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REDUCING VIBRATIONS IN A FOOTBRIDGE USING A SEMI-ACTIVE TUNED MASS DAMPER

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Abstract. *The stress-ribbon footbridge located at the campus of the Faculty of Engineering of University of Porto (FEUP) is a slender structure that connects the main buildings of the university to the students' canteen. Its dynamic behaviour has been studied over the last few years in several areas of the system dynamics. First, the modal parameters in terms of natural frequencies, damping ratios and modal shapes were identified, and a complex non-linear numerical model of the structure that takes into account the various construction phases was calibrated. Then, a comprehensive study of the analysis of the vibration levels of the footbridge involving either regular and vandal loads was developed. Given the perceptible levels of vibration that often affect that structure, an active vibration control system was implemented for research purposes. Since 2009, a dynamic monitoring system composed of 4 accelerometers and 4 thermal sensors collets time series, enabling the Operational Modal Analysis and the Vibration-based Structural Health Monitoring of the footbridge. In 2013, a Tuned Mass Damper was installed in the context of a research project related to Smart Inertial Vibration Control Systems. At a first stage, this device worked passively, tuned close to the critical natural frequency in terms of proneness to resonant pedestrian loads. More recently, the control system was updated to a semi-active functioning with the objective of increasing the system efficiency. This was done because the footbridge has several critical vibration modes around 2 Hz and only one control device was installed. Using the Phase Control law, it is possible to adjust, in real-time, the vibrating frequency of the inertial mass to the structure frequency, enabling not only the correct tuning of the device but also the possibility of performing multimodal control. After a description about how Phase Control works, this paper describes the laboratory tests of the semi-active device, which showed that the system behaved as numerically expected. Then, the implementation of the device in the footbridge is described and all equipment and instrumentation are listed. Finally, the effect of the control system in reducing the vibration levels of the footbridge over the last few years is analysed. This was done by observing the data from the continuous dynamic monitoring system from 2010 until 2016. It was noted a tendency in the reduction of the peak accelerations of some sections of the deck after the installation of the passive TMD, which were even more attenuated after the activation of the semi-active device.*

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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 system in the functioning of a TMD installed in a slender footbridge. At a first stage, the device that was installed in February of 2013 worked in passive mode until September 2014. The objective was to experimentally check the effect of a passive TMD in reducing structure vibrations. This part of the work is extensively described in reference [3]. It was concluded that the control device produced a slight reduction in the number of occurrences of high levels of acceleration in certain sections of the deck. As explained in that document, this is in part due to the fact that the TMD is not perfectly tuned to any of the natural frequencies of the footbridge.

To correct this problem, the semi-active functioning of the TMD was activated by the end of September of 2014. In this case, the control action was based on the imposing of a correct phase angle between the motion of the structure and the inertial mass of the TMD, which can be achieved by introducing blocking actions at certain positions of the device. The specific version of the Phase Control law used in this work is described in reference [4] and summarized in a further section of this paper. This control law requires the continuous measurement of the structure acceleration and the velocity of the TMD, being different from other proposals that demand the measurement of displacements. The blocking of the inertial mass was 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 popularity in the Structural Control area [2]. This paper gives particular attention to the experimental tests of the semi-active system performed before being installed in the footbridge, as well as to the control system implementation and the analysis of the vibration levels of the structure over last few years, including the period without control, with the passive TMD and with the semi-active TMD.

2 CHARACTERIZATION 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.

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 [5]. 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 [5]. Table 1 and Figure 2 also include a comparison between analytical and experimental results in terms of natural frequencies and modal shapes.

Figure 1: General view of the footbridge.

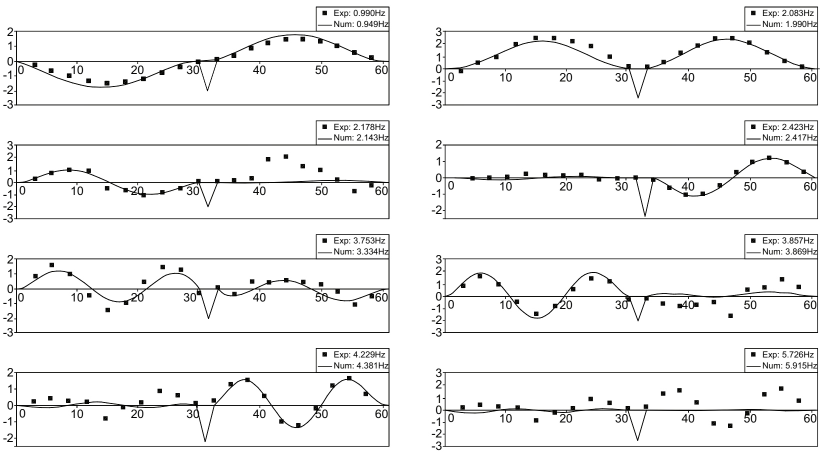


Figure 2: Identified and calculated vibration modes.

