# Passive vibration control in civil structures: experimental results

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***Abstract*— This work is related to the structural and dynamic analysis of vibrations tested in a model of building-like structure which is armed by a three-story building with a Tuned Mass Damper vibration absorber. The structure it is connected to an electromagnetic shaker, which excited the support of the structure, provides forces with a wide range of excitation frequencies, including some resonance frequencies of the structure. The vibration absorber is a typical passive absorber known as Tuned Mass Damper (TMD), located over the third story building to reduce the vibrations. The overall mechanical structure is modeled using Euler-Lagrange methodology. The passive control is synthesized to actively attenuate the vibration system response via the TMD substructure, caused by excitation forces of earthquake acting on the base of the structure to improve the performance of the system and reduce the effect of vibrations. Some experimental results are included to illustrate the overall system performance.**

***Index Terms*— Passive vibration control; earthquakes; civil structures; TMD.**

## I. Introduction

The study on structural control of mechanical vibrations in buildings has recently become a research topic of importance, especially in highly populated cities, where civil structures are usually affected by the presence of transportation systems and seismic phenomena [1-3]. Research on vibration control in buildings is generally focused on the use of passive, semi-active and active vibration control schemes [4,5]. Passive schemes, also summarized by the well-known *Tuned Mass Damper* (TMD), this category of energy absorbers are limited in their response since they are designed to inject extra damping or minimize a certain frequency or a particular vibration mode on some structure. A TMD is a device consisting of a mass, a spring, and a damper that is attached to a structure in order to reduce the dynamic response of the structure. In the literature is possible to find several real cases related with building structures that contains tuned mass dampers configurations. The John Hancock Tower in Boston was designed with two dampers to reduce the response to wind gust loading. The dampers are placed at opposite ends of the fifty-eight story in order to counteract the building movement both laterally and torsional [9]. The Chiba Port Tower was the first tower in Japan to be equipped with a TMD. The purpose of the TMD is to increase damping of the first mode for both the $x$ and $y$ directions. The recent versions employs a multiassemblage of elastomeric rubber bearings, which function as shear springs, and bitumen rubber compound (BRC) elements, which provide viscoelastic damping capability [9].

The theory of structural control in buildings evaluate the use of active schemes, also well-known as *Active Mass Damper* (AMD), can provide a feedback and/or feedforward controller for a wide range of frequencies or vibration modes. The AMD control scheme usually adds extra degrees of freedom and an actuator to the original model of the structure, which usually increases the complexity of the overall system dynamics. The suppression or damping of the vibration frequencies in the system is performed by computing a control force provided by an electrohydraulic or electromechanical actuator [4]. Recently the active vibration control in structures is possible to do using smart materials and actuators, with practical application in mechanical and civil engineering. In this classification of smart devices we can remark the piezoelectric actuators and the magnetorheological dampers [10]. The schemes of active vibration control using heuristic models is possible and his applications are related with systems such as petrochemical plants, gas turbine power plants and large structure as wind turbines and buildings and others.

In this work, the modeling, characterization and experimental validation of a small scale three-story building-like structure with a TMD is considered for evaluation of an passive vibration control scheme to compensate or reduce the overall vibration response under harmonic and earthquake ground motion.

## II. EXPERIMENTAL SETUP OF THE BUILDING-LIKE STRUCTURE

The primary mechanical system consists of a small scale three-story building-like structure, which was designed and

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built in aluminum alloy with nominal stiffnesses $k_i = 12EI/L^3$, with Young's modulus $E$, moment of inertia $I$ and total length $L$ between floors, as described in the schematic diagram and overall experimental setup shown in Figure 1b (see [11]). The maximum height of the structure is 450 mm with a rectangular base of 150 x 100 mm. The building-like structure is assumed to have three degrees of freedom $(y_1, y_2, y_3)$, describing the lateral motion of each floor and associated to the first three dominant lateral modes of the structure and characterized by three concentrated masses $(m_1, m_2, m_3)$, each of them interconnected by two flexible beams in each mass represented by the equivalent stiffnesses $(k_1, k_2, k_3)$, while equivalent (linear) viscous damping $(c_1, c_2, c_3)$ are considered on each interconnection.

