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One-year Dynamic Monitoring of a Bridge: modal parameters tracking under the influence of environmental effects

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ABSTRACT: In order to evaluate the usefulness of approaches based on modal parameters tracking for Structural Health Monitoring of bridges, on September of 2007 a dynamic monitoring system with 12 accelerometers was installed on a concrete arch bridge that spans 280m over the Douro River at the city of Porto, in Portugal. This paper characterizes the bridge and its modal parameters (identified with an ambient vibration test), describes the monitoring hardware and the implemented software, reports the results obtained with the algorithms developed for the modal parameters automatic identification and characterizes the influence of the environmental temperature and traffic intensity on the identified modal parameters.

1 INTRODUCTION

The structural health monitoring of bridges based on dynamic measurement is a subject that has deserved an increasing interest, not only due to the recent technological developments that have contributed to the production of more powerful, economical and easy to install monitoring systems, but also because of improvements in data processing techniques and system identification algorithms. One of the possible approaches for the condition assessment of bridges using dynamic measurements is based on the tracking of the structure natural frequencies and subsequent elimination of the environmental effects (e.g. temperature), so that the remaining natural frequencies shifts can be correlated with stiffness reductions due to possible damages.

In order to show the potential and also the drawbacks of this approach, a monitoring project of a long span concrete arch bridge was started. This project comprehends five main phases: (i) numerical modelling and ambient vibration test to characterize the dynamic behaviour of the bridge and better design the monitoring system, (ii) installation of the monitoring equipment, (iii) development of software to retrieve from the bridge to FEUP the data series continuously generated and to perform the on-line automatic identification of the bridge modal parameters, (iv) study of the modal parameters variations during one year to obtain numerical models to eliminate the effect of environmental variables, and finally, (v) evaluation of the type of anomalies that are detectable with the installed monitoring system.

This paper characterizes the bridge and its modal parameters (identified with the developed

ambient vibration test), describes the monitoring hardware and the implemented software, reports the results obtained with the algorithms developed for the modal parameters automatic identification and characterizes the influence of the environmental temperature and traffic intensity on the identified modal parameters. The precision achieved in the continuous identification of several natural frequencies of the instrumented structure is already very promising and the contribution of such monitoring systems to a better understanding of bridges behaviour is shown in this paper.

2 THE "INFANTE D. HENRIQUE" BRIDGE

2.1 Geometric characteristics

The "Infante D. Henrique" Bridge, over the Douro River, was open to traffic in 2004 to link the cities of Porto and Gaia, located at the north of Portugal.

The bridge is composed of a very rigid prestressed concrete box beam, 4.50 m deep, supported by an extremely shallow and thin reinforced concrete arch, 1.50 m thick (Figure 1). The arch spans 280 m between abutments and rises 25 m until the crown, thus exhibiting a shallowness ratio greater than 11/1. In the 70 m central segment, arch and deck join to define a box girder 6 m deep. The arch has constant thickness and its width increases linearly from 10 m in the central span up to 20 m at the springs (Adão da Fonseca and Millanes Mato (2005)). Owing to the high stiffness of the deck in relation to the slenderness of the arch, the structure behaves as a beam bridge defined between abutments, with intermediate elastic supports 35 m apart, materialized by the vertical elements that connect arch and deck.

Figure 1: "Infante D. Henrique" Bridge.

2.2 Modal Parameters

After the bridge construction and before the installation of the dynamic monitoring system, an ambient vibration test was performed in order to obtain a good characterization of the bridge modal parameters. The description of this test and the corresponding outputs are detailed by Magalhães et al. (2006). In this section, only the results that are relevant to characterize the dynamic behaviour of the bridge and to interpret the results of the monitoring system are presented.

During the ambient vibration test, accelerations along three orthogonal directions (vertical, longitudinal and transversal) were measured in a total of 32 points. This provided a good characterization of the mode shapes associated with the natural frequencies in the frequency range between 0 and 5 Hz. The first 8 modes are represented in Figure 2.

These experimentally obtained modal parameters were compared with the numerical counterparts. The developed numerical work and the good agreement between the 'tuned' numerical model modal parameters and the experimental ones are characterized in Magalhães et al. (2006).

