PAPER REF: 4111

IMPLEMENTATION AND MONITORING OF A PASSIVE CONTROL SYSTEM IN A LIVELY FOOTBRIDGE

Elsa Caetano[1(*)], Carlos Moutinho[1], Álvaro Cunha[1]

[1]Department of Civil Engineering, Faculty of Engineering of the University of Porto, Portugal
(*)*Email:* ecaetano@fe.up.pt

ABSTRACT

The paper describes the studies developed for the assessment, mitigation and monitoring of vibrations on a footbridge located in Portugal. The design of this steel arch footbridge with 60 m chord pointed to a lively behaviour that was investigated upon construction. The decision to install a passive control system based on two tuned mass dampers (TMDs) to mitigate vertical vibrations implied an experimental characterisation of the footbridge, the tuning of the TMDs and the verification of their efficiency. Finally, the need to verify the efficiency of the implemented control system led to the installation of a dynamic monitoring system. The paper will discuss the efficiency of the implemented control solution on the basis of experimental tests and will discuss some results of the measured response during the first months of operation of the monitoring system.

Keywords: footbridge vibrations; tuned mass dampers, dynamic testing; dynamic monitoring

INTRODUCTION

Whether constructed in steel or in concrete, certain ranges of spans in footbridges are associated with proneness to pedestrian induced vibrations. In effect, susceptibility to vertical vibrations frequently exists for spans longer than 50 m, while spans of 80 m to 120 m may be prone to horizontal vibrations and lock-in.

Recent guidelines and recommendations (SETRA, 2006; Butz et al, 2008) have brought an important insight into the problem of characterisation of pedestrian induced effects, providing methodologies for quantification of loads and for assessment of the degree of comfort of a footbridge at design stage. These constitute important tools in the design of structures, allowing the optimisation of structures and the early prediction of measures to mitigate vibrations of the constructed structures.

However, the uncertainties related with the characteristics of the final constructed structures, and the difficulties in defining realistic load models to represent pedestrian traffic in footbridges, justify the need to treat the problem of pedestrian induced vibrations in two phases: first, during design, the susceptibility of the footbridge to pedestrian vibrations is studied by means of numerical modeling, leading eventually to design modifications involving the supports, the choice for concrete/composite/steel slabs, or the local stiffening of the structure in areas that potentially may have to accommodate damper devices. In a second stage, the experimental assessment of the dynamic properties of the constructed structure allows for a final decision on the need and characteristics of control measures.

The two-phase design approach has been used in the structure that is object of the present paper. A numerical study developed by the Structural Engineer on a steel arch footbridge with 60 m chord has led to the identification of potential vertical and horizontal vibrations and to the preliminary design of a control system based on tuned mass dampers (TMDs). The assessment of the dynamic properties of the constructed footbridge based on ambient and free vibration tests allowed the calibration of the numerical model and the design of final TMDs. The installation of 2 TMDs with a total mass of 2100 kg proved to be an efficient measure to mitigate vibrations. The footbridge has been object of a dynamic monitoring program, with the purpose of checking the efficiency of the implemented control system.

The present paper aims at describing the footbridge characteristics and dynamic behaviour, as well as the implemented control solution. Finally, the efficiency of this system will be discussed, based on results of the final assessment of the footbridge after construction and on preliminary information of the permanent monitoring initiated recently.

FOOTBRIDGE CHARACTERISTICS

Integrated in the Parque da Rabada, a green park in the north of Portugal, the footbridge is formed by a steel arch with 60 m chord and 6 m rise, supporting a 5m wide concrete slab (Fig. 1). The total length of the structure is 84 m, divided by spans of 12 m. The deck cross section, formed by a light concrete slab 0.15 m thick supported by 3 longitudinal hot-rolled profiles, is slightly asymmetric, due to the inclusion of a timber path on one edge.

