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ANALYSIS OF THE VIBRATION LEVELS OF A SLENDER FOOTBRIDGE MEASURED BY A CONTINUOUS DYNAMIC MONITORING SYSTEM

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Abstract. *This paper is related to the work involving the numerical and experimental dynamic analysis of a very flexible pedestrian bridge located in Porto. Given the high level of vibrations reported by the users of that structure, the Laboratory of Vibrations and Structural Monitoring (www.fe.up.pt/vibest) from Faculty of Engineering of University of Porto (FEUP) became interested in this case, following the previous work of this research group in this area of Civil Engineering. In a first stage, the structure is described and the identified dynamic properties are listed. Then, experimental and numerical simulations of several scenarios of pedestrian loads exciting the bridge are presented. Given the "lively" behavior of the structure, it was decided to install a dynamic monitoring system in order to characterize the effective levels of vibration experienced by that structure during long periods of time. The results of the dynamic monitoring are exposed in this paper, which gives reason to the actual existence of complaints from pedestrians.*

1 INTRODUCTION

Many Civil Engineering structures have vibration problems in terms of serviceability limit states due to several transient or periodic dynamic loads, e.g., footbridges subjected to pedestrian actions, road and railway bridges excited by traffic loads and tall buildings exposed to wind forces. Generally, the safety of the structure is not compromised, affecting only its proper in-service functioning.

In the case of pedestrian bridges, the excessive vibrations are often attributed to the existence of resonance phenomena arising from the proximity of step frequency of pedestrians relative to the natural frequencies of the structure. This problem may assume particular relevance in very flexible structures often characterized by having low inherent damping, in line with the current trends of footbridge conception and design. For new structures, the use of recent guidelines in this area, for instance Sétra [1] or Hivoss [2] guidelines, may serve to prevent the occurrence of these problems. However, in existing footbridges the situation is already installed, which often requires the adoption of corrective measures such as the use of vibration control devices.

In these cases, and before any rehabilitation, the implementation of continuous dynamic monitoring systems is useful for making a very realistic assessment of the vibration levels, thus enabling a subsequent rigorous study of the intervention in the structure. This is the context of this paper, where a specific case of a footbridge located in Porto was instrumented with one accelerometer at a critical section, with the data being collected during the last months crucial to the evaluation of the situation and to study a possible implementation of a control system.

2 CHARACTERIZATION OF THE STRUCTURE

2.1 General description

The footbridge under analysis is a structure that connects a commercial infrastructure located by the sea, known as Transparent Building, with the Porto City Green Park (see Figure 1). It comprises two spans of 30m each, simply supported at the ends with hinges and at mid-length by means of a concrete column. The deck is 3.5 m wide and has an inclination of 6% starting with a lower elevation at the green park and ending in the Transparent Building at a higher level. The cross-section is composed of two lateral steel girders type IPE600, 600 mm high, connected by a secondary steel structure which, in turn, gives support to a wood floor. The mass of the structure, including all structural and non-structural elements, was estimated at 380kg/m.

Figure 1: General view of the footbridge.

2.2 Identification of modal properties

The identification of the modal properties of the structure in terms of natural frequencies, damping ratios and modal shapes, was performed in the context of the research work developed by Abreu [3] and Antão [4]. For this purpose, two ambient vibration tests were performed. Aiming at a preliminary evaluation of the natural frequencies of the structure, a first test was conducted using a single seismograph including force-balance accelerometers positioned in several sections of the deck, namely, at mid-span and at 1/3rd span sections of one side of the footbridge in order to capture symmetrical and anti-symmetrical vibration modes (see Figure 2a)). For each measurement point, acceleration-time series lasting 9 minutes were acquired and subsequently processed in order to obtain estimates of Power Spectral Density functions (PSD). The Average Normalized Power Spectral Densities (ANPSD), including all measurements, is shown in Figure 2b) which allows identifying the natural frequencies of the structure associated with the peaks of the graph. Second column of Table 1 summarizes the results obtained in this test regarding the first four natural frequencies, allowing to conclude that the first two frequencies are 1.85 and 2.02 Hz, critical in terms of resonance with pedestrians walking along the bridge, and two other higher frequencies of 3.03 and 3.56 Hz, which may be excited by pedestrians in running or jogging activities. Frequencies above the 4th mode were not considered because they are not relevant in terms of resonance phenomena involving pedestrians.

The second test consisted of using 3 accelerometers (see Figure 3a)) distributed along the deck according to Figure 3b). In this case, the total length of the footbridge was divided into 8 equal spaced intervals. The reference accelerometer was positioned in one side of section 3 and the other two units were used to measure the other points, one on each side of the deck in order to capture torsion effects. By calculating each Frequency Response Function (FRFs) from the reference accelerometer to the non-reference accelerometers the modal shapes associated with each natural frequency were identified. The modal shape of the first 2 bending modes is represented in Figure 4a) and 4b), with the description of the first 4 modes indicated in Table 1.