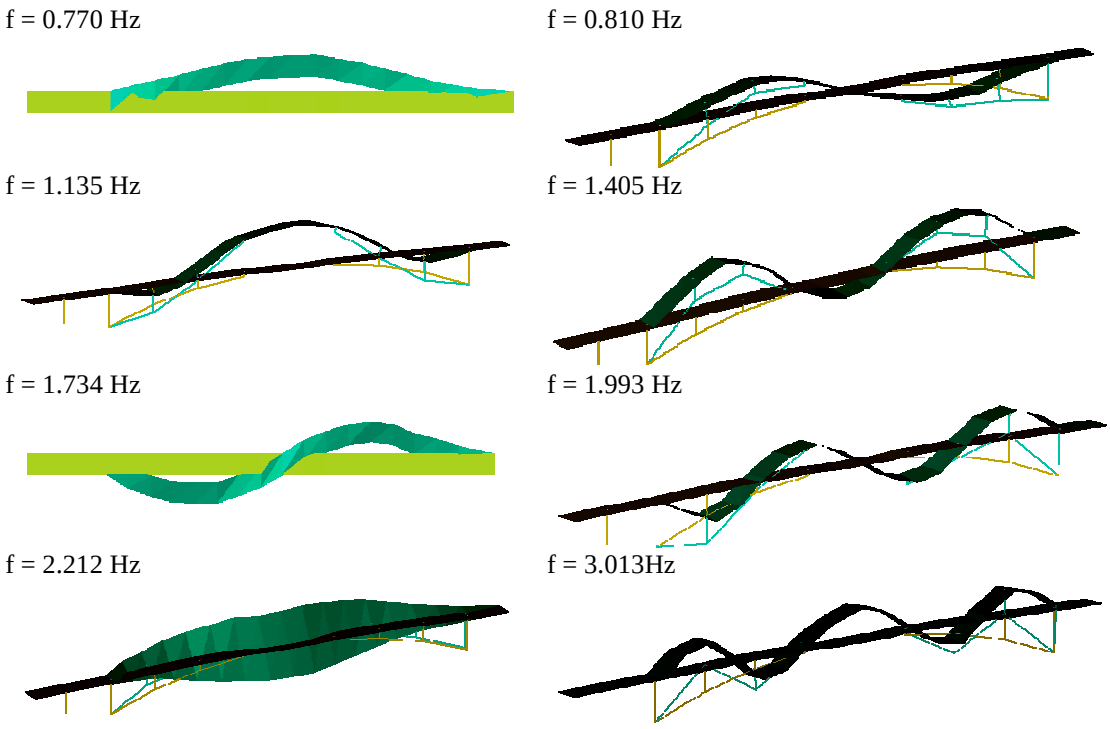

Figure 2: Identified natural frequencies and mode shapes of the first 8 modes.

3 DYNAMIC MONITORING SYSTEM

3.1 Monitoring Hardware

Traditional monitoring systems are based on one central acquisition system to which all the sensors are connected. However, it is more convenient to have the digitizers distributed along the monitored structure, in order to reduce the length of the sensor cables, as these are sensitive to electrical interferences that can corrupt the sensor's electrical signals. Additionally, after digitization, the information collected by several sensors can be transmitted by a single Ethernet cable. Therefore, with this alternative solution, the installation becomes simpler and the signal noise is reduced. These advantages are enhanced when large civil structures are involved. As high signal synchronization is essential for modal analysis, this type of architecture of the monitoring system requires good synchronization of the digitizers' clocks. This can be achieved with a synchronization cable connecting the distributed digitizers or with one GPS antenna and receiver for each digitizer to synchronize their internal clocks using the information provided by the "in view" satellites.

