IMPLEMENTATION OF A SEMI-ACTIVE TUNED MASS DAMPER TO REDUCE VIBRATIONS IN A SLENDER FOOTBRIDGE

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Summary: *This paper describes the work involving the implementation of a control system aimed at reducing vibrations in a slender footbridge located at FEUP campus. This structure was extensively studied in the past, mainly due to the clear exhibition of very perceptible vibrations induced by pedestrian loads. For that reason, a passive Tuned Mass Damper was installed in one of the spans of the structure for research purposes. That device was then upgraded to work as semi-active instead of having a purely passive functioning. In this context, this document starts off by characterising the footbridge in terms of its dynamic properties and vibration problems, and how the passive TMD contributed to its attenuation. Thereafter, the interest in a semi-active solution is justified and detailed in terms of the semi-active mechanism and adopted control law. After performing laboratory tests, the device was installed in the structure and the first results regarding its functioning are presented.*

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.

In these situations, the implementation of control systems can improve the structural performance by reducing the vibration levels to acceptable values, which are established for each case. To achieve this, several passive, active, semi-active or hybrid control schemes can be adopted. The most popular techniques are those that involve passive systems because, compared to other cases, they are more reliable, more robust, relatively more economical and require low maintenance. When controlling harmonic vibrations, one of the most interesting devices is the vibration absorber, also known as Tuned Mass Damper (TMD). However, these devices may have some functioning problems common to passive systems. In fact, because they are purely passive, they don't have the possibility of adapting themselves to the actual characteristics of the external actions or to the identified structural properties. In case

of external harmonic excitations, to work properly TMDs must be accurately tuned to the system's vibration frequency, otherwise they will lose a significant portion of their efficiency. One possible way is to solve this problem is to use active TMDs, which are not so sensitive to the vibrating frequency of the structure [1]. However, active systems are not so attractive because of their cost, particularly dealing with large structures. Indeed, they require sophisticated technology as well as powerful actuators and energy supply, which also calls for a lot of maintenance. For these reasons, in last few years, special attention has been given to semi-active systems which are still based on feedback control schemes, but require much simpler technology and actuators. Besides, they can work with a small amount of energy, including the possibility of operating with batteries [2].

In this context, this paper presents the research work involving the application of a semi-active in the functioning of TMD, aimed at correcting tuning problems. This is achieved by imposing a correct phase angle between the motion of the structure and the inertial mass of the TMD, which can be achieved by imposing blocking actions at certain positions of the device. For this purpose, the phase control law specifically developed in the context of this research project will be used [3]. The control of the inertial mass is implemented by using a solution based on a Magneto-Rheological (MR) damper, which seems to be a very interesting device and recently gained a certain degree of popularity in the Structural Control area [2].

The development of this research work comprises the following stages: *i*) Numerical simulations confirming the effectiveness of the proposed control system; *ii*) Development of a prototype; *iii*) Laboratory testing to confirm the actual operation of the device and to make corrections to its functioning; *iv*) Implementation in an actual structure. This paper gives an overview about the main results obtained in this application, which involves an actual footbridge located at FEUP campus.

2 CHARACTERISATION OF THE FOOTBRIDGE

2.1 General description

The footbridge under analysis provides a pedestrian link between the main buildings of FEUP and the student's canteen and parking areas (Figure 1). This structure is characterized as a stress-ribbon footbridge formed by two spans of 28m and 30m. The deck comprises four prestressing cables embedded in reinforced concrete and it takes on a catenary shape over the two spans with a circular curve over the intermediate support. The deck is a rectangular cross-section of external design dimensions of 3.80m×0.15m.

Figure 1: General view of the footbridge.

2.2 Identified and calculated modal parameters

The natural frequencies of the structure were identified through ambient vibrations tests using four seismographs including force-balance accelerometers, duly synchronized via GPS [4]. The ambient response of the system was recorded according to several setups, using two fixed reference stations and eighteen other measurement stations distributed over the total length of the deck. Using the conventional peak peaking method applied to the set of FRFs, it was possible to identify the natural frequencies (listed in Table 1) as well as the corresponding vibration mode shapes, some of which are represented in Figure 2. The numerical model developed to represent the dynamic characteristics of the system was obtained by considering the experimental results, by taking into account the geometrical nonlinearity of the structure and given the different phases of the construction process [4]. Table 1 and Figure 2 also include a comparison between analytical and experimental results in terms of natural frequencies and modal shapes.

Order	Measured frequency (Hz)	Calculated frequency (Hz)	Type of mode
1	0.99	0.949	First antisymmetric (two spans, opposite phase)
2	2.083	1.99	First symmetric (two spans, in-phase)
3	2.178	2.143	Second antisymmetric (L=30m)
4	2.423	2.417	Second antisymmetric (L=28m)
5	3.753	3.334	Second symmetric (two spans, opposite phase)
6	3.857	3.869	Second symmetric (L=30m)
7	4.229	4.381	Second symmetric (L=28m)
8	5.726	5.915	Third antisymmetric (L=30m)
9	6.517	6.82	Third antisymmetric (L=28m)
10	8.262	8.271	Fourth symmetric (two spans, opposite phase)