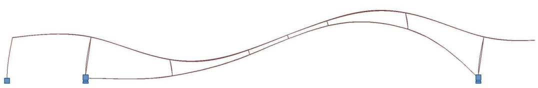
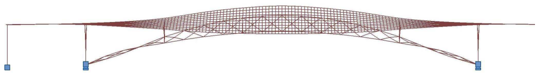
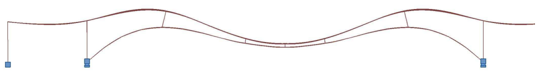
Fig. 1 General view of footbridge at Parque da Rabada, Portugal

At design stage, the Structural Engineer (SOPSEC, 2009) understood that the footbridge would exhibit a lively behaviour and, even though various measures were tested in order to increase natural frequencies, it was accepted that the final structure would be prone to vibrations. Numerical studies of the structure in the final design solution evidenced significant amplitudes of vibration in correspondence with vibration modes associated with natural frequencies of 1.50 Hz, 2.45 Hz and 2.88 Hz (calculated in the unloaded situation). Characteristics of these vibration modes, of the critical utilisation scenarios and corresponding calculated amplitudes of acceleration are summarised in Table 1.

Considering the comfort limits defined in (SETRA, 2006; Butz et al, 2008) , it was concluded that the footbridge would exhibit minimum comfort (vertical acceleration in the range 1 to 2.5 m/s^2) in the condition of slow motion of a crowd with density of 0.5 person/m^2, or else by the single use by one pedestrian jogging or running. In all cases, a modal damping ratio of 0.4%

was assumed, compatible with existing experience on similar structures. The installation of 3 TMDs at the antinodes of the three critical vibration modes, tuned to attenuate the associated dynamic response, was then suggested.

Table 1 Characteristics of critical modes and calculated pedestrian induced response

Natural frequency and mode configuration	**a^x_{max} (m/s^2)**	**a^z_{max} (m/s^2)**	**Critical load scenario**
F_1=1.50Hz 	0	1.45	Crowd load, density 0.5 person/m^2
F_2=2.45Hz 	1.46	1.15	1 person jogging
F_3=2.88Hz 	0.27	4.04	1 person running

DYNAMIC BEHAVIOUR OF THE FOOTBRIDGE

Upon construction of the footbridge, ambient and free vibration tests were conducted (Caetano and Cunha, 2011a), in order to assess the natural frequencies, vibration modes and damping ratios. The characteristics of such parameters are summarised in Fig. 2. This figure includes also a superposition of the identified and calculated modal configurations for the 3 critical vibration modes, showing the good correlation, despite the differences in the frequency values. In this respect, it is mentioned that even though very sophisticated numerical models can be constructed to represent the dynamic behaviour of structures, it is often verified that the identified modal properties substantially differ from calculations in the case of light structures, like footbridges, rather than traffic roadway or railway bridges. This is due to the more relevant influence of supports and other end constraints in lighter than heavier structures. In the present case, the constructed structure displayed a stiffer than calculated behaviour in the first mode, but more flexible behaviour in the higher order modes. This was attributed specifically to the degree of connection between the steel longitudinal elements and the concrete slab.

As regards the identified damping ratios shown in Fig. 2, it is referred that higher than expected values were reached.

On the basis of the modal parameters identified on the constructed structure, a series of vibration tests were conducted during which the acceleration was registered at critical locations during the crossing of pedestrians, trying to reproduce the following scenarios: crowd walking in resonance with the first mode (1.64 Hz) or with the second mode (2.03 Hz); crowd walking with half the frequency of the 4th mode (3.84Hz) or the 5th mode (4.09 Hz); jogging in resonance with the third vibration mode (2.71 Hz). The so-called "crowd" tests were in fact conducted with groups of 10 and 20 persons, due to difficulties in mobilising people to participate in the measurements. The jogging tests were conducted with a varying number of pedestrians: 1, 2, 3, 5, 10, 20 and 27.

