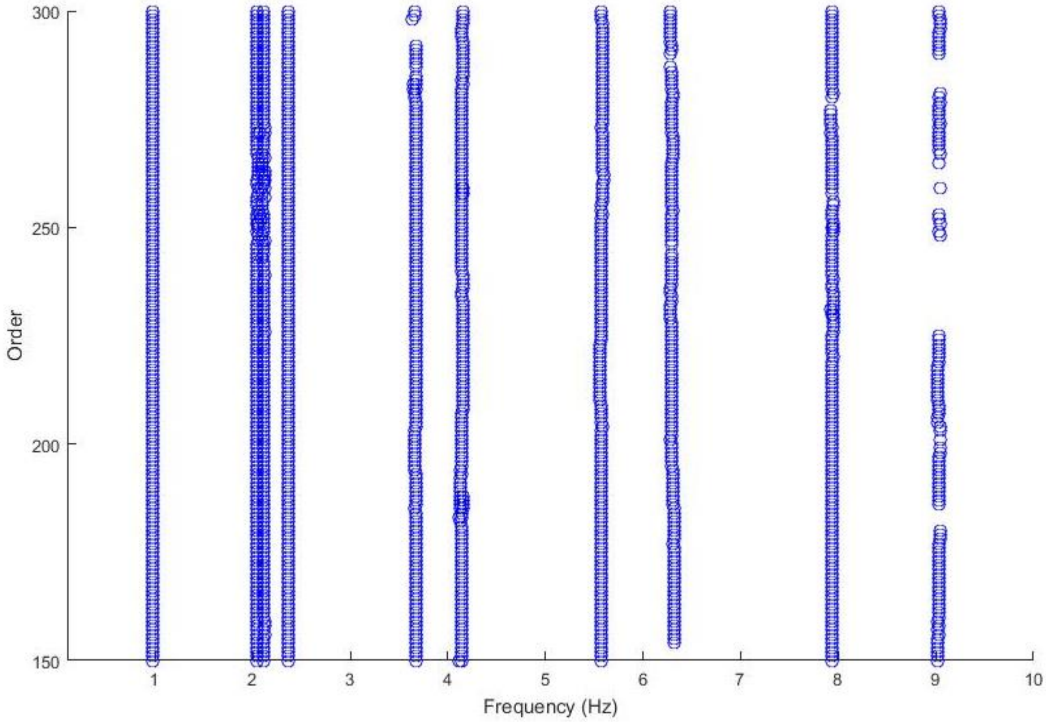

Figure 5 – Stabilization diagram with just the selected poles

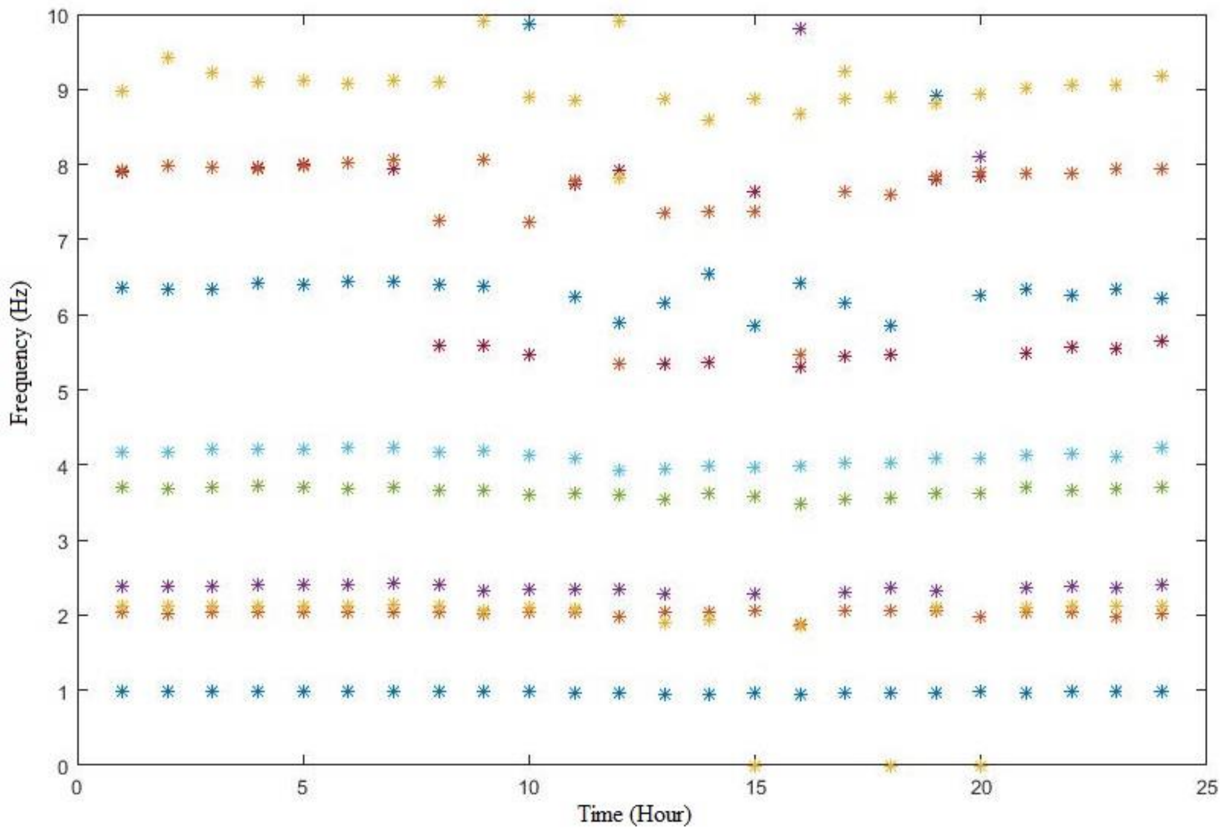

Figure 6 – Modal tracking of the structure during 24 hours

Figure 7 shows the curves of the first mode shape adjusted during all hours of the day. It can be noticed that there are only small variations between them.

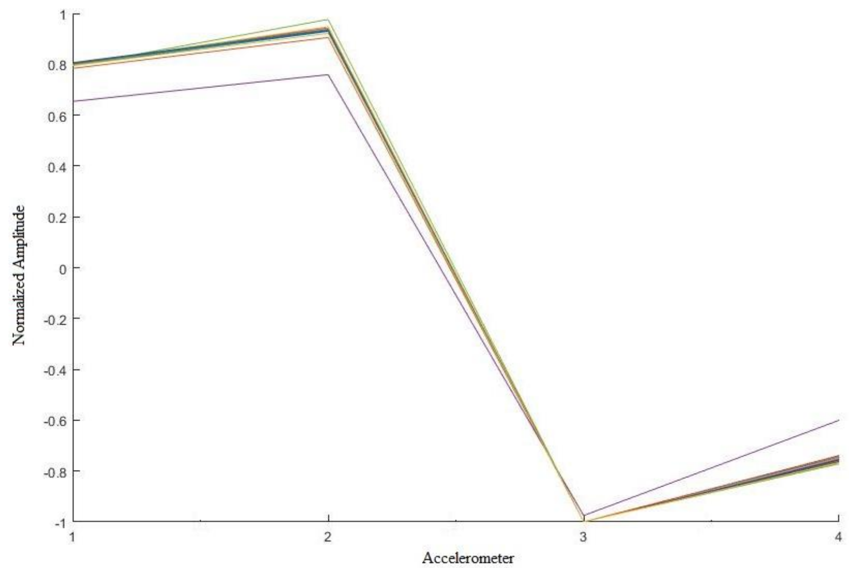

Figure 7 – First vibration mode variation during all day (24 hours)

The monitoring system, although with few sensors, was able to identify the natural frequencies of the structure and modal shapes with good agreement when compared to the finite element model. Figure 8 compares different OMA methods (enhanced frequency domain decomposition - EFDD; Poly-reference Least-Squares Complex Frequency Domain – pLSCF; Covariance-driven stochastic subspace identification method – COV and data-driven stochastic subspace identification – DATA) used for signal analysis with finite element model and the experimental data obtained by Hu (2011).