2.3 Location of the Tuned Mass Damper

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.

To considerer the problem of where to install the TMD and which vibration modes are to be controlled, Figure 3 represents a superposition of the system's numerical main vibration modes. The small dots define equal modal amplitudes of the vibration modes in the critical range inside 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 implement the TMD in 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. 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. The effect of implementing the TMD with this frequency evaluated over several years is described in reference [3].

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.

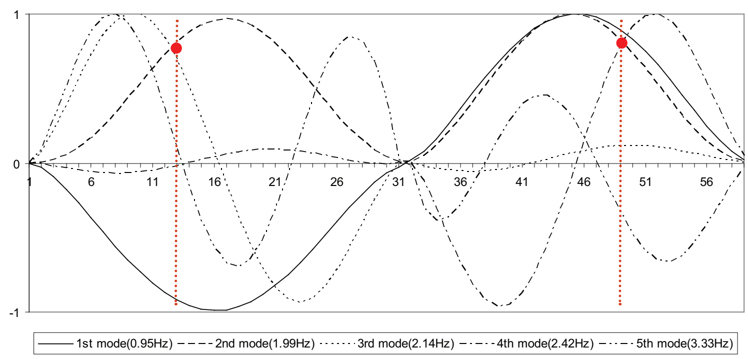


Figure 3: Superposition of the first vibration modes shapes.

3 CONTROL STRATEGY

3.1 Phase Control

The problem of detuning present in the installed TMD may be attenuated by implementing a semi-active mechanism in the functioning of the control device, in such a way that it automatically tunes the TMD to the actual vibrating frequency of the system. This means that the existing TMD may be able to control simultaneously the two critical vibration modes of the second span without the need of two control devices.

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 [4]. 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 [4]. The proposed control law is defined as follows:

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

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. On the other hand, α is defined as $\alpha = \alpha_1 \,.\, \alpha_2 \,.\, \alpha_3$, which 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 [4], 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.

3.2 Expected control effect

The effect of the application of this law in controlling a structure modelled as an equivalent single degree-of-freedom (1-DOF) can be observed by analysing the system dynamic amplification curves of Figure 4a), where an example of an undamped 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 4b), 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.

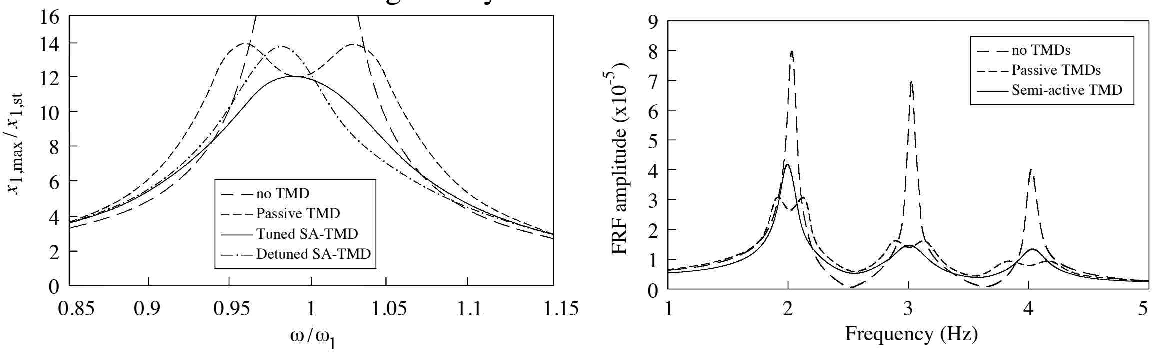


Figure 4: Dynamic amplification curves comparing the effect of passive and semi-active TMDs: a) 1-DOF system; b) multi-DOF system.