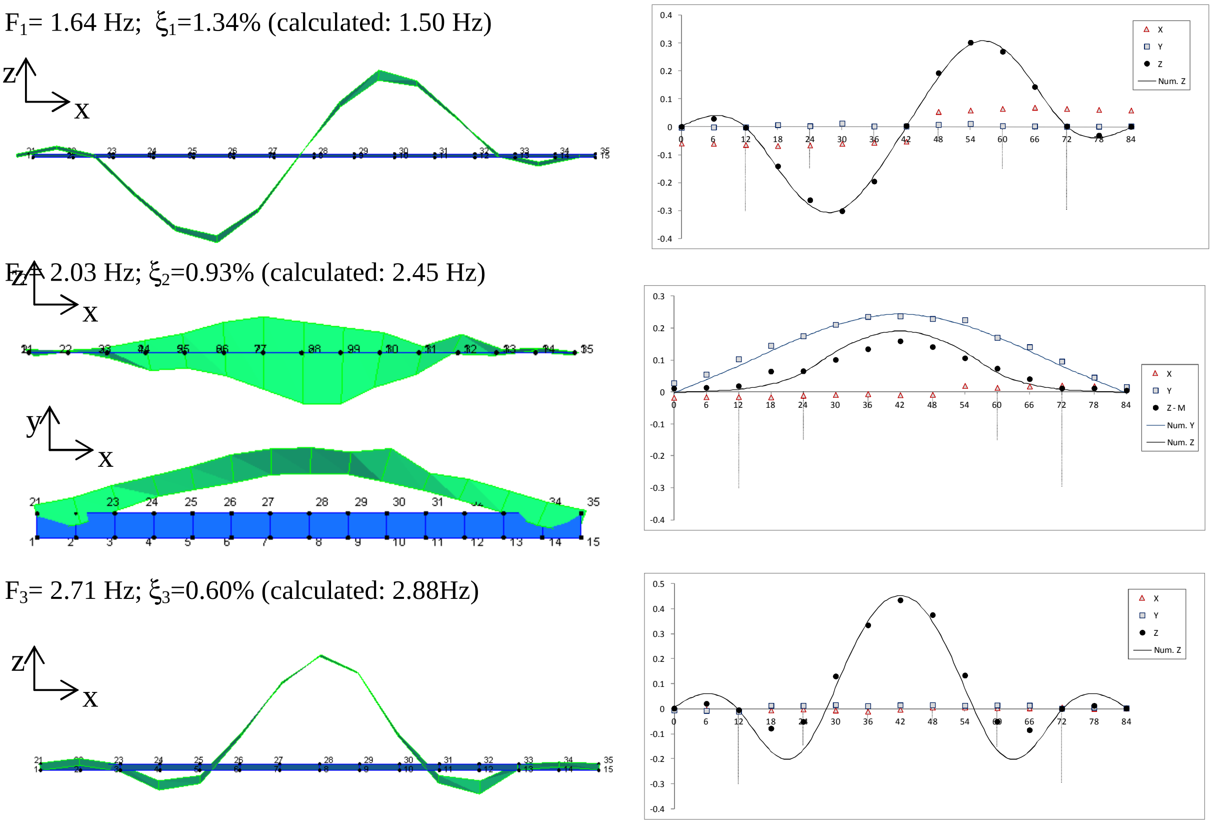


Fig. 2 Identified modal configurations, comparison with calibrated model

Figures 3 and 4 show peak accelerations measured during the two series of tests superimposed with comfort intervals defined as referred previously. The analysis of these figures shows that a medium comfort level was reached with groups of 20 pedestrians walking, the worst situation corresponding to the walking frequency associated with the second mode (2.04 Hz). For the "jogging" scenarios, it can be observed in Fig. 4 that a very small number of pedestrians (2, 3) could generate extremely high amplitudes of vibration, and 5 jogging pedestrians generated intolerable vertical vibrations.