Damping properties of the footbridge were also evaluated by using an expedite method consisting of exciting the structure with a frequency close to each natural frequency using a pedestrian skipping at a fixed position. After achieving a resonant response, the excitation stops suddenly and the free motion of the structure is recorded. By analyzing the free decay curve, the respective damping factor can be estimated using the logarithmic decrement method. This process was repeated by adopting different levels of excitation intensity, because damping ratios are known to increase with the increase of the vibration amplitude. Table 2 summarizes the estimates obtained for the first 2 vibration modes of the structure.

a) b)

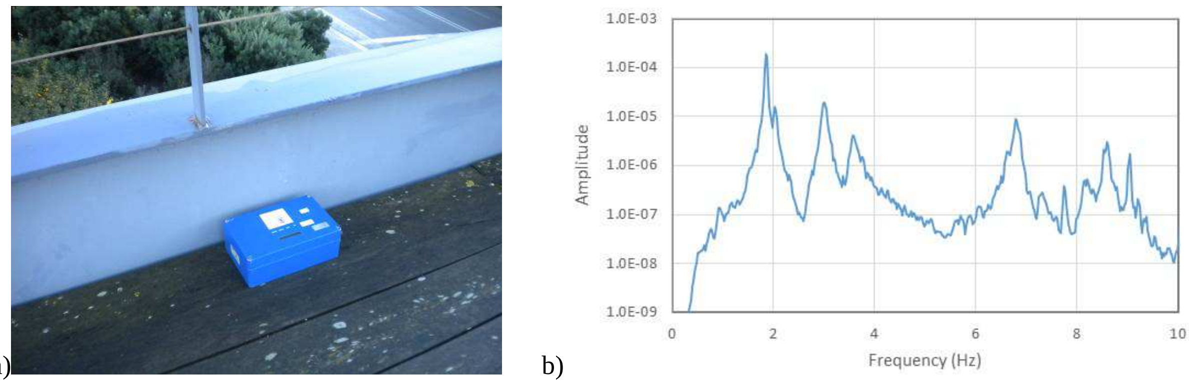


Figure 2: a) Seismograph measuring ambient vibrations; b) ANPSD including all measurements.

a) b)

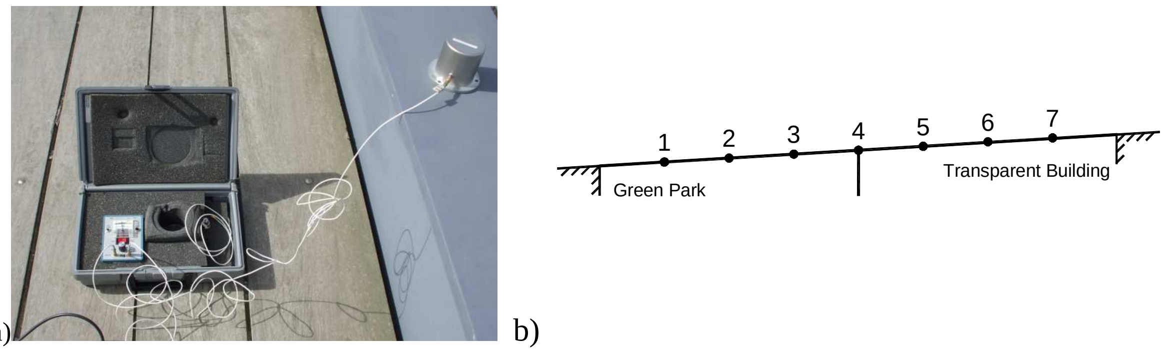
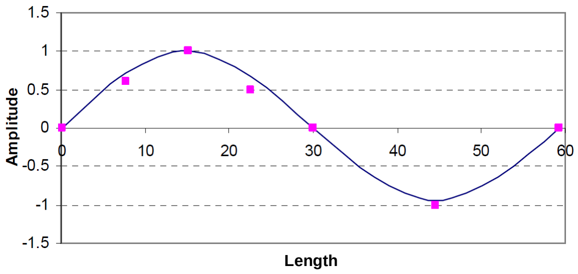


Figure 3: a) Accelerometer installed in one section; b) Numbering of the measurement sections.