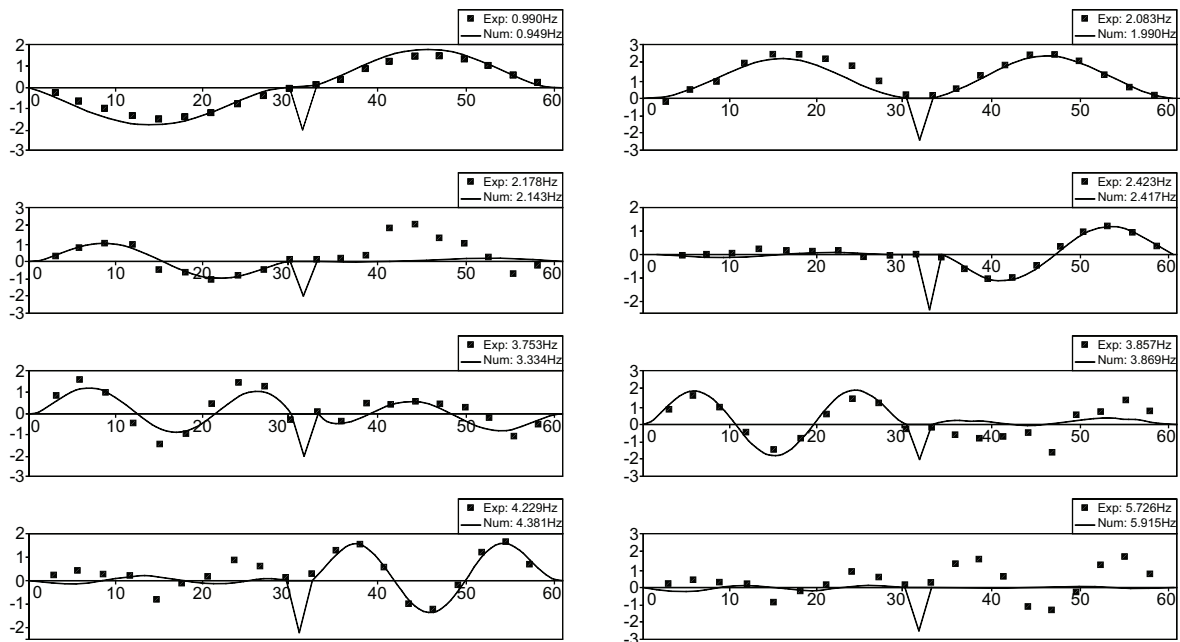Table 1: Identified and calculated natural frequencies.

Figure 2: Identified and calculated vibration modes.

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An expedite method adopted to estimate the damping ratios associated with the first vibration modes consists of exciting the structure with a frequency close to a 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 analysing the free decay curve, the respective damping ratio is estimated by using the logarithmic decrement method. Using excitation frequencies around 1Hz and 2Hz and it was possible to identify a damping ratio of about 1.7% for the 1st vibration mode and 2.6% for the 2nd one.

3 CHARACTERISATION OF THE MEASURED VIBRATION LEVELS

3.1 Description of the continuous data acquisition system

The footbridge under analysis has been extensively studied in the context of several research areas, such as dynamics of footbridges [4], Structural Health Monitoring [5] and Structural Control [6]. In this context, given the great interest in measuring the structure for long periods of time, a permanent data acquisition system has been implemented since 2009.

Taking into account the configuration of the structure's vibration modes, 4 critical sections were selected, namely at $1/3^{rd}$ and mid-span of each main span of the footbridge, as indicated in Figure 3. Each section (S1 to S4) is instrumented with a piezoelectric accelerometer measuring vibrations in the vertical direction, as well as a thermal sensor. The acquisition system is composed of hardware from National Instruments controlled by a desktop computer. All data is organized and stored in a robust database and made available through a server.
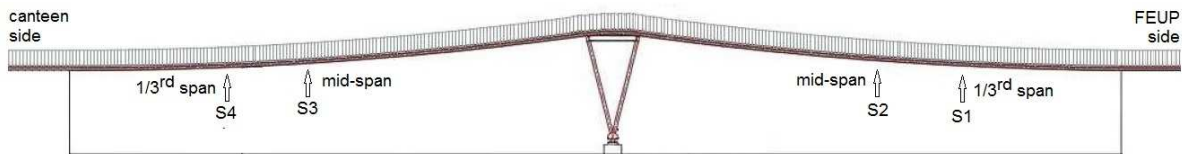

Figure 3: Location of measurement sections (S1 to S4).

3.2 Characterization of the measured vibrations

Figure 4 represents the maximum vibration levels during 2011 at section S4 as representative of a period of the structure without any control system. The horizontal axis represents the 365 days of the year, and the vertical axis represents one day divided into 144 intervals of 10 minutes. The dark areas correspond to periods of low levels of vibrations, which occur essentially in night periods, and in lighter areas the levels of vibration are higher. The coloured bar on the right side establishes a correspondence between colour and RMS acceleration (in m/s^2). Analysing this graph, several interesting conclusions can be drawn just from observing the structure's vibration levels: *i*) Pedestrians use the footbridge mainly during lunch period; ii) Time shifts at the end of March and October immediately change people's habits; *iii*) During summer holidays, in August, there is a reduced use of the footbridge; *iv*) Weekends are characterized by the structure's low vibration levels.

In any case, looking at Figure 5, where the daily maximum vibration levels over 2011 at section S4 are depicted, it can be observed that vibrations often reach values higher than 0.5m/s^2, which highlights the structure's "lively" behaviour. In fact, by framing these vibration levels in the comfort classes suggested by Sétra [7] or Hivoss guidelines [8] indicated in Table 2, it can be concluded that the footbridge provides only medium and