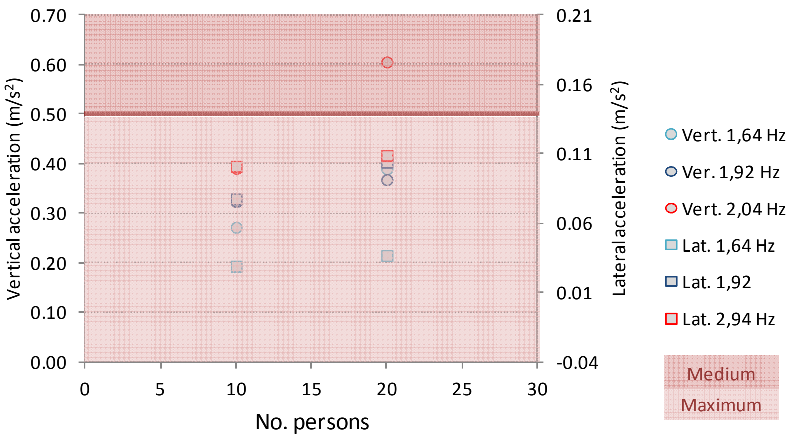


Fig. 3 Maximum vertical and lateral acceleration measured with groups of 10 and 20 persons walking at varying rates

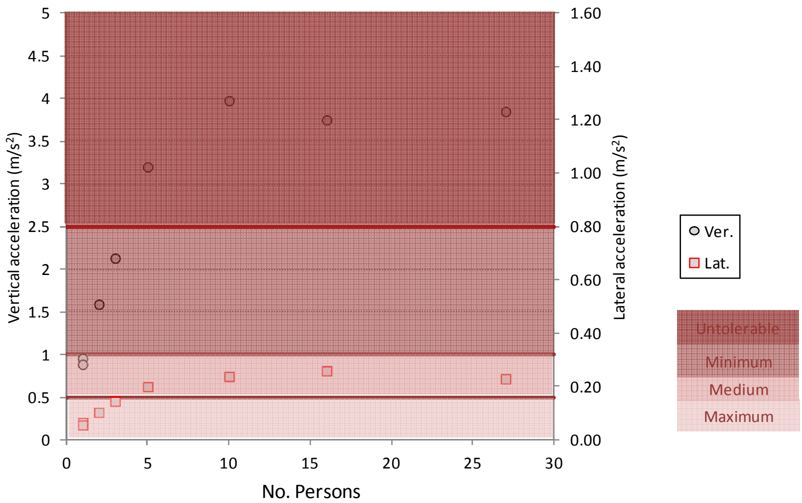


Fig. 4 Maximum vertical and lateral acceleration measured with jogging pedestrians

Upon evaluation of the results of the measurements, the Structural Engineer suggested the installation of two TMDs for mitigation of vibrations induced by crowd walking in resonance with the first vibration mode (1.64 Hz) and by jogging in resonance with the third vibration mode (2.71 Hz). The TMDs were located at sections corresponding to the antinodes of the vibration modes to control, according to the representation of Fig. 5. The corresponding final characteristics are systematised in Table 2 and were defined on the basis of the identified modal parameters (Caetano and Cunha, 2011b). The characteristics of the TMD designed to mitigate vibrations in the first mode were defined for a mass variation of the structure in correspondence with a crowd density of 0.5 person/m^2, while those for the third mode were based on the modal properties of the empty footbridge.

According to the calculations conducted with the calibrated numerical model, the installation of TMDs with a total mass of 2100 kg would provide an added damping ratio of 4%, largely contributing to the attenuation of resonance effects on the footbridge.

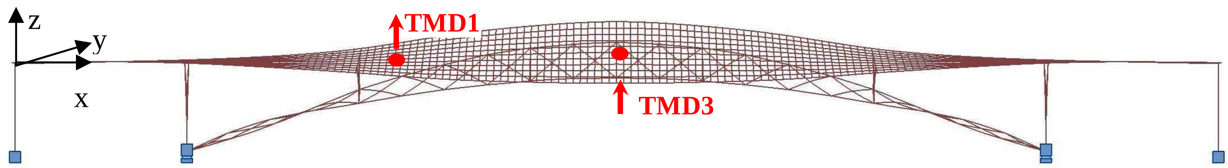


Fig. 5 Location of installed TMDs

Table 2 Final specifications for the TMDs

Mode/ TMD	**Frequency (Hz)**	**Modal mass (kg)**	**Characteristics of TMDs**				
			Freq. $_{TMD}$ **(Hz)**	**Mass TMD (kg)**	K_{TMD} **(N/m)**	C_{TMD} **(Ns/m)**	**Rel. displ (mm)**
1	1.59	81544	1.56	1400	135050	2150	±100
3	2.65	40792	2.61	700	187570	1790	±100

Considering the space available underneath the footbridge for installation of the TMDs, it was decided to divide each TMD in two units with half the mass. Fig. 6 shows images of the installation of the TMDs, after checking and tuning at the workshop.