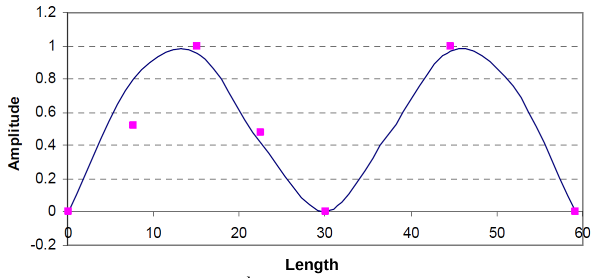


Figure 4: a) Identified 1st bending mode; b) Identified 2nd bending mode

Order	Measured Frequency (Hz)	Calculated Frequency (Hz)	Type of Vibration Mode
1	1.85	1.82	1st bending
2	2.02	2.06	1st torsion
3	3.03	3.09	2nd bending
4	3.56	3.38	2nd torsion

Table 1: Identified and calculated natural frequencies.

Vibration Mode	Damping ratio Low vibrations (%)	Damping ratio High vibrations (%)
1	1.28	1.88
2	1.35	1.67

Table 2: Identified damping ratios.

2.3 Tests with pedestrians

In order to have an estimate of the vibration levels of the structure caused by pedestrians walking along the deck, a simple test was conducted, consisting of using either single or group of young students. In a first stage, the pedestrians passed through the structure at a time with a step frequency close to the 1st vibration mode. The maximum response obtained in the middle of one of the two main spans of the structure was 0.56 m/s^2. Then, the pedestrians crossed the footbridge together two times, synchronizing the step frequency between them and make it coincide with that of the 1st vibration mode, as well. In that case, the maximum response was very close to 2 m/s^2. These values should be seen as indicative of the structure response to such actions.

3 NUMERICAL MODELING

3.1 Numerical model of the structure

Based on the geometrical and material characteristics of the footbridge and given the identified dynamic properties, a numerical model of the structure was developed using Robot software. The accuracy of the numerical model was improved by slightly adjusting the characteristics of the structural sections and element masses, until a good approximation between experimental and numerical natural frequencies and mode shapes is achieved. This was not a difficult task, given the simple structural functioning of the system under analysis. Table 1 contains the numerical natural frequencies of this model, which can be compared with the experimental data, and Figure 5 shows the 3-dimensional representation of the first 4 mode shapes obtained numerically, which are in very good agreement with the experimental estimates.

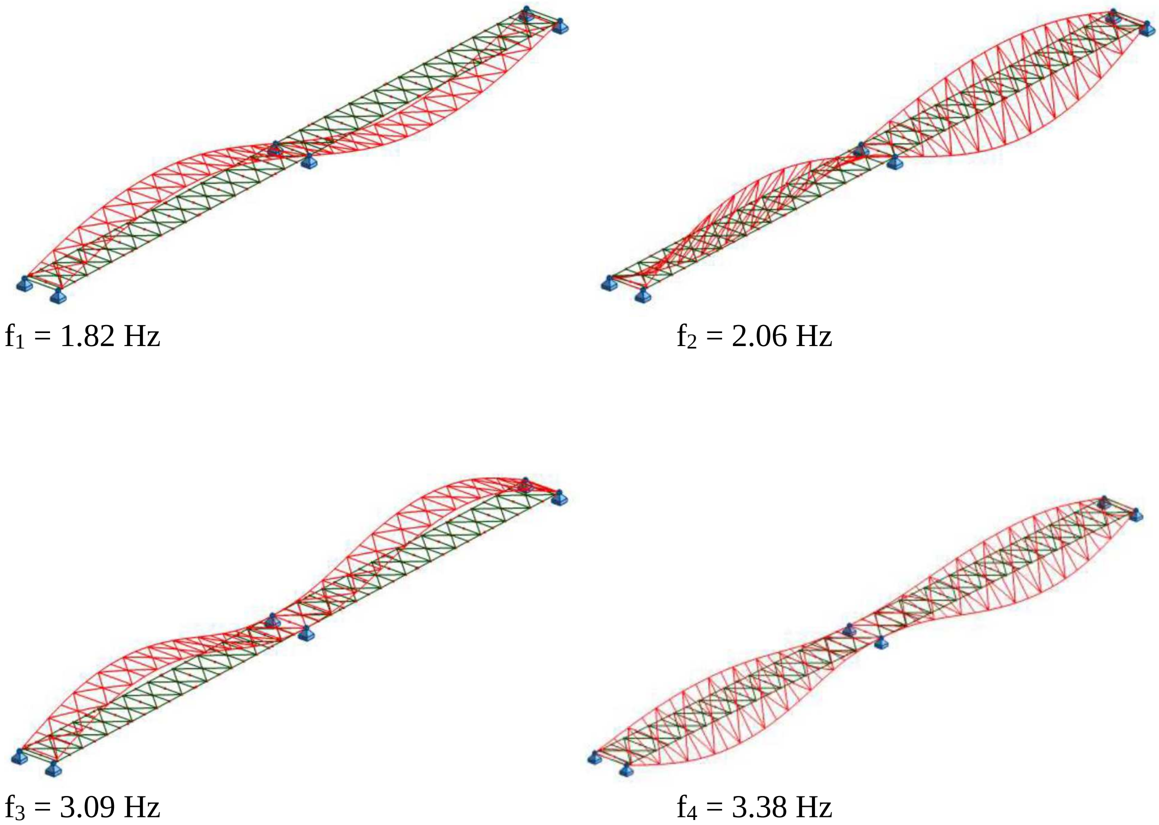


Figure 5: First 4 vibration modes obtained numerically.