The dynamic monitoring system of the "Infante D. Henrique" bridge is essentially composed by 12 force balance accelerometers, 2 digitizers and an internet router, which are installed inside the deck box girder and distributed along the bridge according to the scheme presented in Fig. 3. Since the structure is almost symmetric and the previously performed ambient vibration test has proven that the mode shapes are also approximately symmetric, it was decided to instrument

just one half of the bridge. Therefore, the 12 available accelerometers were distributed along four sections. Three sensors equip each section: one to measure the lateral acceleration and two for the vertical acceleration at the downstream and upstream sides (the ambient test showed the existence of torsion modes in the analysed frequency range). The force balance accelerometers used (FBA ES-U2 from Kinemetrics) have a dynamic range of 145 dB, are sensitive in the frequency range DC to 200 Hz and their measuring range can go up to 4 g. In the present application a measuring range between -0.25 and +0.25 g was fixed, in order to optimize the sensitivity of the sensors and so reduce the effect of noise, while keeping a conservative acceleration range (the maximum observed acceleration is lower than 10 mg). Each digitizer (www.Q330.com) allows the connection of six dynamic channels, is equipped with a 24-bit analog-to-digital converter and permits simultaneous telemetry of the acquired data to a central site and a link to a local recording unit. In the present installation, the digitizers were placed at sections S2 and S4 (Fig. 3). Digitizers located at sections S2 and S4 are connected to each other by an Ethernet cable. Another Ethernet cable links section S4 and the router that is the interface between the local network and the Internet. Synchronization between digitizers is achieved with two GPS antennas and receivers that allow continuous update of the internal clocks of both units.

The data produced by the two digitizers becomes available at FEUP in the form of ASCII files with as many columns as the number of sensors, containing acceleration time series sampled with a predefined rate and length. For monitoring this bridge, a sampling frequency of 50 Hz and a length of 30 min were selected. Finally, it is important to state that configuration of the system (e.g. sampling frequency and length of the time segments) and analysis of parameters used to check the system condition (e.g. quality of the GPS signals, digitizer internal temperature and input voltage) are performed remotely.

This dynamic monitoring system is complemented by an independent static monitoring system (performing six acquisitions per hour) that was installed in the bridge during construction, comprising strain gages, clinometers and temperature sensors (http://www.kinesia.net/). In particular, the temperature sensors embedded in the concrete (see Figure 3) were crucial for the study presented at section 4.

3.2 Monitoring Software

The Dynamic Monitoring system produces one file with acceleration time series each half-hour. These are then handled by a set of Matlab routines developed at the Laboratory of Vibration and Structural Monitoring (www.fe.up.pt/vibest) of FEUP. This software, called DynaMo (standing for DYNAmic MOnitoring), each half-hour executes the following tasks:

- archiving of the original data (sampled at 50 Hz) in a database, so that it can be later used to test alternative processing methodologies;
- pre-processing of data to eliminate the offset and to reduce the sampling frequency from 50 to 12.5 Hz (the first 12 modes are below 5 Hz);
- processing of data for automatic identification of modal parameters using three different identification algorithms: Frequency Domain Decomposition (FDD), Covariance driven Stochastic Subspace Identification (SSI-COV) and poly-Least Squares Complex Frequency Domain (p-LSCF);
- creation of a database with the results of the processing.

The database with all the results can then be consulted using a graphical user interface (DynaMo Viewer) that comprehends tools to create several types of plots for a given time interval, like the ones presented in section 4.

The most relevant feature of the developed software is the use of algorithms for the automatic identification of modal parameters based on the measured acceleration time series. Three different approaches were implemented: a non-parametric method in frequency domain (FDD), a parametric method in time domain (SSI-COV) and a parametric method in frequency domain (p-LSCF). In order to make both parametric methods fully automated and sufficiently robust to work on an on-line basis, a new algorithm was developed to post-process the outputs of the identification algorithms. This is based on a hierarchical clustering algorithm and is fully described in Magalhães et al. (2009), together with a review of existent alternatives. The performance of the three methods is compared in Magalhães et al. (2008) and Magalhães et al. (2009). All of them presented success rates (ratio between the setups where a certain mode was identified and the total number of processed setups) higher than 98 % for the bridge first 12 modes. However, the p-LSCF method proved to provide slightly better results, especially for the characterization of the modal damping ratios variation. Therefore, in the next section only the results of this method are presented.