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.
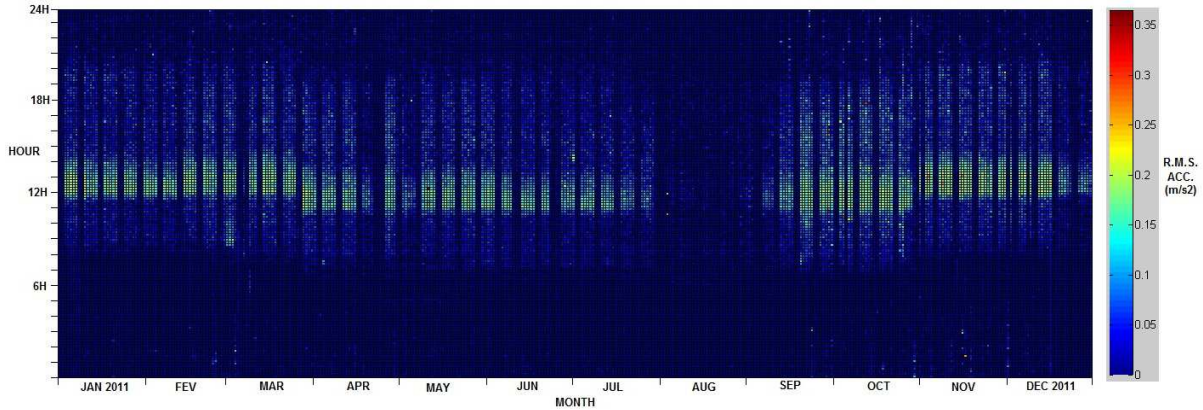
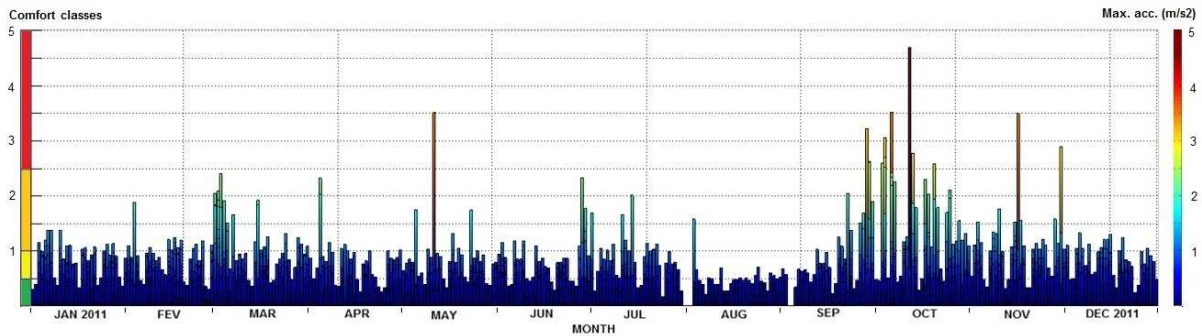Figure 4: RMS accelerations during 2011 at section S4.

Figure 5: Maximum daily accelerations during 2011 at section S4.

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

4 IMPLEMENTATION OF A TUNED MASS DAMPER

4.1 Conception of the control system and numerical evaluation of efficiency

By consulting Table 1, it can be stated that the structure has 3 natural frequencies in the range of 2 – 2.5Hz, which is considered critical in terms of the possibility of occurring resonance phenomena with the pedestrians' step frequency. From this point of view, 1st vibration mode with a frequency close to 1Hz is not critical, and the same can be concluded for the vibrations modes higher than the 4th order.

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Assuming that the 2nd to 4th vibration modes (inside the critical range) are the candidates to be controlled, it is important to mention that 2 of these 3 modes are local, i.e., have significant modal components only in one (and different) span of the footbridge. As a result, it is not possible affect the dynamics of all these modes with only one control device. To consider this problem, Figure 6 represents a superposition of the numerical main vibration modes of the system. The small dots define equal modal amplitudes of the critical vibration modes in each span. In the first span, section 13 has equal modal amplitudes of the 2nd and 3rd vibration modes with natural frequencies of 1.99 and 2.14Hz, respectively. In the second one, section 49 equalizes modal amplitudes of the 2nd and 4th vibrations modes with natural frequencies of 1.99 and 2.42Hz, respectively. Because only one TMD is available for installation, it was decided to study its application to the second span, mainly because it is more accessible and has vibration modes with more separate frequencies. In this case it would be possible to reduce the dynamics of the 2nd (global) vibration mode and the 4th (local) one. However, it is necessary to consider that one TMD cannot be optimally tuned to both vibration modes, which means that a decision about the frequency of the device must be taken.

Given the proximity of mean step frequency of pedestrians around 2 Hz, the 2nd vibration mode of 1.99 Hz frequency is more critical than the other of 2.42 Hz, which means that preferably the TMD should be tuned to this lower frequency. However, the existing TMD for this project has a minimum vibrating frequency of 2.06 Hz, meaning that the TMD cannot be optimally tuned to this vibration mode. Even so, this corresponds to an intermediate tuning between the two critical vibration modes, which still leads to a level of reduction of vibrations associated with these modes.
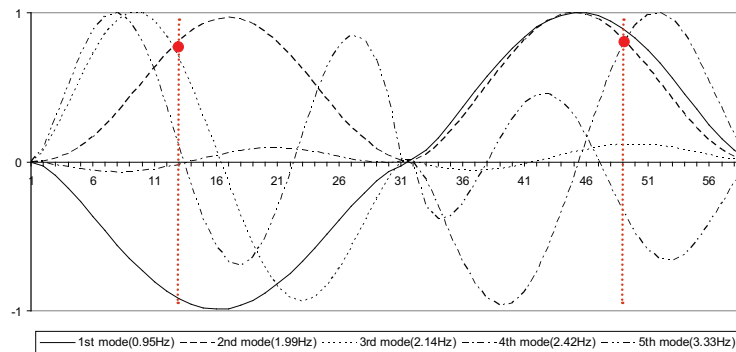

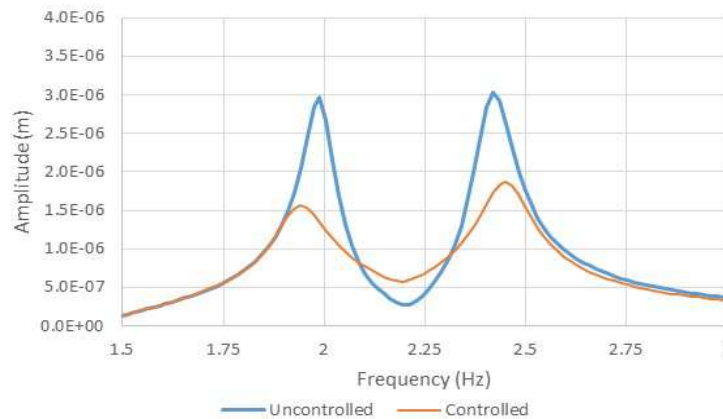Figure 6: Superposition of the first vibration modes shapes.