3.2 Simulation of the structural response to pedestrians actions

This numerical model was used to simulate the structural response to several scenarios of most probable pedestrian loads. It was considered that only the first 4 vibration modes are critical in terms of occurrence of resonance phenomena. Other higher modes are difficult to excite by regular activities of pedestrians, even considering the higher harmonic components of the dynamic load. Scenarios involving crowds crossing the bridge were also assumed to be non-realistic, mainly because the structure serves as an entrance to a building with limited access. Therefore, only single and groups of pedestrians were considered, consisting of the following idealized situations: Single or 3 synchronized pedestrians walking in the center of the deck in resonance with the 1^{st} vibration mode; Single or 2 synchronized pedestrians walking laterally to the deck in resonance with the 2^{st} vibration mode (torsion); Single pedestrian running in the center of the deck in resonance with the 3^{rd} vibration mode; and a single pedestrian running laterally to the deck in resonance with the 4^{th} vibration mode.

The loads corresponding to these scenarios were modeled according to reference [5] and the damping ratios of all vibration modes assumed a conservative value of 1%. The maximum vibration levels achieved in each situation were evaluated at critical sections, as summarized in Table 3. In that table, a classification of vibrations according to Sétra and Hivoss guidelines in this area is also indicated (see Table 4 for proposed classification).

Scenario	Maximum Acceleration (m/s^2)	Comfort Class
1 pedestrian walking (f=1.82 Hz)	0.80	Medium
1 pedestrian walking (f=2.06 Hz)	0.97	Medium
3 pedestrians walking (f=1.82 Hz)	2.40	Minimum
2 pedestrian walking (f=2.06 Hz)	1.94	Minimum
1 pedestrian running (f=3.09 Hz)	2.18	Minimum
1 pedestrian running (f=3.38 Hz)	0.70	Medium

Table 3: Structure response to several idealized scenarios.

Comfort classes	Maximum Acceleration Limits (m/s^2)
Maximum comfort	< 0.5
Medium comfort	0.5 – 1.0
Minimum comfort	1.0 – 2.5
Intolerable vibrations	> 2.5

Table 4: Comfort classes for vertical accelerations according to Sétra and Hivoss guidelines.

4 CONTINUOUS DYNAMIC MONITORING SYSTEM

4.1 Description of the system

Given the symmetry of the structure and shape of the first vibration modes, the evaluation of the maximum vibration levels can be performed at mid-span in one of the two spans at any side of the deck. As a result, only one sensor was adopted and positioned at the mid-span close to the green park at the south-west side. This way, it was possible to install a solar-powered acquisition system by means of a solar panel installed on the outside of the lateral girder (see Figure 6a)). The acquisition system is composed of a microcontroller able to perform Analog-to-Digital Conversion (ADC) of 16-Bit resolution, which saves data in a local micro SD-card. Inside the box that is used to keep this electronic device, there also exits a battery to guarantee the functioning of the system during night periods and a solar controller (see Figure 6b)). The accelerometer is of MEM type and measures acceleration in the vertical direction. The acquisition system produces data files lasting 10 minutes, which results in 144 files or 16.1 MB per day of information, considering a sampling frequency of 40 Hz.

a) b)

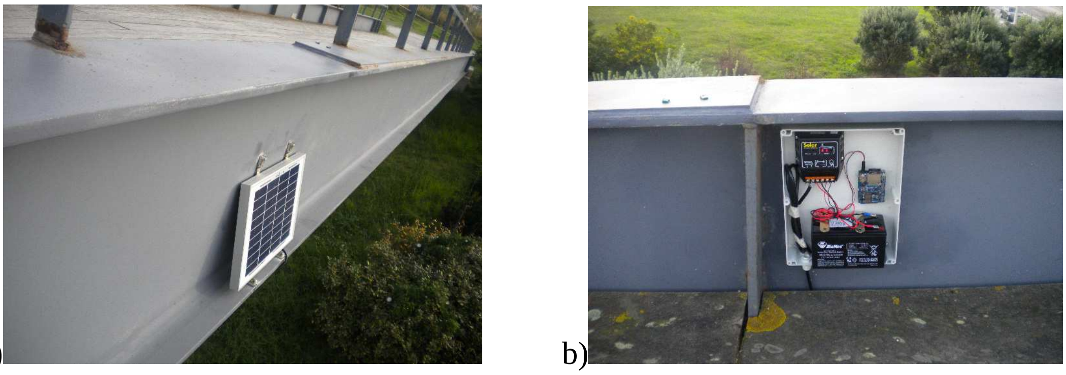


Figure 6: Data acquisition system: a) Solar panel; b) Box with microcontroller, battery and solar controller.