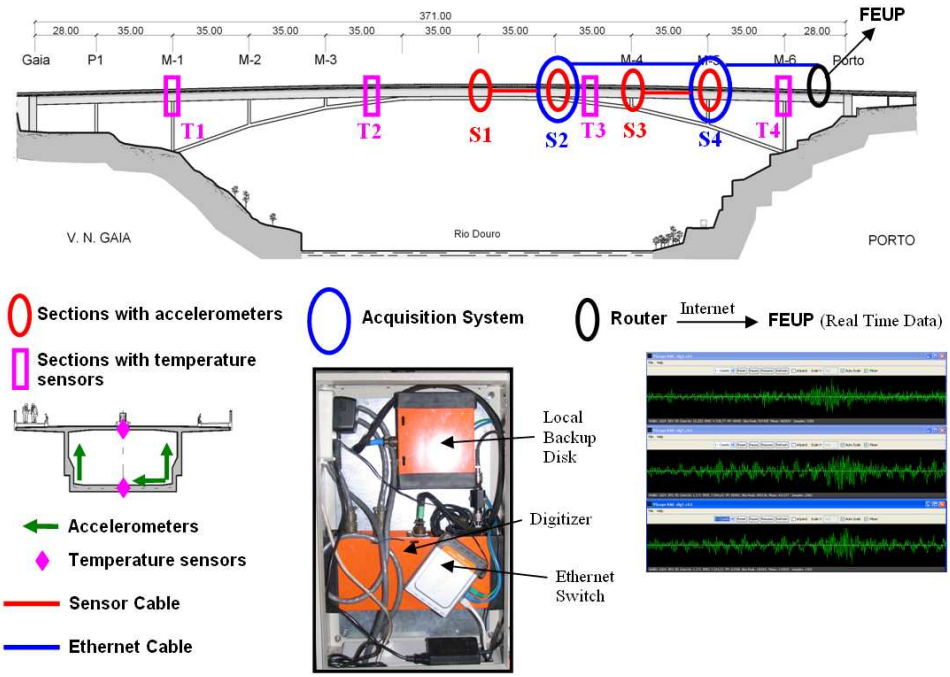

Figure 3: Scheme of the Dynamic Monitoring Hardware and position of the temperature sensors.

4 STUDY OF MODAL PARAMETERS VARIATION

The Dynamic Monitoring system of the "Infante D. Henrique" bridge is working since the 13th of September of 2007. Therefore, a database with the variation of the bridge modal parameters identified with the three implemented methods during more than one year is available. In the present paper the period from 13/09/2007 to 30/09/2009 is studied using the modal parameter provided by the p-LSCF method.

Figure 4 presents the evolution of the bridge first 12 natural frequencies during the period under analysis. Figure 5 characterizes, for the same period, the variation of the temperatures measured by the 8 sensors embedded approximately in the middle of the top and bottom flanges of the deck concrete box sections marked in the scheme of Figure 3 (section T1 to T4). This graphic shows minimum temperatures of 5 ºC in the winter and maximum temperature of 30 ºC in the summer. Due to high thermal inertia of the deck section, justified by the thickness of its walls

(varying from 30 to 100 cm) and by the air mass inside the box beam, the observed daily thermal variations are only of the order of 2 ºC, despite the higher fluctuations of the outside air temperature. The sensors placed at similar sections, as for instance sections T1 and T4, should present very similar time histories, however the sensors were not positioned exactly at the same depth and therefore, there exist some differences in terms of amplitude and time of occurrence of the daily maxima and minima.

As illustrated in Figure 6, for the first mode, the bridge temperature is the major justification for the annual natural frequencies variations. This plot demonstrates the high correlation between the two variables and illustrates the ability of the monitoring system to well characterize very small variations of the natural frequencies, of the order of milli-Hertz.

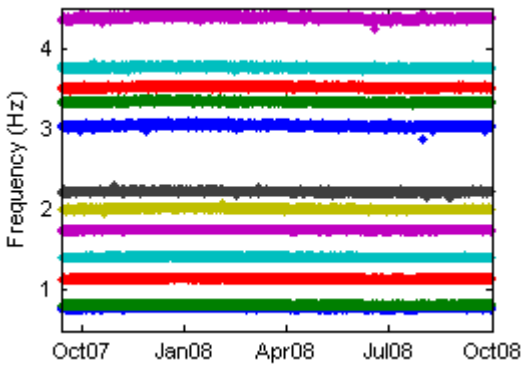

Figure 4: Variation of the bridge first 12 natural frequencies identified with the p-LSCF method, from 13/09/2007 to 30/09/2008.