Figure 7: FRF of the structure at section S1.

The experimental identification of the TMD used to control vibrations in the footbridge concluded that, besides the natural frequency of 2.06 Hz, the device has a total mass of 550 kg and an equivalent viscous damping ratio estimated between 6 and 8%. Taking into account these properties and the structural characteristics described in section 2.2, an inclusion of the device at section S1 of the deck would lead to the Frequency Response Function (FRF) indicated in Figure 7. As mentioned in reference [9], this FRF does not reflect the effective reduction of vibration that can be achieved with this TMD, mainly because the actual pedestrian load does not induce a steady-state structural response, and also because the TMD is only activated for a certain level of acceleration of the deck, being blocked with the structure most of the time. As a result, the expected reduction of vibrations should be less than suggested by Figure 7.

4.2 TMD efficiency in reduction vibrations

The passive TMD was installed in early 2013 at a section S1, close to the 1/3rd span on the FEUP side. The effect of the control device in reducing vibrations in the structure can be observed by analysing Figures 8a) to 8d), where the maximum acceleration values over the last 3 years are plotted. During 2011 and 2012 the structure is not controlled (first 2 left graphs) and in 2013 the footbridge is considered controlled by that device (graph on the right side). The organization of the graphs in four rows aims to depict the vibrations in the four critical sections of the deck (S1 to S4), corresponding approximately to the anti-nodes of the main vibration modes.

From the analysis of the mentioned figures, it cannot be said that there is a significant reduction of vibration levels in the footbridge due to the installation of the TMD in 2013. However, it is clear that in the sections where the dominant vibration modes are those that are under the influence of the TMD (2nd and 4th modes), a slight reduction in the number of occurrences of higher levels of acceleration is observed. It is also interesting to notice by consulting 8c) that, although the TMD is positioned on the FEUP's side span, it seems to slightly reduce the dynamics of the other span of the footbridge. The same doesn't happen with the vibrations measured in section S4, located at 1/3rd span, on canteen side (Figure 8d)), which is mainly dominated by the contribution of a local vibration mode (3rd mode) of 2.28 Hz frequency, and therefore, out of the influence of the TMD.

5   UPGRADE OF THE CONTROL DEVICE TO A SEMI-ACTIVE TMD

5.1 Justification of a semi-active system and the adopted control law

Because there are several critical natural frequencies close to 2 Hz, a single device cannot simultaneously control these vibration modes. As a rule, as many vibration modes to be controlled as there are TMDs will be necessary. In addition, the TMD used in this work is not optimally tuned to any vibration mode, which limits its efficiency in reducing vibrations.

This problem may be attenuated by implementing a semi-active mechanism in the functioning of the control device, in such a way that it automatically tunes to the actual vibrating frequency of the system, even enabling the control of several vibration modes. This would cause the TMD to work in a more proper manner in the control of each mode individually, which in theory constitutes a better solution than the implemented passive solution.
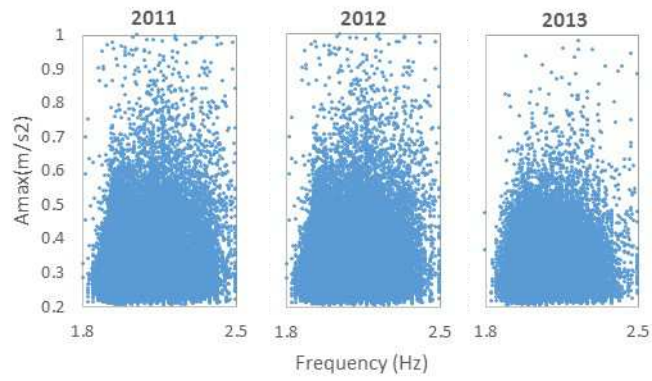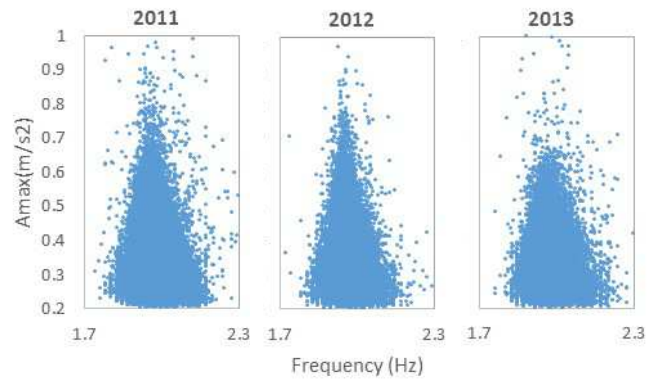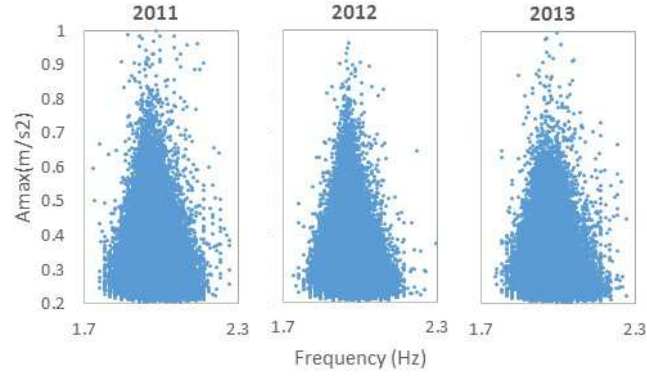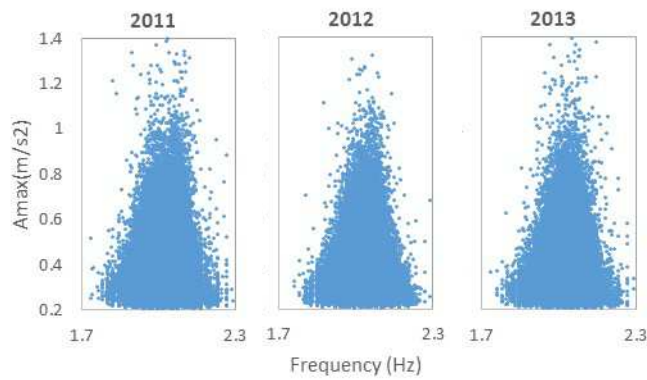
Figure 8: Maximum vibration levels at sections: a) S1; b) S2; c) S3; d) S4