4.2 Evaluation of autonomy and robustness

Unlike many applications installed in structures by Vibest, this particular one was developed specifically for this application, which means that the autonomy and robustness of the system are variables that were not completely known initially. The solar system was designed for relatively sunny days, which means that the autonomy was not assured for cloudy days. At the same time, because of the continuous functioning of the system during many months, the robustness for faults in the acquisition was not proven.

After 6 months of operation, these aspects could be evaluated. For this purpose, the graph of Figure 7 shows the periods where valid data exist or do not exist. The horizontal axis represents the total period of 178 days from 5th October 2014 to 31st March 2015, and the vertical axis represents one day divided into 144 intervals of 10 minutes. The failures (dark spots) occurred exclusively due to power issues, especially during the night or on dark days. No problems were detected in the acquisition system itself. This shows that the system worked 90.5% of the time, corresponding to a very good performance of hardware solution, specially taking into account that the acquisition included the winter period.

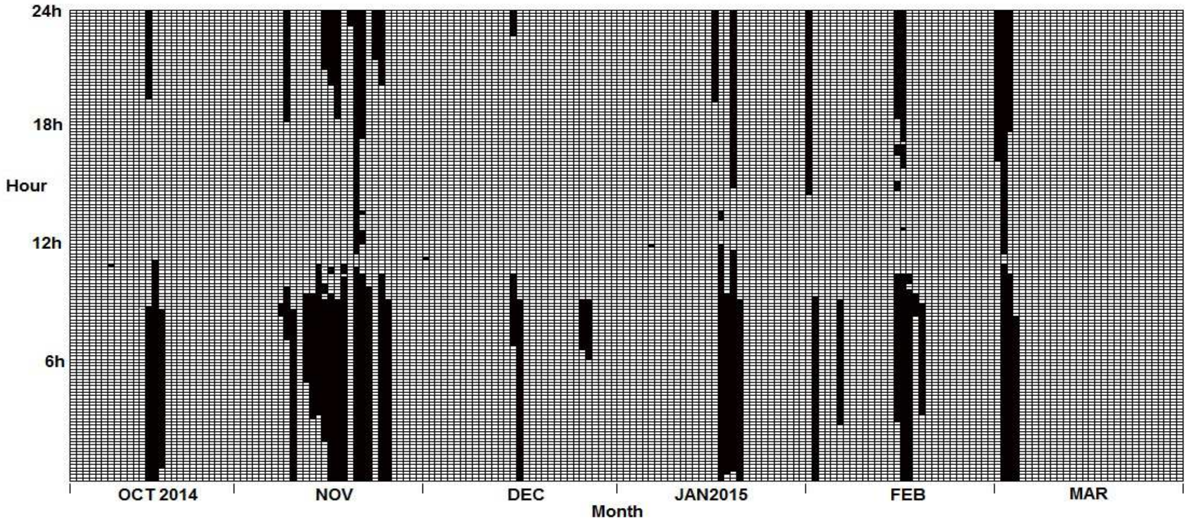


Figure 7: Failures on the signal acquisition detected for 6 months.

5 ANALYSIS OF MEASURED VIBRATIONS OVER TIME

5.1 Maximum vibration levels

The maximum levels of vibrations in the considered period are showed in Figure 8, where the horizontal and vertical axes have the same meaning as the previous Figure 7. The dark areas correspond to periods of low levels of vibrations, which occur essentially in night periods. In an opposite situation, in lighter areas the levels of vibration are higher. The colored bar on the right side establishes a correspondence between color and maximum acceleration values (in m/s^2). Analyzing this graph, several interesting conclusions can be drawn just by observing the vibration levels of the structure. For instance, it is clear that pedestrians use the footbridge mainly in the afternoon, which is also evident in the representation of the daily vibration amplitudes shown in Figure 9. In addition, the time shift of 1 hour occurred in the end of October is visible in Figure 8, by changing the people's schedules at lunch time.

In any event, Figures 8 and 9 show that the maximum vibration levels induced be pedestrians often reach values between 0.5 and 1.5 m/s^2 approximately, which highlights the “lively” behavior of the structure. In fact, by framing these vibration levels in the comfort classes suggested by Sétra or Hivoss guidelines, indicated in Table 4, it can be concluded that the footbridge provides only minimum comfort in many practical situations. In more specific cases, the structure may experience vibration levels higher than 2.5 m/s^2 attributed to intentional resonant loads, inducing intolerable vibrations from the human comfort point of view.