Fig. 6 Installation of TMDs in the footbridge

EFFICIENCY OF INSTALLED TMDs

In order to verify the efficiency of the installed TMDs, a new series of dynamic tests was conducted on the footbridge after their installation (Caetano and Cunha, 2012). These tests involved the measurement of the dynamic response induced by a group of 10 pedestrians walking in resonance with the first vibration mode (1.64 Hz), or else by jogging pedestrians in resonance with the third vibration mode (2.7 Hz).

Table 3 systematises the maximum response recorded under identical circumstances prior to and after installation of TMDs on the footbridge for the walking and jogging tests.

The analysis of this table shows the important attenuation of the response achieved with the installation of the TMDs. It could be observed, for example, that the acceleration of 3.2 m/s^2 caused by 5 pedestrians jogging reduced by 3 times upon installation of the TMDs, causing the evolution of the footbridge classification from “intolerable comfort”, prior to installation of TMDs, to “medium comfort” level upon installation of TMDs, in the situation of excitation by groups of joggers.

As for the identification of the level of damping introduced by the TMDs, free vibration tests were conducted. During these tests, one pedestrian jumped in resonance at the antinodes of the controlled modes and suddenly interrupted its motion. As exemplified in Fig.7, the free vibration record of accelerations is formed by two branches, the first being characterised by a higher slope and corresponding to the phase of activation of the TMD, during the higher vibrations, while the second branch reflects the vibration of the footbridge when the TMD de-activates due to a reduction of the response. For the third vibration mode, a damping ratio of 2.5% was measured in the first branch, reducing to 0.7% in the second part of the record (0.6% had been measured formerly).

Table 3 Maximum measured acceleration in lateral and vertical directions induced by walking and jogging of pedestrians, without or with installed TMDs

No. pedestrians, type of test	**Max. acc. (m/s^2) (Without/ TMDs)**		**Max. acc. (m/s^2) (With TMDs)**	
	Lateral (Y)	**Vertical (Z)**	**Lateral (Y)**	**Vertical (Z)**
10, centred walking 1.64 Hz	0.03	0.27	0.02	0.19
1, jogging 2.7 Hz	0.07	0.96	0.04	0.50
2, jogging 2.7 Hz	0.10	1.59	0.05	0.60
3, jogging 2.7 Hz	0.15	2.13	0.07	0.81
5, jogging 2.7 Hz	0.20	3.20	0.08	1.03

The inauguration of the footbridge took place on 21st January 2012. Considering this as possibly one of the most critical utilisation scenarios, associated with a crowd walking at low rate, it was decided to conduct additional measurements during this event. Fig. 8 shows one image of the footbridge during the crowd load, as well as one record of vertical accelerations. The maximum measured lateral and vertical accelerations were $0.1 m/s^2$ and $0.35\ m/s^2$, respectively, which are associated with maximum comfort level.