5.2 Adopted control law

This objective may be achieved by using a control law designated by phase control. In the context of this research, a simplified version of the classical formula was derived [3]. The goal was to improve the functioning of semi-active TMDs by simplifying the measurement process and reducing the number of variables involved, making the control system more feasible and reliable. Because the control law is of ON/OFF type, combined with appropriate trigger conditions, the activity of the actuation system may be significantly reduced, which may be of a few seconds a day in many practical cases, increasing the durability of the device and reducing its maintenance. Moreover, due to the ability of the control system to command the motion of the inertial mass, the semi-active TMD is relatively insensitive to its initial tuning, resulting in the capability of self-tuning and in the possibility of controlling several vibration modes of a structure over a significant broadband frequency [3]. The proposed control law is defined as follows:

$$\begin{cases} \ddot{x}_1 \cdot \dot{x}_2 \leq 0 \Rightarrow c_2 = c_{\min} \\ \ddot{x}_1 \cdot \dot{x}_2 > 0 \Rightarrow c_2 = c_{\max} \end{cases} \tag{1}$$

In this case, x_1 is the displacement of structure where the TMD is attached, with the second derivate as the respective acceleration, and x_2 is the displacement of the TMD mass, with the first derivate as the respective velocity. $c_{\min}$ and $c_{\max}$ are damping constants imposed on the control device, assumed to be an MR damper, as a means of applying control actions by imposing a correct phase angle between the motion of the TMD mass relative to the structure.

The effect of the application of this control law can be seen in the system dynamic amplification curves of Figure 9a), where an example of an undamped single degree-of-freedom (1-DOF) of 1 t mass and 2 Hz natural frequency have an attached TMD characterized by a mass ratio of 1%. If the semi-active (SA) TMD has the same tuning as the optimal TMD, it exhibits a higher efficiency than the passive device. However, the great advantage of the semi-active solution lies in its ability to adjust its vibration frequency in the presence of detuning as shown in that figure, where the case of a detuning of the natural frequency of the semi-active TMD of 5% is represented. The interest in using semi-active TMDs increases when extending their use in controlling vibration modes with frequencies away from their initial tuning. This can be seen in Figure 9b), where a single semi-active TMD is used to control a 3-DOF system, by contrast to the use of 3 independent passive TMDs tuned to each natural frequency. Knowing that the semi-active TMD is passively tuned to the 2nd system frequency, its ability in reducing the dynamics of vibrations modes out of its tuning is truly remarkable.
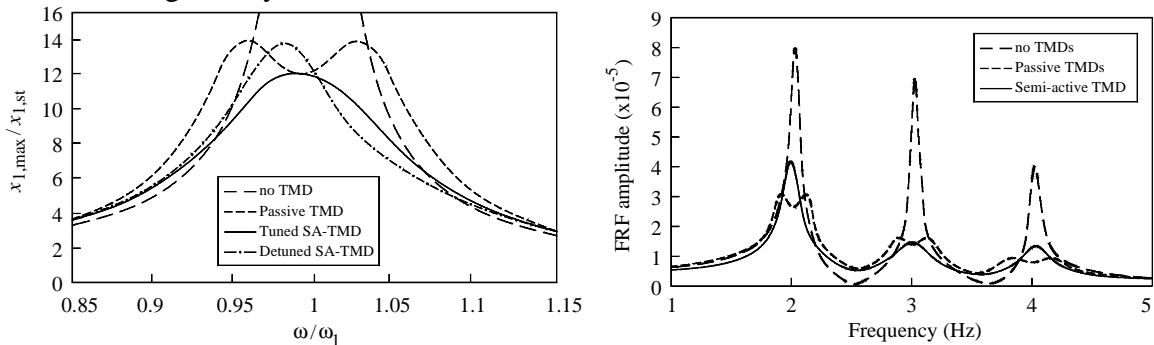

Figure 9: Dynamic amplification curves comparing the effect of passive and semi-active TMDs: a) 1-DOF system; b) multi-DOF system

Regarding the implementation of the semi-active TMD in actual structures, the control law indicated in equation (1) may by slightly adapted in order to minimize the control functioning without affecting its effectiveness. In particular, combined with adequate trigger conditions, the activity of the actuation system can be reduced, with significant benefits in terms of durability of the control device. The proposed control law takes the following form:

$$\begin{cases} \ddot{x}_1 \cdot \dot{x}_2 \leq 0 \Rightarrow c_2 = c_{min} \\ \ddot{x}_1 \cdot \dot{x}_2 \cdot \alpha > 0 \Rightarrow c_2 = c_{max} \end{cases} \qquad (2)$$

$$\alpha = \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \qquad (3)$$

In this case, α is a variable that only assumes binary values, 0 or 1, which, in turn, depends on other α_i variables (i=1, 2, 3), also binary valued. Each α_i is associated with a specific condition. The first condition is related to evaluation of the actual levels of vibration of the structure and the need for the existence of a control action. If the vibrations levels are considered excessive according to some design criteria, the control should be activated, i.e., α_1=1. By contrast, if the vibration levels are low, the structure does not need to be controlled, which leads to α_1=0. This is an important condition because, in many practical situations, structures have excessive vibrations for short periods of time, which greatly decreases the activity and saves the control system.