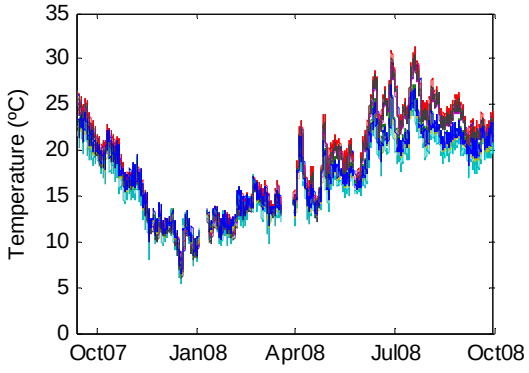

Figure 5: Variation of the temperature measured by the embedded temperature sensors, from 13/09/2007 to 30/09/2008.

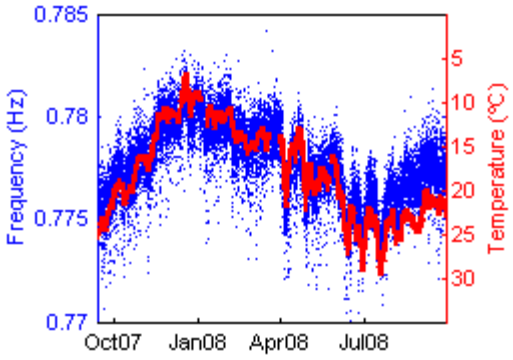

Figure 6: First natural frequency (dots) versus temperature at the top of section T3 (line).

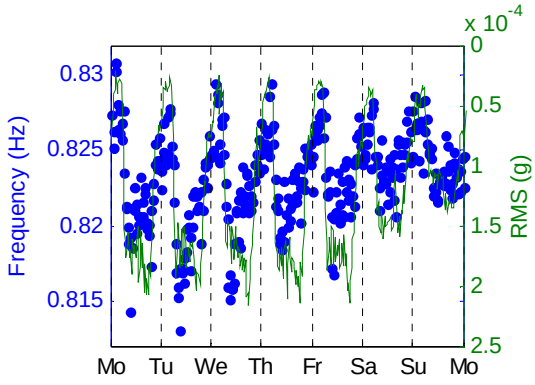

Figure 7: Second natural frequency versus vertical vibration amplitude at section S3, 3/3/08 - 9/3/08

A second factor with relevant influence on the natural frequencies is the amplitude of the bridge vibration, which is related with the traffic intensity. This dependency is characterized in Figure 7 for the second mode during the first week of March, using the root mean square (RMS) as a measure of the vibration intensity. The second mode is the one from the twelve analysed modes that experiences higher daily fluctuations. This is because this mode has a relevant movement in the longitudinal direction and therefore the friction forces of the abutments bearings are mobilized. For low vibration amplitudes the bearings behave has a fix connection, for large amplitudes the friction forces are overcome and as consequence the natural frequency decreases (note that the scale associated with the RMS is inverted).

The comparison of the natural frequencies identified in the ambient vibration test with the ones provided by the monitoring system shows that the first set of values are consistently lower. This is certainly motivated by the concrete hardening manifested during the last three years (last pouring: June 2002; ambient vibration test: June 2005; dynamic monitoring: 2007/2008). This is an interesting feature of the dynamic monitoring systems, as their installation since the bridge construction allows to indirectly quantify the time evolution of concrete elasticity modulus.

Recently, several sophisticated statistical methods have been developed to eliminate the effects of the environmental variables on the structures modal parameters, as for instance the ones presented by Peeters and De Roeck (2001) and by Deraemaeker et al. (2008). However, at a first step, it is essential to use a simple method in order to better understand the effect of each variable. Therefore, in this work the variability of modal parameters is explained with a multi-linear regression.

The factors with more relevant influence on the independent variables (natural frequencies) have been already identified: temperature, vibration amplitude and concrete hardening. These have to be represented by a set of independent variables.

Instead of selecting all the measured temperature records, the correlation coefficients (Hair et al. (1998)) between all pairs of temperature time series and between the temperature time series and the 12 natural frequencies time series were calculated. This allowed to group similar temperature records (the ones presenting correlation coefficients higher than 0.99) and to select the representative of each group (the one with higher correlation coefficient with the frequencies time series). This statistical procedure created two groups: one with the temperatures measured on the top flanges and another with the ones measured at the bottom flanges. The sensor placed at the bottom of section T1 ($T1b$) and the sensor positioned at top of section T3 ($T3t$) were selected as representatives of each group.