4 LABORATORY TESTS

4.1 Description of models and equipment

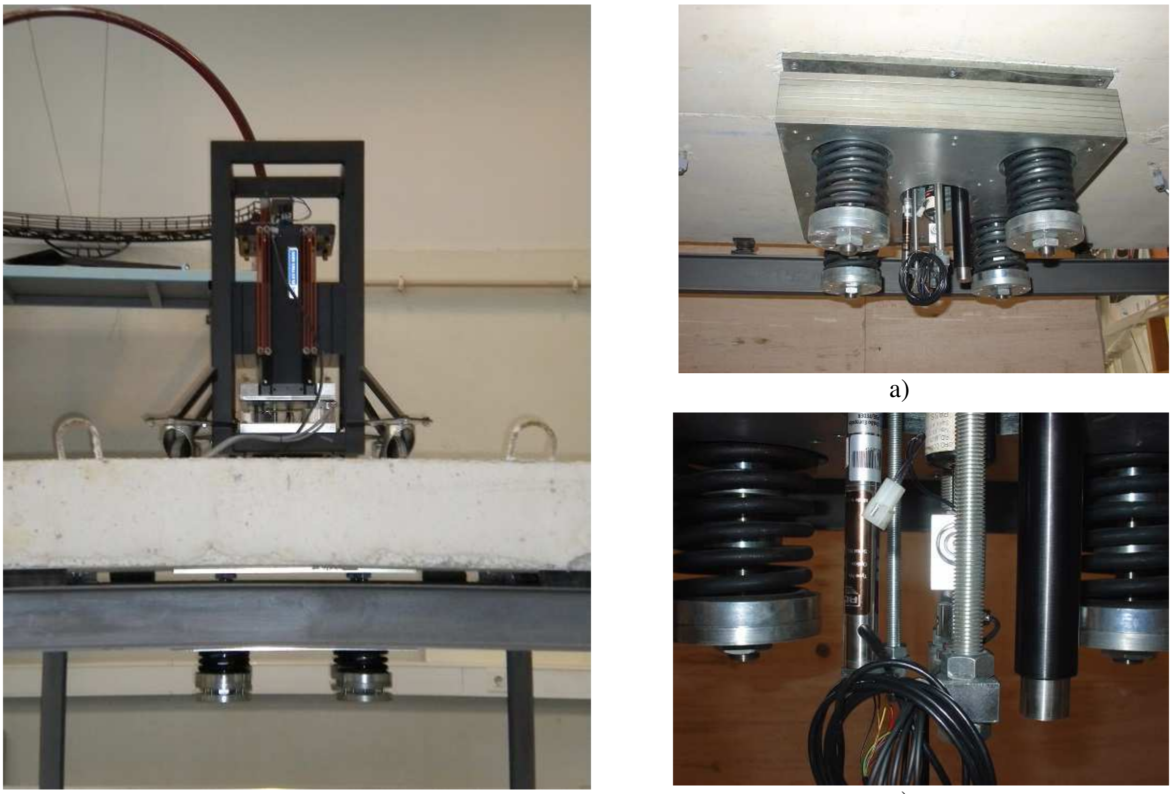
Prior to installing the TMD in the footbridge, the device was subject to several laboratory tests in order to characterize its dynamic properties and mechanical functioning. Reference [3] describes several aspects of the passive functioning of the device and reference [6] briefly describes other aspects related to the semi-active operation. In this paper, more detailed results of the tests of the semi-active component are included. The objective of these tests was to verify experimentally that the system works as predicted in the previous section, which encouraged its actual implementation in the footbridge. The developed semi-active TMD is depicted in Figure 5a), 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 5b)).

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 5c)). 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 adequate to guarantee determinism in control loops.

4.2 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 ton 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 [3]. 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%.



a) b) c)

Figure 5: Laboratory setup: a) Semi-active TMD; b) Shaker on the slab; c) Detail of the LVDT and force sensor.

4.3 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 challenge.

At a first stage, a numerical model of the coupled system slab plus semi-active TMD was developed. Figure 6a) 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 (1). In this case, α_1 was permanently set to α_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 6a) 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.