The second condition is related to the fact that the blocking of the motion of the TMD's inertial mass does not need to occur twice in a cycle. As indicated in reference [3], the application of the control law expressed in equation (1) corrects the phase of the motion of the mass in both its extreme positions. A possible simplification is to correct the phase once in a cycle, which would be sufficient and desirable in most cases. This decision to correct the motion once or twice in a cycle can be implemented by observing the acceleration signal of the TMD mass because it has opposite signs at each extreme position. For instance, if it is intended to correct the motion once in a cycle when the mass is in positive acceleration extreme, α_2=1 for positive acceleration and α_2=0 for negative acceleration. If the option is to correct to motion twice in a cycle, α_2 will always be set to 1.

The third condition is about the error (ε) allowed in the evaluation of the condition expressed in equation (1). In other words, it is not be necessary for the phase angle of acceleration of the structure and the velocity of the TMD mass to be exactly in the opposite phase. In practical cases, it would be enough to have a very close opposite phase instead of an exact one. Therefore, the control signal should be only activated, i.e., α_3=1, if the product of the second equation of inequality (2) is greater than the error ε, being null in the opposite case.

6 LABORATORY TESTS

6.1 Description of models and equipment

Before the installation of the TMD in the bridge to work passively for a long period of time, the device was prepared to work as semi-active and tested in the laboratory. The objective was to characterize its dynamic properties and mechanical functioning, as well as to validate the previously described control strategy. The device developed for this application is depicted in Figure 10a), which is composed of several layers of individual masses that are connected to each other and can be added or subtracted in order to achieve a desired level of total mass with a maximum of 550 kg. The mass is guided by means of shafts and has 4

compression springs connecting it to the structure. The damper used in this device is of MR type which can work passively if no electrical current is applied, or can work in semi-active mode which is the ultimate purpose of its use. The TMD was installed under a concrete slab which, in turn, is supported in steel frame by means of helical springs. This structure can be excited either manually or by means of a shaker installed at the top of the slab (Figure 10b)).

In order to measure all variables involved in the control problem, several sensors were installed. The TMD is instrumented with an LVDT to measure relative displacements between the mass and the structure, and the damper force is measured by means of a load cell installed between the MR damper and the structure (see Figure 10c)). The vertical motion of the slab and the TMD mass is measured by 2 accelerometers. All these sensors and equipment are controlled by a National Instruments PXI platform, taking advantage of the real-time operating system specifically designed to guarantee determinism in control loops.

6.2 Dynamic properties of the laboratory model and TMD

The concrete slab of dimensions 1.5×2.5 m^2 area and 0.2 m thickness that is used to suspend the TMD has a mass of approximately 2 t and functions as a primary structure. Its natural frequency was measured and evaluated at 3.5 Hz. Because it is supported on helical springs, a free decay test revealed a rather low associated damping ratio, such that, after several minutes, the slab was still vibrating.

Similarly, the TMD was subjected to dynamic tests which are described in reference [9]. It was concluded that its springs have a non-linear behaviour depending on the compression ratio associated with several TMD masses. Considering the total mass of 550 kg, the natural frequency was estimated at 2.06 Hz. Given the MR damper type used with this device, the estimated equivalent viscous damping ratio was estimated as varying from 6 to 8%.
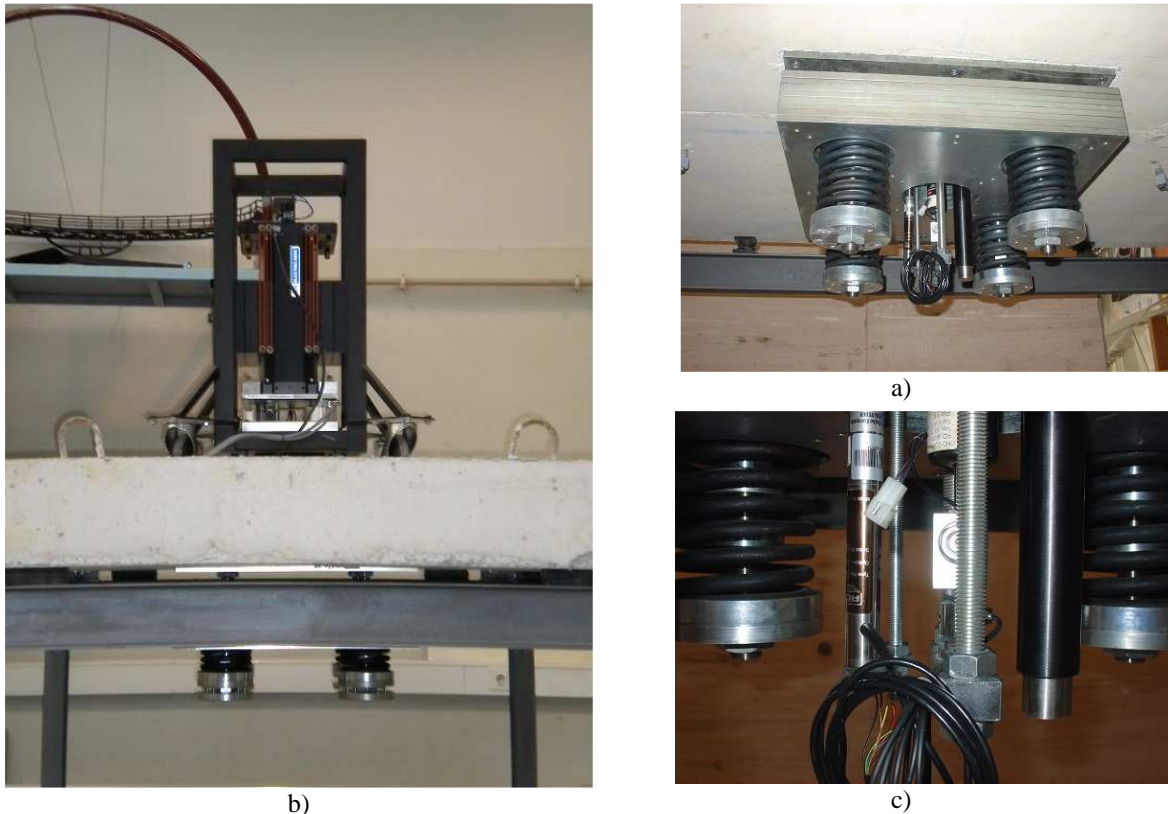