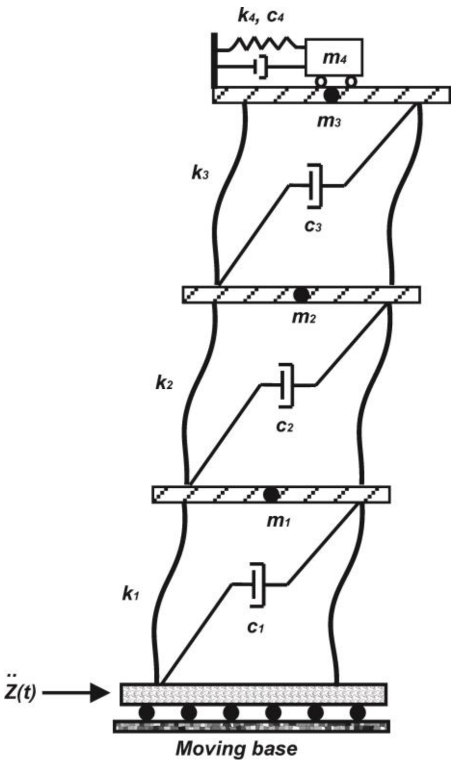

Fig. 1 (a) Schematic diagram of building-like structure

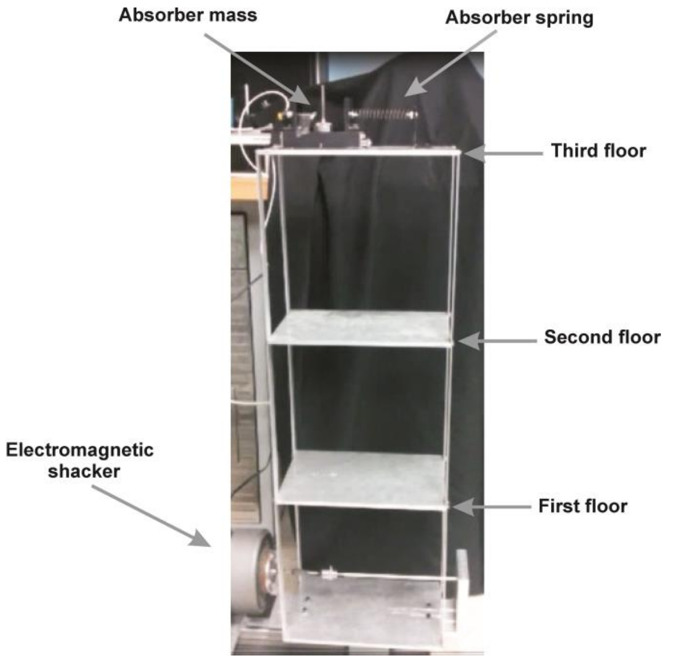

Fig. 1 (b) Set-up platform of building-like structure

The complete structure is mounted on an anti-friction ball bearing rail and the moving base is connected directly to an electromechanical shaker, which is used to provide the ground motion with low-frequency harmonic components in a frequency sweep from 0 to 60 Hz as well as to emulate some realistic records from seismic events occurred at Mexico City. This ground motion is represented as $\ddot{z}(t) = -Z\omega^2 \sin(\omega t)$. The electromechanical shaker is a *Labworks*® ET-139 controlled via a linear power amplifier *Labworks*® PA-138. The accelerations on the ground and third floors are measured with accelerometers by means of *Sensoray*® Model 626 which is a Multifunction I/O card, connected via PCI system in a PC, to obtain and process the signals in *Matlab/Simulink*®.