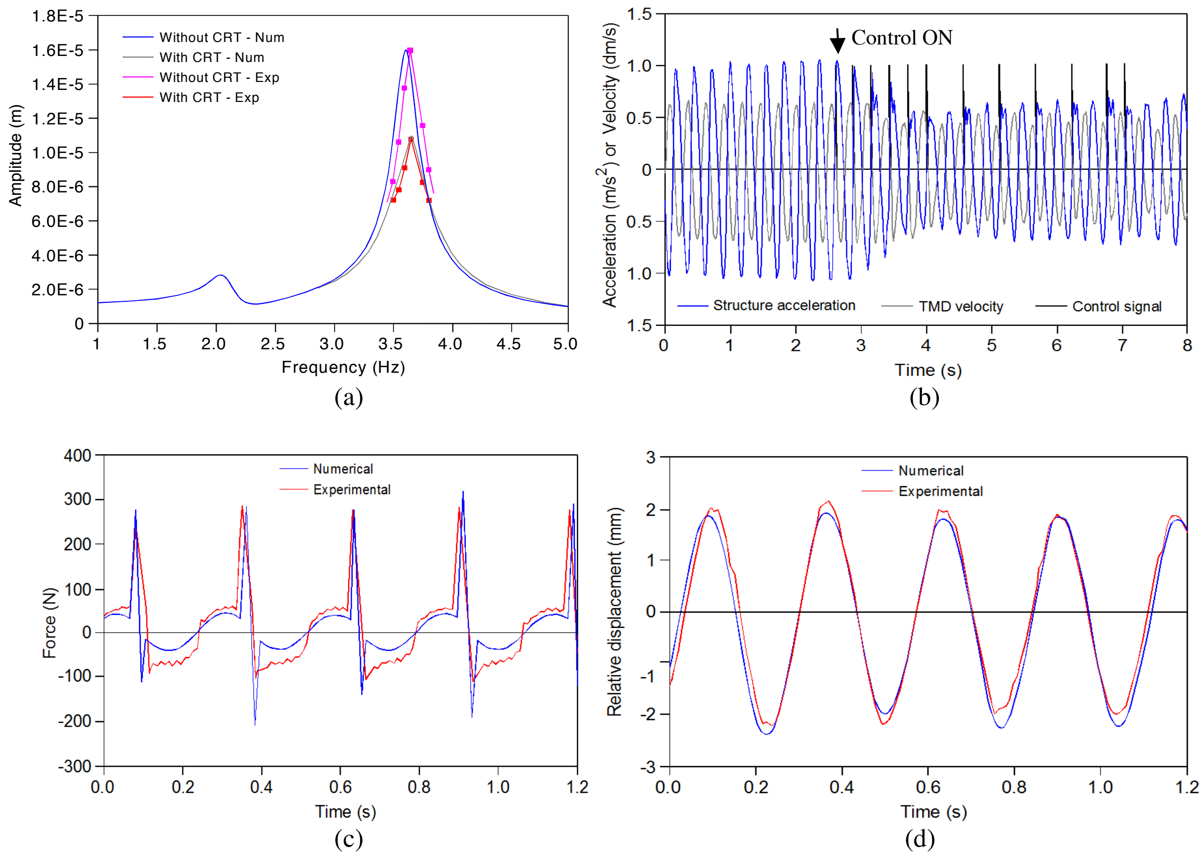


Figure 6: System with and without semi-active control: a) FRFs curves; b) Time signals; c) Force measured at the damper; d) Measured relative displacement.

To show the effect of the control action, Figure 6b) 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 3.6 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 [4]. To achieve this, impulsive control forces correct the motion of the TMD at specific moments in certain maximum relative positions. Figure 6c) depicts a sample of the time signal of the control force applied by the MR damper, where the peaks of the force may ascend, in this case, to around 300 N. On the other hand, Figure 6d) represents the corresponding relative displacement between the structure and the TMD mass, where it can be seen that the control action is produced when the relative displacement is maximum as required by the control law [4]. Again, in both previous figures there is a good approximation between the experimental measurements and numerical predictions, which allowed gaining confidence in the function of the control system and its further implementation in the footbridge.

4.4 Evaluation of time delay

Time delay is an undesirable effect in control systems which may arise from several stages of the control process, particularly during system measurement, control force computing and mechanical actuation. Time delay may be compensated by introducing some anticipation capability to the control system in such a way that the control inputs are calculated taking into account the predicted time needed for the effective implementation of the control action. However, this process usually introduces some complexity to the control algorithm which was avoided in this application. Besides, Civil Structures are characterized as having low vibrating frequencies in the range of interest (typically below 10Hz), which reduces the time delay effects.

In order to evaluate this parameter in the actual semi-active control system, a test consisting of measuring the electrical current that feeds the MR damper and the corresponding developed force when the control signal is switched on was performed. Figure 7 shows a normalized representation of these signals in order to be possible to compare them in one graph. The control signal represents the control order given by the controller, which takes some time to be implemented. At least, one control loop is always necessary to see the control effect. However in this case, the system took longer to react. The current amplifier takes some time to respond to the control input, and takes some time to reach full power. On the other hand, the MR damper seems to respond quite fast to the electrical signal.