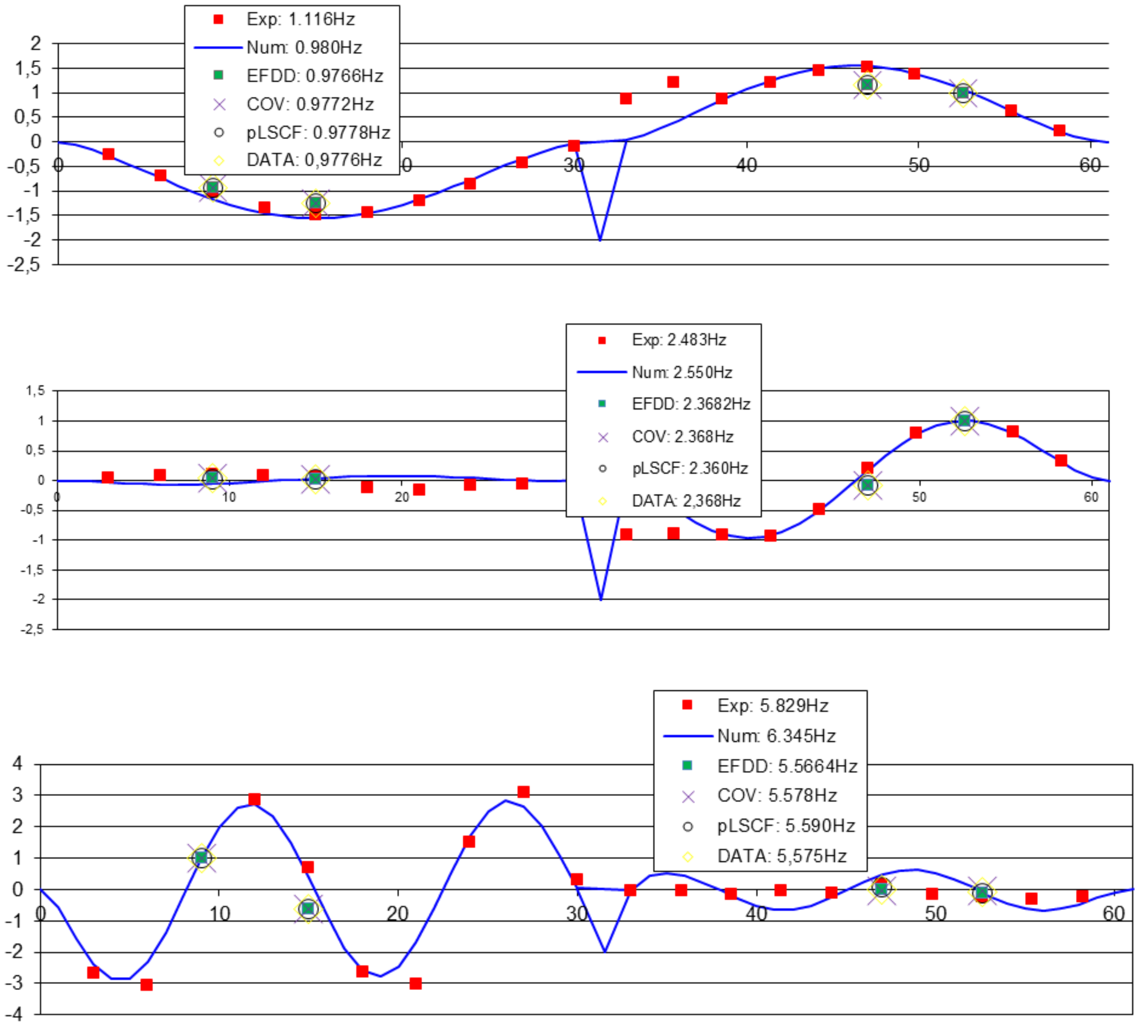

Figure 8 – First (above), fourth (center) and seventh (below) vibration modes at 21st hour of the day (X axis = position along the footbridge; Y axis = Modal amplitude)