## III. MATHEMATICAL MODEL OF THE BUILDING--LIKE STRUCTURE

A simplified mathematical model of the three-story building excited by ground motion is obtained as follows (Figure 1a)

$$M_3 \ddot{y}(t) + C_3 \dot{y}(t) + K_3 y(t) = -M_3 e_3 \ddot{z}(t) \qquad (1)$$

where $y = [y_1, y_2, y_3]^T \in R^3$ is the vector of generalized coordinates of relative displacements with respect to a fixed frame of reference, $\ddot{z} \in R$ is the ground acceleration at the base of the structure and $M_3, C_3, K_3$ are $3 \times 3$ real matrices of mass, damping and stiffness, respectively. Here, the vector $e_3 = [1, 1, 1]^T \in R^3$ denotes the influence vector, which allows the transformation of the effect of the ground acceleration as forces acting on each mass [2].

The mass, stiffness and damping matrices for the three-story building are given as follows

$$M_3 = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix},\ C_3 = \begin{bmatrix} c_1 + c_2 & -c_2 & 0 \\ -c_2 & c_2 + c_3 & -c_3 \\ 0 & -c_3 & c_3 \end{bmatrix},$$

$$K_3 = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 \\ -k_2 & k_2 + k_3 & -k_3 \\ 0 & -k_3 & k_3 \end{bmatrix} \qquad (2)$$

For modal analysis purposes, the Rayleigh or proportional damping model is considered, which means that $C_3 = a_0 M_3 + b_0 K_3$ where $a_0 = \xi_i \times \frac{2\omega_i \times \omega_j}{\omega_i + \omega_j}$ and $b_0 = \xi_j \times \frac{2}{\omega_i + \omega_j}$, with $\omega_i$ and $\omega_j$ the resonant frequencies of the structure, and $\xi_i$ and $\xi_j$ the damping proportion in the structure for the $i$ and $j$ modes, respectively [7,8].

## IV. EXPERIMENTAL MODAL ANALYSIS OF THE STRUCTURE

For modal analysis validation the three-story building-like structure was harmonically perturbed on the ground, with a frequency sine sweep on the electromagnetic shaker, from 0 to 60 Hz during 60 s, thus resulting the ground motion measured with a head impedance as described in Figure 2.

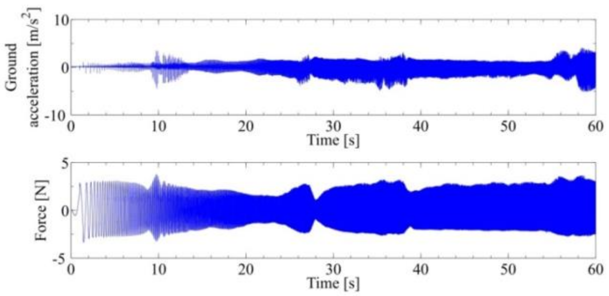


Fig. 2 Ground acceleration and force of the external excitation

The experimental Frequency Response Function (FRF) is analyzed using modal analysis techniques like *Peak Picking* and *Curve Fitting* methods [6,7]. The corresponding experimental FRF obtained from the third floor in open loop without the presence of the TMD is described in Figure 3, where one can observe the three dominant (lateral) modes of the structure.

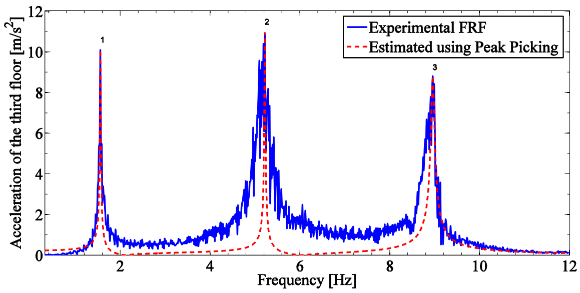


Fig. 3 FRF of the building-like structure using *Peak Picking* method

The *Peak Picking* and *Curve Fitting* methods leads are simple frequency domain modal identification techniques for single degree-of-freedom systems, which under the assumption of modes sufficiently separated and the well-known superposition principle, then, one resonance can be analyzed at a time, extracting the modal parameters associated to each single mode. Of course, there are several limitations to these modal analysis techniques, mainly that concerning with very close or repeated modes, which in some cases can be dealt with software or application of special windowing spectral functions. For more details on theoretical aspects and application issues about these modal parameter identification techniques we recommend Refs. [6,7].