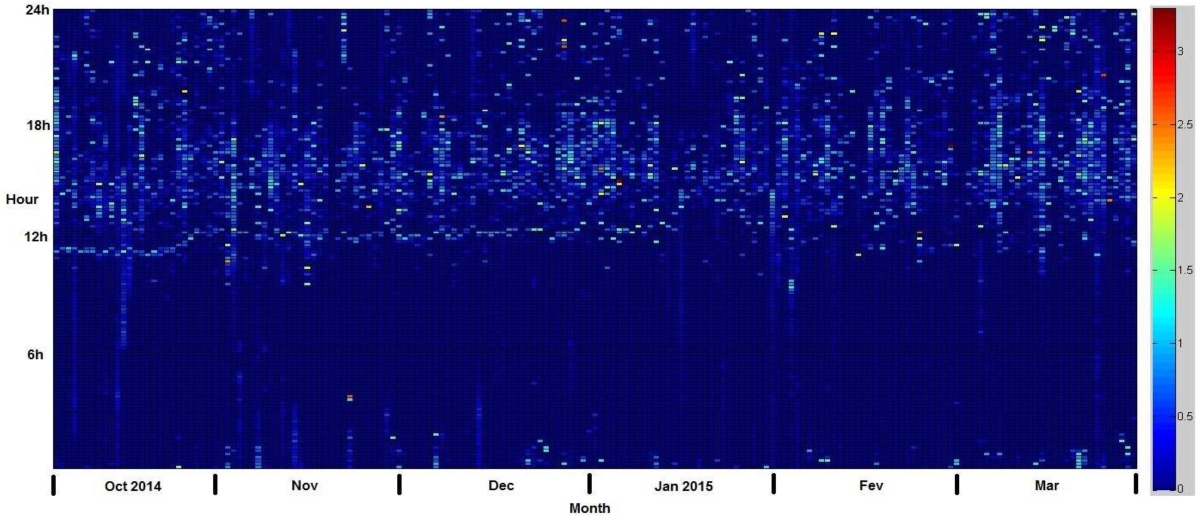


Figure 8: Maximum vibration levels during 6 months.

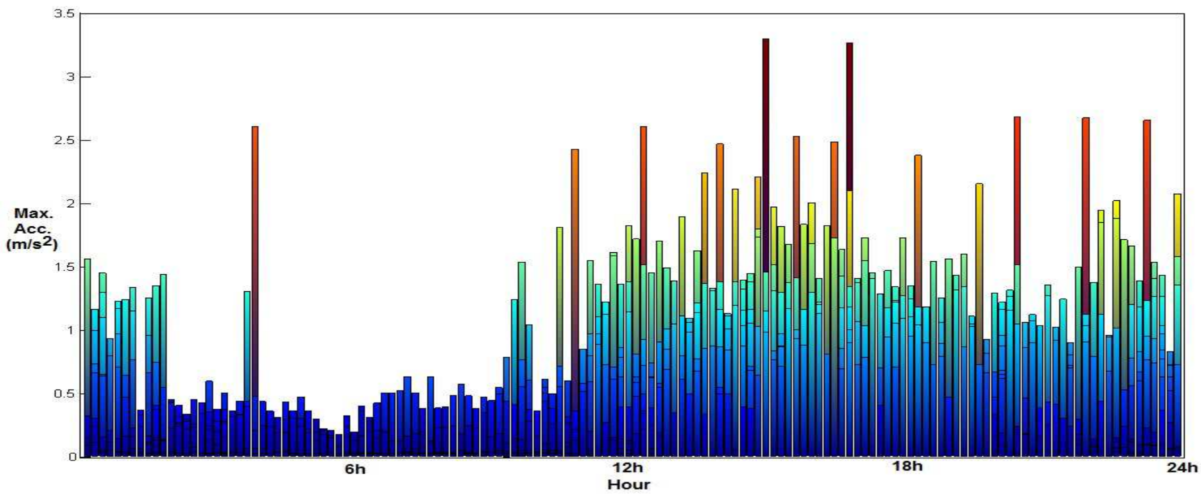


Figure 9: Daily maximum vibration.

5.2 Frequency distribution of vibrations

There is often interest not only in identifying the maximum vibration levels, but also in characterizing the correspondent vibrating frequency. This allows finding out which vibration modes are more active in the dynamics of the structure, which can be useful for some applications, such as vibration control. That analysis was performed for the same period of 6 months, with the main results shown in Figure 10a). In this case, each dot represents an occurrence of a maximum in the acceleration records which was selected according to some criteria. In particular, vibrations should be characterized by very stable and clean pseudo-sinusoidal signals dominated by a single frequency after being filtered by a low pass filter at 6 Hz. This means that only vibrations arising from the dynamics of the first vibration modes are considered. This procedure rules out situations of peaks conditioned by punctual spikes in signals, and cases where the response has contributions of several frequencies in order to facilitate the construction of graphs with the frequency in one axis.