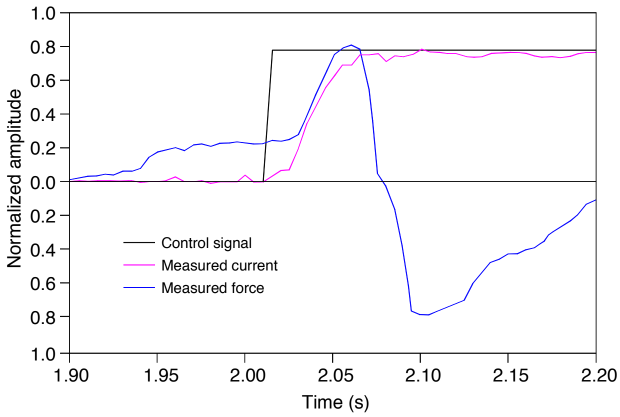


Figure 7: Evaluation of time delay.

When observing Figure 7, it is not possible to identify the exact value of the time delay. Instead, it can be said that the damper takes about 10 ms to respond to the control order, it needs about 20 ms to implement 50% of the total force, 30 ms to implement 75% of the total force and takes about 40 ms to reach the total control force. As explained in reference [4], taking into account that the control action does not need to be a complete blocking of the TMD mass, the time delay in this case may be estimated between 20 and 30 ms. In the previous comparisons between experimental measurements and numerical simulations, time delay was set at 20 ms, which led to good approximations between them.

Regarding the expected loss of efficiency of the semi-active system in controlling vibrations in the footbridge due to time delay, and taking into account that the critical frequencies are in the range of 2 – 2.4 Hz, the corresponding delay angle ranges from 14 to 17 degrees. According to reference [7], in structures with 1% damping ratio, delay angles of that order lead to a loss of efficiency of the semi-active control system less than 6% when comparing the amplitude of the controlled response with the uncontrolled one. Because this loss of efficiency is relatively low, it was decided to assume it and keep a simple control law instead of trying to compensate time delay.

5 INSTALLATION OF THE SEMI-ACTIVE SYSTEM IN FEUP FOOTBRIDGE

5.1 Implementation of the controller using NI hardware and software

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 8 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 has 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. In addition, 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.

5.2 Implementation of the controller using a microcontroller

The previous described control system operated during September 2014 and January 2015. Since then, given the potentialities and popularity of microcontrollers, the control system was substituted by a device of this type. The main advantage of this is the simplicity of the controller compared to the previous solution. In addition, there is a significant saving of power consumption. The controller may also be located very close to the TMD, reducing the length of the cables and the noise in sensors. This way, the controller receives the signals from the MEMs installed in the structure and the TMD, integrates the acceleration of the TMD to obtain velocity and generates the control signal according to the control law indicated in section 3.1.

The National Instruments hardware and software was also used in the recording of all previously indicated control variables. Therefore, it is possible to verify all steps in the control process and to monitor the control system itself.

6 EVALUATION OF THE CONTROL SYSTEM PERFORMANCE

6.1 Evaluation of the reduction of vibration levels over last few years

The effect of the control system in reducing vibration of the footbridge may be evaluated by several methods. One possible way is to obtain the FRF curve of the structure with and without control, as done in laboratory tests described in section 4.3. However, the 2nd and 4th vibration modes under control have 55 and 36 ton of modal mass, respectively, which cannot be excited with the existing means at the laboratory due to the amplitude of required dynamic force. Another possibility involves turning to tests with pedestrians or groups of pedestrians. In this case, the amplitude of the structure response is not the same for several tests of the same type, due to the variability of the excitation applied by the pedestrians. Therefore, the effect of the control system cannot be accurately quantified this way.

On the other hand, the dynamic monitoring system of the FEUP footbridge was installed in 2009 and, since then, has been measuring the accelerations at 4 critical sections, which may be used to evaluate the vibration levels over the last 7 years. This analysis may include the period when no control system was installed in the footbridge, as well as in the period that the TMD worked in passive mode, and in the period when the TMD worked in semi-active mode.

Figure 8: Layout of control system using National Instruments hardware and software.

The 4 critical sections that are being monitored by the dynamic monitoring system are located approximately at the anti-nodes of the structure's main vibration modes. Section S1 is where the TMD was positioned, which is close to the 1/3rd span of the FEUP side, and S2 is at mid-span on the same side. Sections S3 and S4 are located at mid-span and 1/3rd span of the canteen side, respectively. The location of all instrumented sections is schematically depicted in Figure 9.