A comparison of the resonance frequencies obtained experimentally and numerically is detailed in Table 1. Note that, the results are close enough to validate the simplified model of the three-story building-like structure (see Fig. 1a), with respect to the first three dominant lateral modes.

Table 1. Modal parameters estimated with *Peak Picking* method.

| **Mode** $i$ | **Natural frequency** $\omega_i$ **[Hz]** Numerical | Experimental | **Modal damping** $\xi_i$ |
|---|---|---|---|
| 1 | 1.7020 | 1.556 | 0.0056 |
| 2 | 5.1607 | 5.219 | 0.0020 |
| 3 | 8.0274 | 8.957 | 0.0044 |

The system parameters of the three-story building-like structure, obtained from direct measurements (e.g., masses), computations from the geometries and physical properties of materials or via modal parameter estimations, are given in Table 2.

Table 2. System parameters.

| | | |
|---|---|---|
| $m_1 = 1.1164kg$ | $m_2 = 1.1327kg$ | $m_3 = 1.9224kg$ |
| $k_1 = 897.0277N/m$ | $k_2 = 933.3893N/m$ | $k_3 = 888.2334N/m$ |
| $c_1 = 0.2755\ \frac{Ns}{m}$ | $c_2 = 1.1884\ \frac{Ns}{m}$ | $c_3 = 2.1885\ \frac{Ns}{m}$ |

It is important to note that, the viscous damping coefficients were indirectly obtained from the FRF, by considering the experimental modal damping $\xi_i$ and resonance frequency of the structure $\omega_i$. The modal damping is approximated using the *Peak Picking* method.

## V. PASSIVE VIBRATION ABSORBER

The building-like structure shown in the Figure 1a the TMD is represented in terms of the followings parameters $(m_4, k_4, c_4)$, and is designed to mitigate one of the critical resonance frequencies in the system. In this case, the effect of motion on the base of the structure in terms of the acceleration $\ddot{z}(t)$ is achieved attenuated the primary system, to a small range of excitation frequencies and under stable operating conditions [9]. The weakness of this control scheme is the absence or low robustness with respect to uncertainties and unknown parameters including variations in the excitation frequencies.

The building-like structure with TMD placed on the third floor of the structure, which is subject to movement $\ddot{Z}(t)$. The TMD is designed to compensate the first mode of vibration of the system. The equations that govern the dynamics of the system complete four degrees of freedom are

$$M_4\ddot{y}(t) + C_4\dot{y}(t) + K_4 y(t) = -M_4 e_4 \ddot{z}(t) \qquad (3)$$

where $y = [y_1, y_2, y_3, y_4]^T \in R^4$ is the vector of generalized coordinates of relative displacements with respect to a fixed frame of reference, $\ddot{z} \in R$ is the ground acceleration at the base of the structure and $M_4, C_4, K_4$ are $4 \times 4$ real matrices of mass, damping and stiffness, respectively. Here, the vector $e_4 = [1, 1,1,1]^T \in R^4$ denotes the influence vector, which allows the transformation of the effect of the ground acceleration as forces acting on each mass [2]. The matrix form of the mass, stiffness and damping are expressed as

$$M_4 = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{bmatrix},$$

$$K_4 = \begin{bmatrix} k_1+k_2 & -k_2 & 0 & 0 \\ -k_2 & k_2+k_3 & -k_3 & 0 \\ 0 & -k_3 & k_3+k_4 & -k_4 \\ 0 & 0 & -k_4 & k_4 \end{bmatrix},$$

$$C_4 = \begin{bmatrix} c_1+c_2 & -c_2 & 0 & 0 \\ -c_2 & c_2+c_3 & -c_3 & 0 \\ 0 & -c_3 & c_3+c_4 & -c_4 \\ 0 & 0 & -c_4 & c_4 \end{bmatrix} \qquad (4)$$

The TMD is designed to passively attenuate the frequency of interest from the expression $\omega_j = \sqrt{\frac{k_4}{m_4}}$ where $\omega_j$ is the $j$-th resonance frequency of the structure to be attenuated and $m_4$ and $k_4$ are the equivalent mass and stiffness of the TMD. Particularity, the TMD was designed to the first experimental vibration mode, that is, $\omega_1 = 1.556$Hz. The parameters of the building-like structure with TMD are given in the Table 3.