Equivalent procedure was followed for the time series with the RMS of the 12 acceleration channels, providing the selection of other two independent variables: RMS of the upstream vertical accelerations at section S2 ($VS2U$) and RMS of the lateral accelerations at section S3 ($LS3$).

Consequently, the time history of each identified natural frequency (f_i) is explained by the following model:

$$f_i(t_k) = a_i + b_i \cdot t_k + c_i \cdot T1b(t_k) + d_i \cdot T3t(t_k) + e_i \cdot VS2U(t_k) + f_i \cdot LS3(t_k) + \varepsilon_i(t_k) \quad (1)$$

where $T1b(t_k)$, $T3t(t_k)$, $VS2U(t_k)$ and $LS3(t_k)$ are the selected independent variables (also called predictors) at the time instant t_k, $\varepsilon_i(t_k)$ represents the effects that are not explained by the model and a_i, b_i, c_i, d_i, e_i, f_i are the parameters of the model to be estimated. The first term of the expression (a_i) is equal to the average value of the frequency f_i and the second term ($b_i \, .t_k$) is used to model, in a very simple way, the possible frequency increase due to the concrete hardening.

After the identification of the model parameters associated with each natural frequency, it is possible to eliminate from the estimated natural frequency time series the effect of temperature and vibration amplitudes. This is demonstrated by Figures 8 and 9 for the third natural frequency, similar results were found for the other modes. It is relevant to observe that with the described procedure it is possible to define a very narrow frequency band (of about 0.01Hz) for the expected natural frequencies of the healthy structure.

The model fitted using data from the past year can now be used to eliminate, on an online basis, the effects of the temperature and vibration amplitude on the new natural frequencies estimates, allowing an immediate identification of anomalous values that might be justified by structural damages.

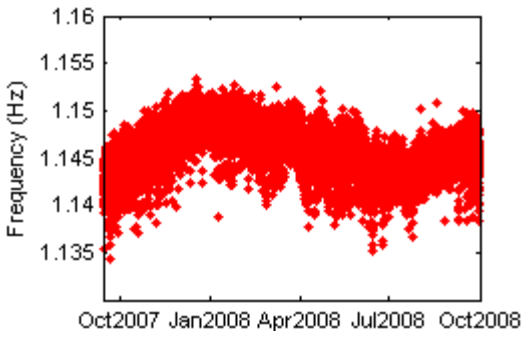

Figure 8: Time evolution of the 3rd natural frequency.

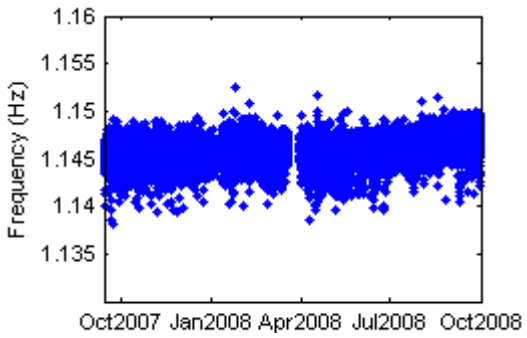

Figure 9: Time evolution of the 3rd natural frequency after correction.

5 CONCLUSIONS

This paper characterizes the hardware and the software of a dynamic monitoring system installed on a large concrete arch bridge. The developed software includes the online automatic identification of the bridge modal parameters using three different identification techniques: FDD, SSI-COV and p-LSCF, which have been able to characterize the evolution of the bridge dynamic properties for more than one year.

The variables with more relevant influence on the identified natural frequencies are identified and their effects are modelled by a multi-linear regression. The model adjusted with the data from the past permits to obtain very narrow frequencies bands for future expected natural frequencies of the healthy structure, allowing the detection of abnormal values that might be indicators of structural damages. The observed results are very promising but future numerical studies are still needed to identify the type of damages that might be identified with this methodology. These will be conducted using a numerical model tuned with the modal parameters identified based on the ambient vibration response.

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