The analysis of Figure 10a) shows that there are 2 dominant vibration modes, namely, the 1st mode of 1.85 Hz and the 3rd mode of 2.90 Hz approximate frequency, which corresponds to the first pure bending modes of the footbridge. This means that, generally, pedestrians walk near the center of the deck and don't excite torsion vibration modes, which seems an obvious situation. Considering that Figure 10a) represents more than 13,000 occurrences, and selecting the critical ones above 0.50 m/s^2, figure 10b) establishes the histogram of the significant events associated with each vibration mode. More than 80% of significant vibration levels are due to dynamics of the 1st vibration mode and about 15% are due to the 3rd mode.

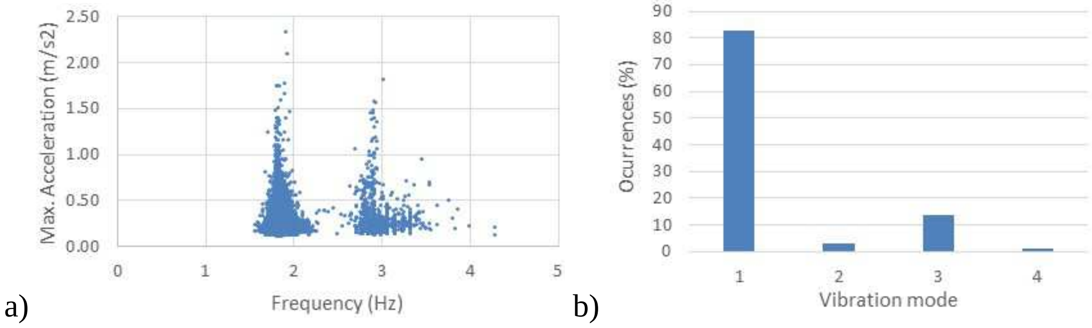


Figure 10: a) Frequency vs amplitude of vibrations; b) Histogram of significant levels of vibration.

5.3 Identification of natural frequencies

Beyond the evaluation of the vibration levels, the data collected over time can also be used to identify modal properties of the structure. The practical interest of this information in the context of this research work is related to a possible implementation of control devices to reduce vibrations in this footbridge, especially if it involves inertial vibration absorbers (also known as Tuned Mass Dampers). It is well established that these devices are very sensitive to frequency tuning, which may consist of a major problem in their use.

The identification of modal properties of dynamic systems can be achieved using several methods. A preliminary view about how natural frequencies distribute over time can be obtained by calculating the Power Spectral Densities of time signals of a previously defined length, windowing and overlapping, and then averaging them over a certain period of time in a process known as the Welch method [6]. Figure 11 illustrates the 3D graph that can be obtained using a daily averaging over a total period of 178 days, where the natural frequencies of the structure are shown as elevations in a frequency ranging from 0 to 10 Hz.

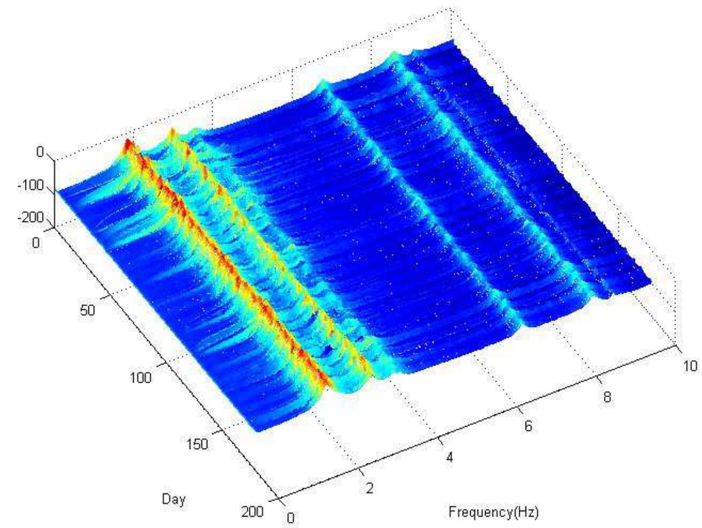


Figure 11: Daily averaged Power Spectral Densities for a period of approximately 6 months.