Table 3. The parameters of the building-like structure

| | | |
|---|---|---|
| $m_1 = 1.1164kg$ | $m_2 = 1.1327kg$ | $m_3 = 1.9224kg$ |
| $k_1 = 897.0277N/m$ | $k_2 = 933.3893N/m$ | $k_3 = 888.2334N/m$ |
| $c_1 = 0.0885\frac{Ns}{m}$ | $c_2 = 0.0289\frac{Ns}{m}$ | $c_3 = 0.1189\frac{Ns}{m}$ |

| |
|---|
| $m_4 = 0.784kg$ |
| $k_3 = 75N/m$ |
| $c_4 = 0.9337\frac{Ns}{m}$ |

The viscous damping coefficients were indirectly obtained from the FRF, by considering the experimental modal damping $\xi_i$ and resonance frequency of the structure $\omega_i$. The modal damping is approximated using the *Peak Picking* method. The three-story building-like structure was harmonically perturbed on its base, with a frequency sine sweep on the electromagnetic shaker, from 0 to 60 Hz. The results of experimental modal analysis are shown in Table 4, where a reasonable approximation is observed with respect to the numerical results.

Table 4. Modal analysis using *Peak Picking* method.

| **Mode** $i$ | **Natural frequency** $\omega_i$ **[Hz]** Numerical | Experimental | **Modal damping** $\xi_i$ |
|---|---|---|---|
| 1 | 1.3148 | 1.2512 | 0.0056 |
| 2 | 2.2648 | 2.2583 | 0.0091 |
| 3 | 5.4448 | 5.5848 | 0.0026 |
| 4 | 8.1023 | 9.1402 | 0.0031 |

The experimental dynamic response (displacement) in the overall floors of the building-like structure with / without TMD is shown in the Figures 4 and 5.

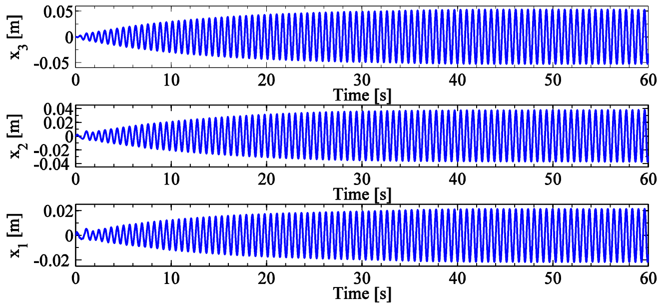


Fig. 4 Experimental response of the building-like structure without passive control.

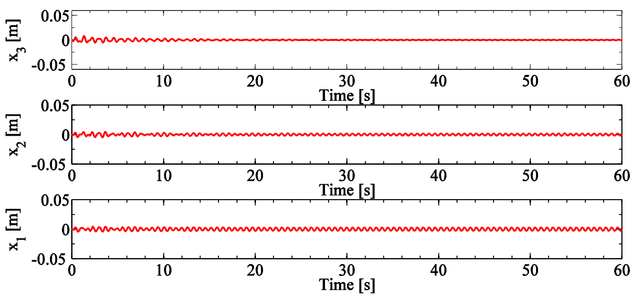


Fig. 5 Experimental response of the building-like structure with passive control.

## CONCLUSIONS

The analysis of vibrations in civil structures can be investigated using a simplified mathematical model of three floors excited by external force at the base. The goal is reduce the lateral displacement when it is disturbed by external forces such as an earthquake. The TMD is used as mechanical absorber tuned for a specific resonant frequency of the system.

The experimental results obtained indicate that the movement of the structure can be reduced indirectly by controlling the mechanical vibrations in the system, reducing the effects of lateral displacements caused by earthquake force. Future work could focus on the implementation of active vibration controls to reduce the displacement of the structure significantly by using modal controllers based on optimal Model Predictive Control (MPC) and others.

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