Figure 10: Laboratory setup: a) Semi-active TMD; b) Shaker on the slab; c) Detail of the LVDT and force sensor

6.3 Experimental verification of the semi-active system

The objective of the laboratory tests was to validate the functioning of the semi-active TMD comparing the numerical predictions with the experimental results, as well as to verify the effectiveness of the control device in reducing the slab vibrations. In this case, given the natural frequency of the structure to be controlled of 3.5 Hz, the use of an out-of-tuning semi-active TMD of frequency 2.06 Hz is a real challenge.

In a first stage, a numerical model of the coupled system slab plus semi-active TMD was developed. Figure 11a) includes a representation of the FRF of the slab response where a first peak can be seen associated with the functioning of the TMD and the second one representing the large amplitude motion of the slab. If the TMD was properly tuned to the natural frequency of the primary structure, two low picks with same amplitude would characterize the system response. However, the TMD is not tuned and the peak of the structural response is not damped. To correct this problem, the semi-active system was switched on guided by the control law indicated in equation (2). In this case, α_1 was permanently set to $\alpha_1=1$, α_2 assumes values in order to enable the semi-active system to correct the motion of the TMD mass once in a cycle, and α_3 follows the procedure indicated in section 5.2. c_{min} corresponds to the passive functioning of the TMD and c_{max} was imposed by applying an electric current of 0.5 A to the MR damper.

As a result, Figure 11a) also includes the numerical prediction of the effect of this control system, as well as the respective experimental evaluation at specific vibration frequencies. It can be observed that the semi-active TMD is able to attenuate vibrations in a frequency away from its passive tuning. In addition, the remarkable approximation between numerical predictions and experimental results can be noted, leading to the conclusion that the proposed control system may be effectively used in practical cases of actual structures. To show the effect of the control action, Figure 11b) represents the time signals of the acceleration of the structure and the velocity of the TMD mass. In this case, a resonant excitation frequency of 2.65 Hz was applied, as the control was switched on at a certain time. Before the control, the two signals are not in opposite phase, and, after switching the control on, they are compelled to have opposite phase angles corresponding to an adequate functioning of a damping system [3]. To achieve this, impulsive control forces correct the motion of the TMD at specific moments by holding its movement in certain maximum relative positions.
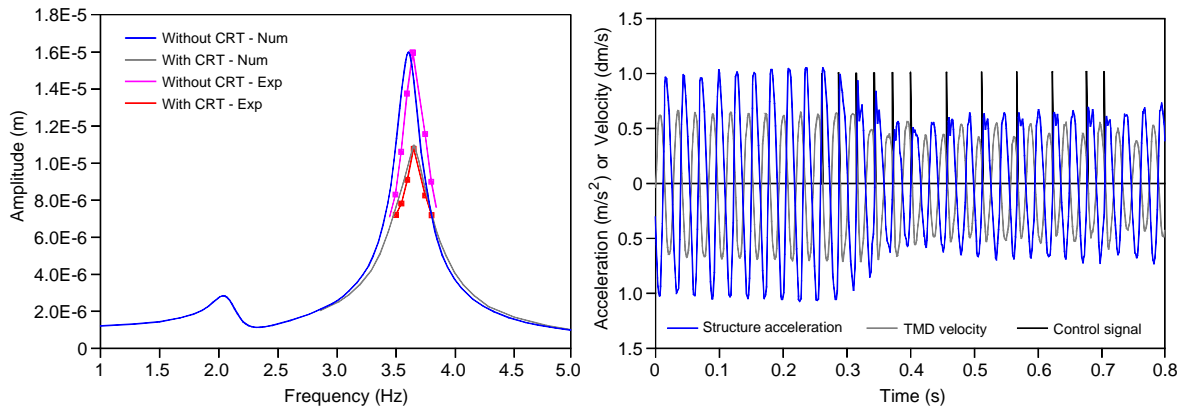

Figure 11: System with and without semi-active control: a) FRFs curves; b) Time signals

7 INSTALLATION OF THE SEMI-ACTIVE SYSTEM IN FEUP FOOTBRIDGE

7.1 Description of system functioning

The implementation of the semi-active system in the footbridge requires the installation of a local controller able to command the MR damper according to the selected control law. As a first option, it was decided to use National Instruments hardware and Labview software to manage all control process. Figure 12 shows a layout of how data flows. The control algorithm is running in a computer inside the building close to the bridge, which, in turn, is connected to an Ethernet cDAQ chassis located in a small box at the abutment of the structure. That connection uses a powerline device to establish communication between both pieces of equipment by means of the power grid, given that it was not possible to install a direct Ethernet cable between them. The MR device is then controlled from the NI chassis by inducing electrical power to the damper. Although somewhat complex, the control loop takes less than 10 ms to complete a turn, which was conducted to the establishment of a fixed-rate loop of 100 Hz.