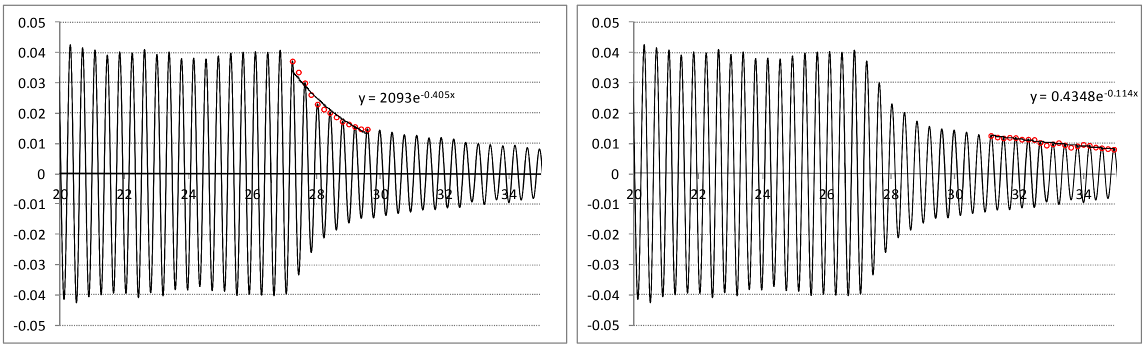


Fig. 7 Free vibration test for identification of damping ratio of the controlled footbridge

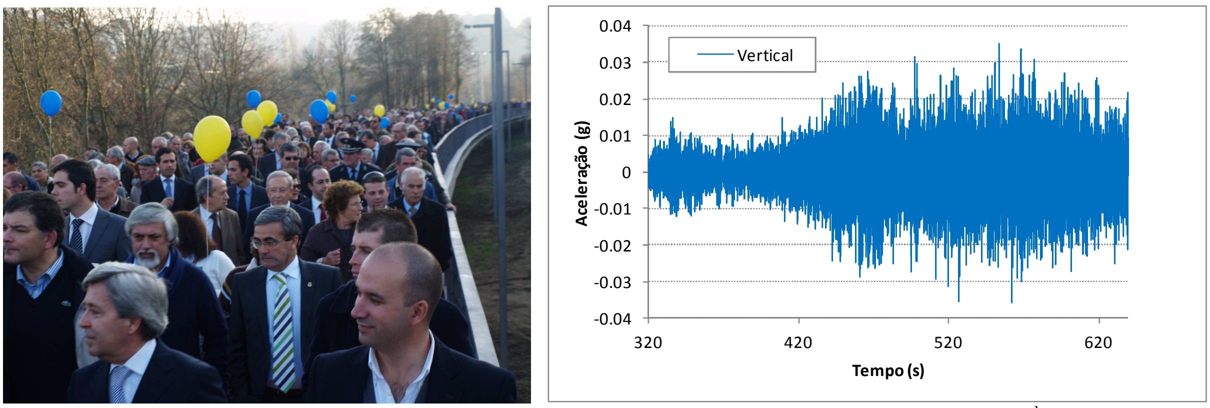


Fig. 8 Inauguration of the footbridge. Example of vertical acceleration record at 1/3rd span

IMPLEMENTATION OF DYNAMIC MONITORING SYSTEM

In order to check the efficiency of the implemented TMDs in service, a dynamic monitoring system was installed in the bridge and a one-year monitoring program was established in agreement with the footbridge Owner. This system comprises 7 accelerometers and 4 thermal sensors which are connected to an acquisition system.

Two of these accelerometers, designated as accelerometers 1 and 2 in Fig. 9, measure directly the vibration of the deck at mid-span in the horizontal and vertical directions. According to the same figure, the accelerometer 3 measures vertical accelerations close to 1/3rd span. Accelerometers 4 and 5 are mounted on each of the masses of the TMD3 (see Table 2) located at mid-span, and accelerometers 6 an 7 are mounted on the masses of the 2 TMD1 units (see Table 1) located close to 1/3rd span.

Thermal sensors were also installed to measure temperature at two sections of the deck, and are placed on the surface between the concrete slabs and the respective metallic supporting structure. Two units measure the temperature on both sides of the mid-span section, and another two other units are placed on both sides of a section located between the mid-span and the 1/3rd section.