The evaluation of the structure's vibration levels during last few years may be achieved by analysing Figure 10. This figure represents the measured maximum accelerations at the 4 sections of the deck from 2010 to 2016. Each dot on the graphs corresponds to an occurrence of a vibration caused by the crossing of pedestrians. It is important to mention that each occurrence was selected taking into account several criteria: *i*) time signals are filtered to remove frequency contributions above 5Hz, ensuring that only harmonic vibrations of the first vibration modes are considered; *ii*) the signal should be clearly dominated by a single frequency, in order to facilitate the construction of graphs of this type; *iii*) each occurrence should have a signal that has a first phase where the amplitude increases as pedestrians excite the structure, and then the signal reaches a maximum amplitude before it starts to decrease; *iv*) the maximum amplitude is identified by the maximum acceleration of the signal just described; *v*) the frequency is calculated taking into account the average of the periods occurring between consecutive local peaks (if the period is not constant unless a small error the signal is rejected); *vi*) only amplitudes higher than 0.2m/s^2 were considered, which are deemed to be representative of the higher levels of vibration.

Taking into account the timing of the implementation of control system in the footbridge, it is noted that the passive TMD was installed in early 2013, meaning that in 2010, 2011 and 2012 the structure is considered uncontrolled (first 3 columns of graphs in Figure 10). Then, the semi-active TMD was activated in September 2014, meaning that in 2013 and in a significant part of 2014 the footbridge may be considered passively controlled by that device (4th and 5th columns of graphs). After that, the footbridge is controlled by the semi-active TMD (last 2 columns of graphs). The organization of the graphs in 4 lines of figures aims to depict the vibrations in the 4 critical sections of the deck (S1 to S4).

From the analysis of Figure 10, even though a drastic reduction of the vibration levels has not been observed after the implementation of control systems, a progressive reduction of the vibrations can be noted over time, especially with regard to section S1 to S3. This is because of the influence of the 2nd and 4th vibration modes in these sections, which are attenuated by the control devices. In the opposite situation is S4, where no significant reduction is observed. This is because S4 is dominated by the contribution of a local vibration mode (3rd mode) of 2.28Hz frequency, which has a very limited modal component in the location of the TMD.

One possible way to quantify the effect of the control system on the structure is to calculate the number of occurrences of maximum vibration levels above a certain limit, relative to the total number of occurrences observed in each section of the deck from 2010 to 2016. Graphs of this type allow estimating the concentration of occurrences in higher vibration levels, which is an indicator of how often high accelerations occur in the structure.

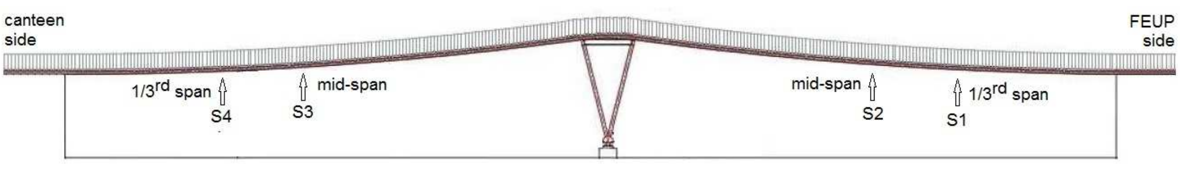


Figure 9: Location of measurement sections (S1 to S4).