The control algorithm only needs to receive feedback of the structure acceleration and TMD velocity to generate the ON/OFF control signal. For this purpose, 2 MEM accelerometers were used to measure the system response, as the velocity of the TMD was obtained by integrating the acceleration signal. Despite this, several other variables are measured and recorded by a parallel application intended to monitor the control process. In this case, files containing periods of 10 minutes make a complete record of the bridge response and control actions, including the TMD velocity, the control order (1 or 0), the force in the MR damper, the temperature of the external surface of the damper, the relative displacement between the structure and the TMD, and the electrical current applied to the MR damper. This last variable is measured by a non-contact LEM sensor which is also connected to a safety circuit to prevent MR damper damage in case of system failure. If the system blocks or the electrical current is excessive according to the manufacturer recommendations, a relay turns off the damper and the TMD switches to passive mode.

Figure 12: Layout of control system

7.2 First results

The described control system only recently started to work in full operation. Therefore, the effect of the implemented semi-active system in reducing the vibration levels of the structure over time can only be evaluated in a few months. Then, graphs like the ones in Figure 8 will be possible to trace and analyse.

Meanwhile, Figures 13a) and 13b) plot an example of a typical situation of the operation of the control system, where the control of vibrations induced by a pedestrian (or a group of pedestrians) crossing the footbridge is shown. In particular, Figure 13a) shows that, by means of corrective electrical current impulses, it was possible to impose an adequate phase opposition between structure acceleration and TMD velocity. It is important to mention that, in this case, the control system is programmed to start working for vibration levels higher than 0.3 m/s^2. Figures 13b) plots the force developed in MR damper with peaks of different amplitude, meaning that corrections in the TMD motion may require higher forces for higher phase angle differences, or lower forces in the opposite case. In any case, the control actions do not occur every cycle due to the inclusion of α_2 parameter in the control law, significantly reducing the control activity without performance degradation.
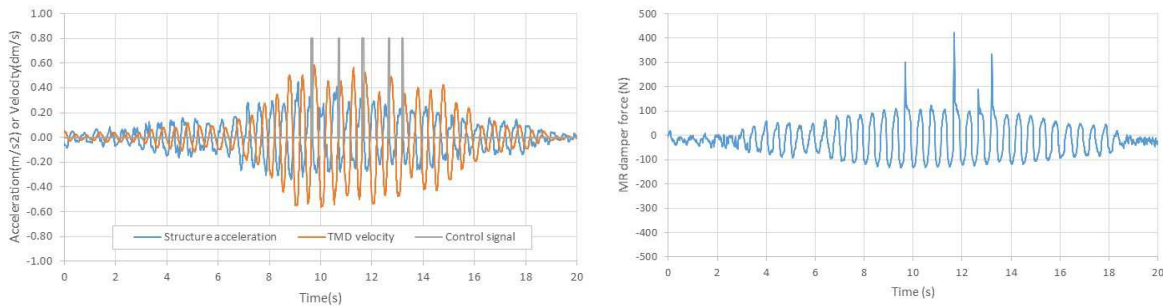

Figure 13: Functioning of the control system: a) System response and control signal; b) Force in the MR damper

8   CONCLUSIONS

This paper describes the research work involving the implementation of a Tuned Mass Damper to reduce vibrations in an actual footbridge located at the FEUP campus. This device worked passively for several months, slightly reducing the vibrations, despite not being optimally tuned to any critical vibration mode. In order to correct tuning problems and to possibly control more than one vibration mode, a semi-active system was developed. The resulting control device takes advantage of an MR damper to command the motion of the mass of the TMD based on an ON/OFF control law designated by phase control. The semi-active TMD was first tested in the laboratory, where its ability to reduce vibrations was proven. These tests also demonstrated a good match between numerical predictions and experimental results, which encouraged the implementation of the device in the FEUP footbridge. The functioning of the control system on the actual structure was described and first results were presented, demonstrating the functioning of the device as expected.

REFERENCES

[1] A. Preumont, Vibration Control of Active Structures – An introduction, *Kluwer Academic Publishers*, 1997.

[2] F. Casciati, G. Magonette and F. Marazzi, Technology of Semiactive Devices and Applications in Vibration Mitigation, *John Wiley & Sons, Ltd*, 2006.

[3] C. Moutinho, Testing a simple control law to reduce broadband frequency harmonic vibrations using semi-active Tuned Mass Dampers, *Smart Materials and Structures*, vol.24, nr5, 2015.

[4] E. Caetano and A. Cunha, Experimental and Numerical Assessment of the Dynamic Behaviour of a Stress-ribbon Footbridge, *Structural Concrete*, *Journal of FIB*, 5, No 1, pp.29-38, 2004.

[5] W. Hu, E. Caetano and A. Cunha, Structural health monitoring of a stress-ribbon footbridge, *Engineering Structures*, Vol. 57, pp. 578-593, 2013.

[6] C. Moutinho, A. Cunha and E. Caetano, Analysis and control of vibrations in a stress-ribbon footbridge, *Structural Control and Health Monitoring*, Vol. 18, Issue 6, pp.619-634, 2011.

[7] SÉTRA, Guide méthodologique – Passerelles piétonnes – Évaluation du comportement vibratoire sous l'action des piétons, 2006.

[8] Hivoss, Design of Footbridges – Guideline, 2008.

[9] C. Moutinho, A. Cunha, W. Hu and E. Caetano, Analysis of the behaviour of a Tuned Mass Damper installed in a stress-ribbon footbridge, *9th International Conference on Structural Dynamics*, Eurodyn 2014, Porto, 2014.