Figure 9 shows the variation of the first and sixth natural frequencies of the structure with the variation of the temperature during all day. There is a clear relation between the temperature and the natural frequencies of the structure. When the temperature rises, the tendency is that the natural frequency falls, with, in this case, variation around almost 8%.

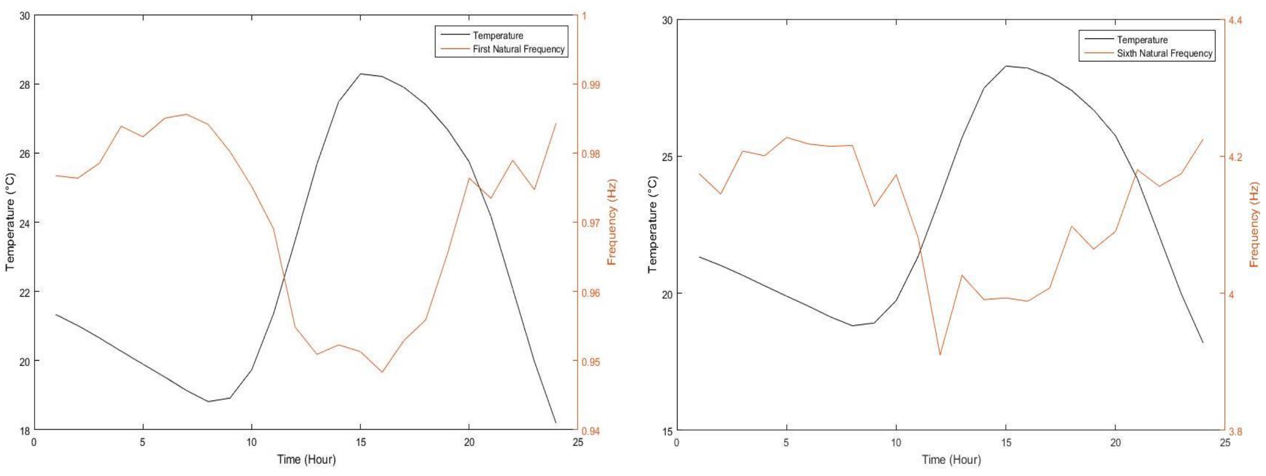

Figure 9 – First (left) and sixth (right) natural frequency variation with temperature

3. CONCLUSION

In this work, an automatic procedure is presented for modal analysis of structures. Analysis were performed using experimental data from a footbridge and taking into account the influence of the environment during the one-day (24-hour) period.

The procedure involved several steps: obtaining the stabilization diagram using the SSI-DATA method, cleaning the diagram considering the damping factor and MPC index, matching poles with similar characteristics through histogram and MAC number, and finally obtaining of the modal parameters (10 first vibration modes).

The operational modal parameters were compared with the numerical parameters obtained by the finite element method. It was noted that the temperature variation has a great influence on the natural frequencies of the system. It was also noted that there was great agreement between the numerical and experimental results. Although it was adjusted, the damping factor presented large fluctuations and was not compared with theoretical values and are not presented in this work.

The continuous monitoring system, although with few sensors, was able to identify the natural frequencies of the structure during the 24 hours with good agreement when compared to the finite element model. The used method (SSI-DATA) and the implemented clustering routine were effective when applied to this structure.

4. ACKNOWLEDGEMENTS

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6. RESPONSIBILITY NOTICE