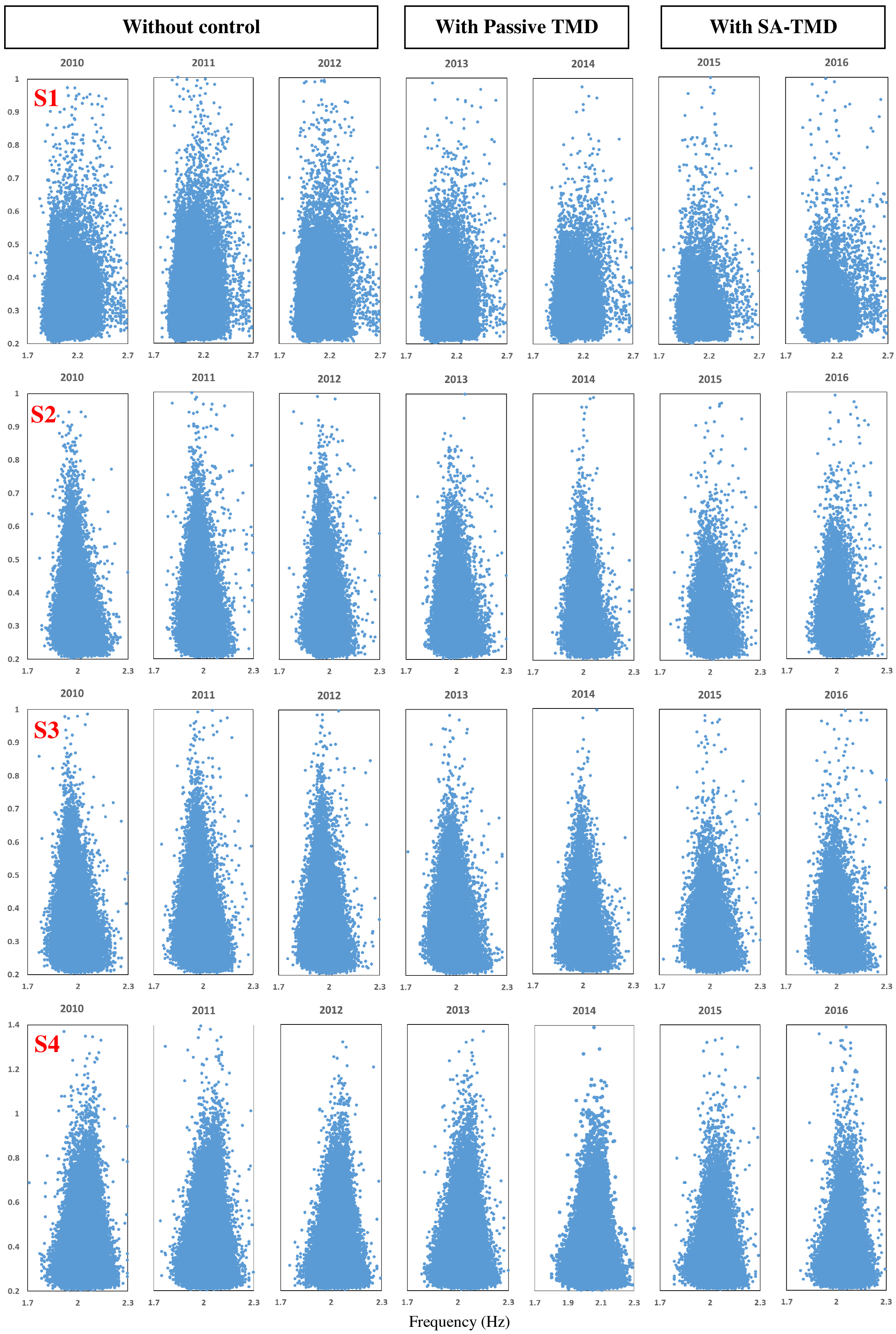


Figure 10: Maximum vibration levels (in m/s^2) at sections S1 to S4 of the footbridge from 2010 until 2016.

For this purpose, Figure 11 represents this parameter obtained by considering vibration levels above 0.4 m/s^2 and Figure 12 above 0.5 m/s^2. The limit of 0.4 m/s^2 was defined according to reference [3] where the TMD shows clear functioning above this threshold after unblocking. On other hand, the limit of 0.5 m/s^2 defines a vibration level above which vibrations are considered in many guidelines, such as Sétra [8], as not providing maximum comfort to pedestrians, thus being the main target of the control systems.

The analysis of both Figures 11 and 12 allows establishing a tendency in the maximum amplitude of the vibrations over past years. From 2010 to 2012, the footbridge was not controlled. Therefore, this period is characterized by higher levels of vibration. The implementation of the TMD clearly led to a reduction of vibrations during its functioning in 2013 and 2014. It should be emphasized that the passive device was not optimally tuned to any natural frequency. Even in this situation, it was able to produce an attenuation of vibrations by conditioning the contribution of the structural natural frequencies close to the TMD frequency, as studied in reference [3]. Figures 11 and 12 also suggest that, after implementing the semi-active system, during 2015 and 2016, the footbridge's vibration levels were further attenuated, fulfilling the objective of the semi-active system in correcting tuning problems in the passive system.

The observed reduction of vibrations over time could not be caused by any other external situation because of the following facts: *i*) the number of students during the considered period remained practically the same (about 7000 registered students); *ii*) the vibration levels of section S4, which is not significantly affected by the control system, also remained practically the same. If the reduction of vibrations was a global phenomenon, S4 would also reflect that, which is not the case. A small reduction of the vibrations in S4 during the last couple of years may even be attributed the ability of the semi-active to perform multimodal control, despite considering a limited modal contribution of the 3rd vibration mode in the section where the TMD is installed.

Despite the effect of the control system in reducing the vibration in the footbridge, it must be mentioned that the higher vibration levels occur at section S4, where the TMD has quite a limited effect. To reduce these vibrations, it would be necessary to install another local TMD in the other span, which is hampered by the difficult access to section S4 caused by the intense car traffic existing in the main street just below that place. However, the objective of installing the TMD was not to reduce the structure's overall behaviour, but, rather, to observe the effect of the installation of a passive and then a semi-active system on a structure, which was widely achieved.