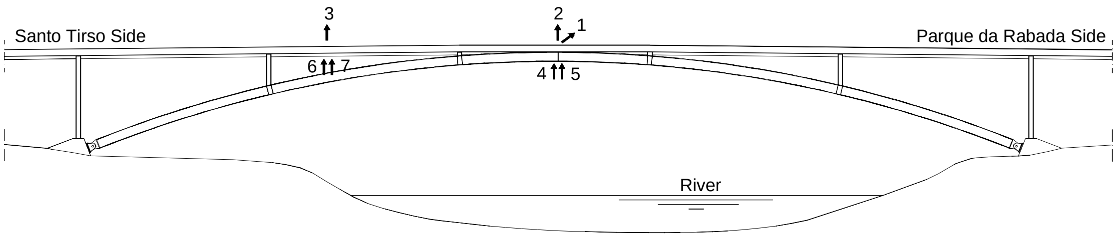


Fig. 9 Location of the accelerometers installed in the deck and TMD masses

The acquisition system consists of a compact chassis integrating two 4-channel acquisition boards for accelerations and one 4-channel board for thermal sensors (Fig. 10 (a)). The chassis is controlled by a computer installed in an observation post located in one of the lateral concrete columns of the structure (Figure 10(b)). The communication between these equipments is achieved with 2 powerlines that enable the data transfer using the electrical installation of the bridge. The communication system for local data transfer or for remote transfer of files to FEUP is also located in that box.

Data are organised in two types of files, respecting acceleration and temperature records. The signals measured by the 7 installed accelerometers are acquired for 10-minute periods at a sampling frequency of 2kHz. These records are band-pass filtered, re-sampled at 50Hz and stored in the local hard disc. In each day, 144 files containing 7 columns of acceleration time series are produced, with a total size of 40Mbytes. Temperature records are collected at the four channels at a sampling rate of 1Hz for periods of 30 minutes. In this case, 48 files are produced every day, with a size of 1 Mbyte.

Fig. 11 shows an example of a 10-minute series of acceleration records collected on one particular day (13/2/2013, 17h20) under normal use of the footbridge. Clearly the lateral amplitude of vibration at mid-span is very low, with a maximum of 0.065 m/s^2, and the vertical amplitudes are also lower than 0.5 m/s^2. The maximum vertical acceleration occurs at mid-span, with an amplitude of 0.36 m/s^2, therefore indicating maximum comfort of the footbridge. At the same time, the TMD masses of the units in correspondence with accelerometers 6 and 7 (see Fig. 9) have similar amplitude of vibration to that of the deck (0.16 m/s^2), while the TMD masses of the units in correspondence with accelerometers 4 and

5 (see Fig. 9) reach amplitudes of vibration of 0.50 m/s^2. This indicates that the TMD 1 (see Fig. 5), designed for crowd excitation, is not activated, while TMD 3 (see Fig. 5), designed for jogging activity, is activated. This should be representative of the normal use of the footbridge by small groups of pedestrians and joggers, while crowd loads should only occur on particular days and events.

(a) (b)