Nevertheless, the natural frequencies of the structure were identified over that period using the p-LSCF method [6]. In this case, it is necessary to consider that the existence of only one sensor limits the identification of the natural frequencies associated with each vibration mode because only one modal component is available. In addition, the existence of pedestrians on the bridge disturbs the modal identification, especially during the afternoon periods. Despite this, it was possible to make a clear identification of the first 4 natural frequencies according to Figure12. The representation of 6 days of results in Figure 13 allows concluding that the natural frequencies have a significant daily variation probability due to temperature effects, which should be considered in future analyses involving this structure.

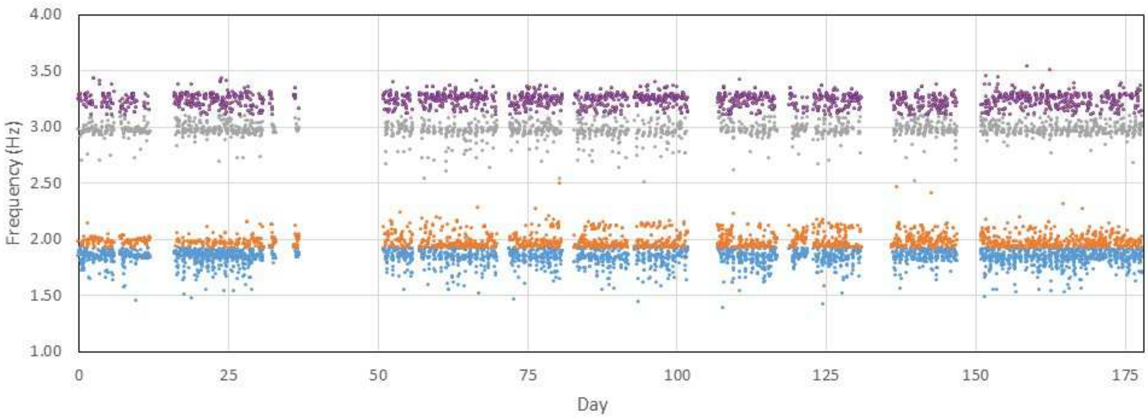


Figure 12: Identified natural frequencies in a period of 6 months approximately.

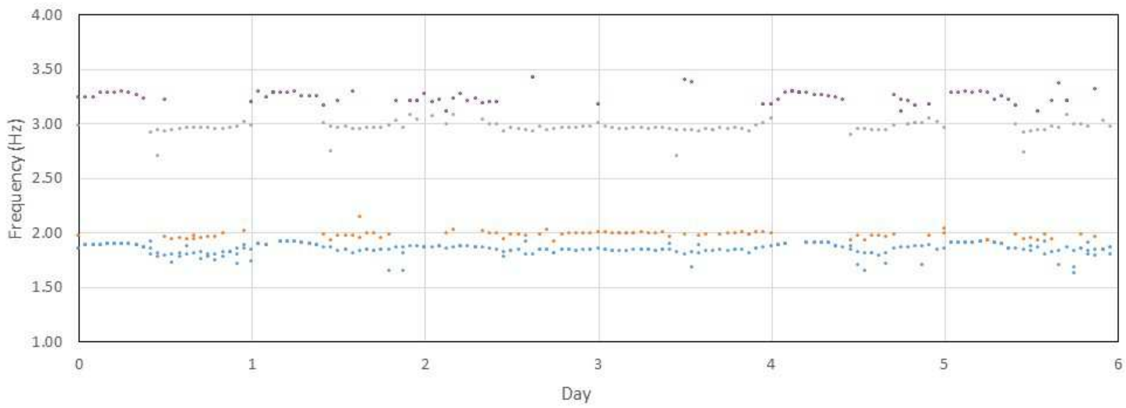


Figure 13: Detail representing 6 days.

6 CONCLUSIONS

This paper allows attesting the vulnerability of the footbridge under analysis to relatively high levels of vibrations. This was concluded by performing initial tests with pedestrians followed by numerical simulations using a calibrated numerical model of the structure. It was found out that a single pedestrian walking in resonance conditions induces maximum accelerations on the footbridge higher than 0.5 m/s^2, which is the limit indicated by several codes as providing high level of comfort to its users. If 3 pedestrians walk synchronously in the same conditions, the vibrations almost reach the intolerable limit.

On the other hand, the implementation of a continuous dynamic system composed of one accelerometer installed at mid-span of one of the two main spans of the bridge allowed recording the effective levels of vibrations for several months. It could be observed that very often the vibrations reach accelerations between 0.5 and 1.5 m/s^2 approximately, corresponding to a range of medium to minimum comfort level. More than 80% of high vibration levels are associated with the dynamics of the 1st vibration mode, meaning that any possible installation of a vibration control device should be mainly directed at this frequency.

However, in this case, it is necessary to consider the relatively high variation of the natural frequencies of the system over time, possibly due to temperature effects or even to the humidity of the wood deck.

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