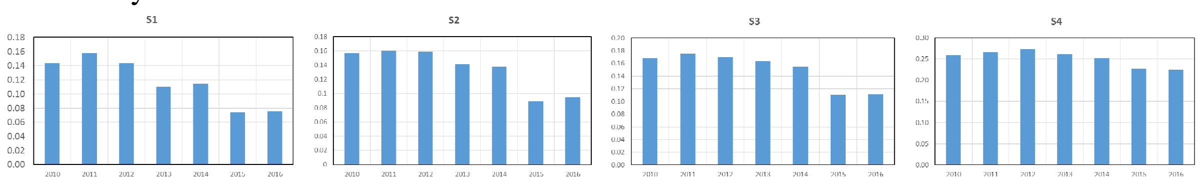


Figure 11: Percentage of occurrences of maximum vibration levels above 0.4 m/s2 relative to the total number of occurrences

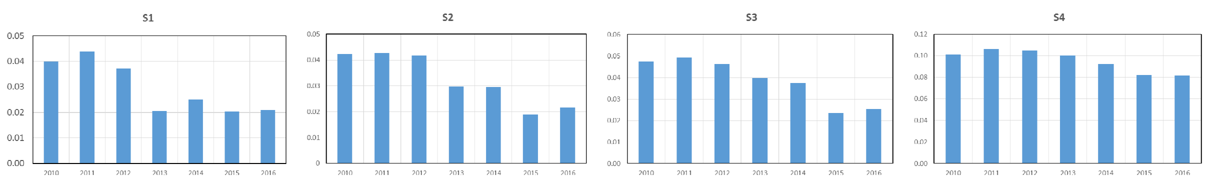


Figure 12: Percentage of occurrences of maximum vibration levels above 0.5 m/s2 relative to the total number of occurrences.

6.2 Power consumption

One of the most important features of semi-active systems is related to power consumption. Compared to active systems, they require much less power and much less sophisticated actuation systems, so much so that semi-active systems are indicated as being able to run on batteries. In order to evaluate this aspect in the semi-active control system of FEUP footbridge, this section exposes detailed information about the implementation of the control forces. For this purpose, one complete month was analysed. In this case, October 2016 was considered as corresponding to a period of classes for all students, who cross the footbridge particularly at lunch time.

The semi-active system commanded by Phase Control law applies a daily average of 232 impulses of electric current to the MR damper with a mean duration time of 41.9 ms, meaning that the actuation system is activated, on average, 9.72 s per day. Each impulse applied to the MR damper requires 0.8 Amps of electric current with a voltage of 12 V, that is, 9.6 W of power. Considering 6 months (180 days) of the operation of the actuation system in the described conditions, it would require a 12 V battery with a capacity of 0.39 Ah or 4.66 Wh, which is really a very low power. It is noted that this is the power needed only for the MR damper. The power required for the entire control system, including structure measurement by accelerometers and the functioning of the microcontroller is not included.

7 CONCLUSIONS

This paper describes the implementation of a semi-active control system used to reduce vibrations in a slender footbridge located at the FEUP campus. For this purpose, a semi-active Tuned Mass Damper including an MR damper was developed, which is controlled by Phase Control law. At a first stage, the TMD was installed in the footbridge working in passive mode. However, due to the existence of several critical frequencies around 2 Hz, the TMD could not be tuned to all these frequencies, which reduced the control efficiency. To solve this problem, the semi-active mode of the TMD was activated in order to correct the tuning of the device to the structure's vibrating frequency, enabling the possibility of performing multi-modal control.

Before being installed in the footbridge, the semi-active TMD was tested in the laboratory, enabling the identification of its main dynamic characteristics, including time delay. These tests allowed concluding that the control device was working as numerically predicted, which has encouraged the implementation of the device in the actual structure. Two types of controllers were implemented. At a first stage, the system was controlled using National Instruments hardware and software, and, secondly, it was replaced with a microcontroller specially designed for this application, which is much simpler than the former.

The effect of the control system in reducing vibrations was evaluated over the past 7 years, using the data provided by the dynamic monitoring system installed in 2009. The analysis of the vibration levels of the structure allowed observing a tendency in the reduction of the peak accelerations of some sections of the deck after the installation of the passive TMD, which were even more attenuated after the activation of the semi-active device. This fact demonstrates the potentialities of a semi-active system of this type, which increased the control efficiency and enabled the performing of multimodal control without introducing an excessive complexity in the control system. In addition, the power requirements of such a control system were evaluated. It was concluded that a battery of 12 V voltage with a capacity of 0.39 Ah or 4.66 Wh was sufficient to supply power to the MR damper during 180 consecutive days, given the actual usage of the footbridge during classes.

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