Figure 10 (a) Compact data acquisition system; (b) Observation post

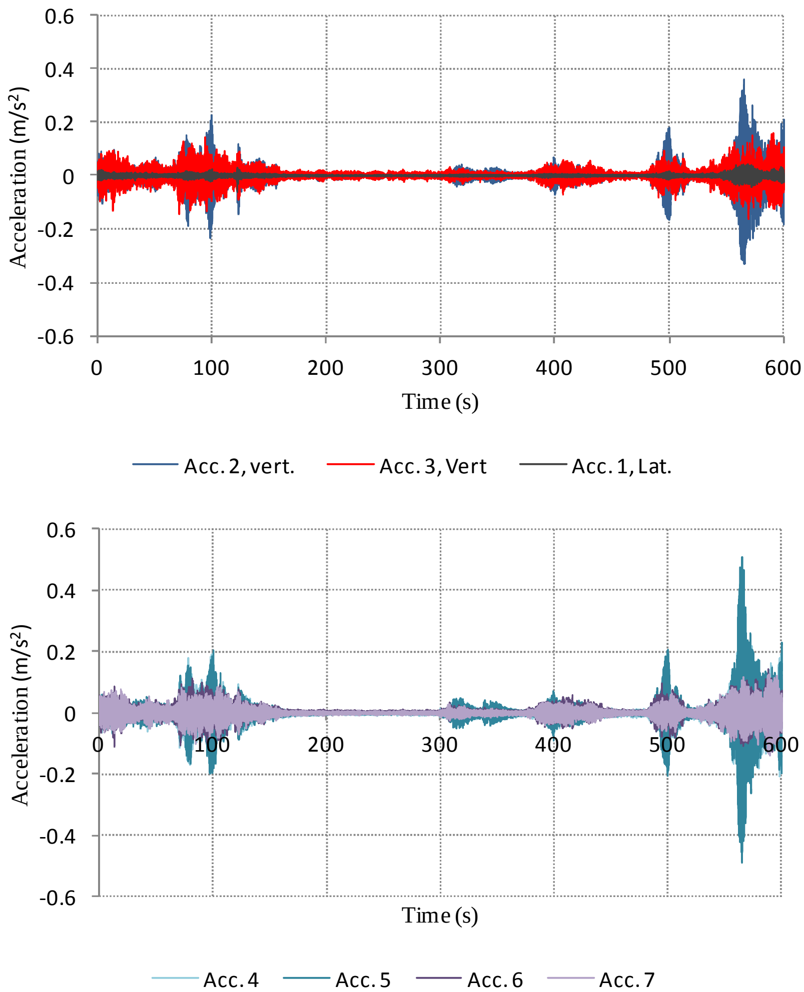


Figure 11 Example of 10- minute records of acceleration. Top: deck acceleration. Bottom: TMD mass acceleration (see accelerometer location in Fig. 9)

CONCLUSIONS

The paper describes the full process of assessment and control of pedestrian vibrations on a newly constructed footbridge. Preliminary design studies pointed to the need of implementation of measures to mitigate vibrations. The experimental assessment of the constructed structure allowed for the full characterisation and for an optimal action on the footbridge which led to the installation of 2 TMDs with a total mass of 2100 kg. The dynamic testing of the structure under identical conditions prior to and after installation of such devices could evidence the efficiency of the installed TMDs. It could be checked that, even though the maximum damping attained by the controlled structure was below predicted according to theory, the maximum amplitudes of vibration induced by joggers or by large crowds allowed the classification of the footbridge as providing medium comfort for the first situation and maximum comfort for the latter. The recently implemented monitoring system will allow a statistic characterisation of the dynamic behaviour of the footbridge. Preliminary analysis of measurements provides indication of the adequate level of comfort of the footbridge as well as indication of the most current use, associated with excitation by joggers and small groups of pedestrians, and of the activation of installed TMDs when required.

ACKNOWLEDGMENTS

The construction and assessment of the footbridge in Parque da Rabada is the result of collaboration between the Municipality of St. Tirso, the Structural Engineer SOPSEC, the Contractor DST, and finally Taylor Devices/Socometal and ViBest/ Univ. of Porto.

REFERENCES

SÉTRA/ AFGC, Footbridges: Assessment of vibrational behaviour of footbridges under pedestrian loads, 2006, 131 pp.

Butz, C.; Heinemeyer, C.; Keil, A.; Schlaich, M.; Goldack, A.; Trometer, S.; Lukic, M.; Chabrolin, B.; Lemaire, A.; Martin, P. –O.; Cunha, A. & Caetano, E. HIVOSS - "Design of Footbridges: Guideline and Background Document". European Commission, HIVOSS Project, http://www.stb.rwthaachen.de/projekte/2007/HIVOSS/download.php,2008.

SOPSEC, "Memória Descritiva e Justificativa do Projeto de Estabilidade da nova ponte pedonal sobre o rio Ave, em St. Tirso, Portugal, 2009 (in Portuguese).

CAETANO, A. and CUNHA, A., "Dynamic testing of the new footbridge over the river Ave at Parque da Rabada", ViBest/FEUP Report, 2011a (in Portuguese).

CAETANO, E. and CUNHA, A.,"Consultancy for the design and implementation of passive dampers at the new footbridge over the river Ave at Parque da Rabada", ViBest/FEUP Report, 2011b (in Portuguese).

CAETANO, A. and CUNHA, A., "Dynamic characterisation of the new footbridge over the rio Ave at Parque da Rabada after installation of TMDs", ViBest/FEUP Report, 2012 (in Portuguese).