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Optimization of PPF Control of a Building-Like Structure for Vibration Control

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Abstract. This work presents a research on intelligent civil structures, like bridges and buildings, which consists in the use of sensors and actuators to monitor and control some specific parameters of the structures. A recent technological breakthrough has been the development of piezoelectric actuators or sensors using special materials, such as Lead Zirconate Titanate (PZT), magnetorheological dampers, shape memory, and others. In particular, the use of smart materials in the structural control of buildings is an interesting and promising subject in civil engineering. The method of active control is used to reduce the negative effects of external forces or perturbations on the performance of the overall system. These forces can be expressed mainly in terms of the effects of winds or earthquakes. This article presents a case of study of a building-like structure perturbed in the ground-borne by an external force and controlled through an active control applied with a PZT actuator joined in a column of the structure. The scheme of control consists in a modal control known as Positive Position Feedback (PPF), which aims to reduce the vibrations in the building-like structure. The gains of PPF control are tuned using an optimization method known as Differential Evolution combined with the Interior Point Algorithm. Experimental and numerical results are shown with the purpose of analyzing the efficiency of the control in the presence of an exogenous force in the dynamics of the system. The numerical results of the optimized PPF control are interesting and promising, reducing the vibrations and lateral displacements by around 97% of the building-like structure.

Keywords. Smart materials, active vibration control, PZT actuator, optimization.

1 Introduction

Buildings are typical civil structures common in every city around the world. They are subjected to stress mainly due to the lateral loads caused by exogenous forces, such as wind or earthquakes. Currently, structural designs of buildings attempt to achieve a reduction of weight and an increase of slenderness, using high-strength materials or exploiting mechanical properties.

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This assures an increase in the building height, with a decent performance in terms of mechanical deflection. In structural engineering three main types of buildings are considered: steel buildings, reinforced concrete buildings and composite buildings [1].

Many tall buildings are built using a combination of the materials mentioned in the previous classification. This is done to have better damping ratios in the overall structure, which reduces the lateral movement of the building affected by the excitation induced by wind loads or earthquakes. In particular, a building can be excited at the base by earthquake forces, causing a movement of all the elements of the structure including the natural frequencies of the building.

This could increase the probabilities of structural damage or even the collapse of the overall structure. Recently, there have been some interesting advances in the development and application of smart materials in the area of civil engineering. These materials are used mainly in bridges and buildings to mitigate problems related with the lateral movements of the structure, contributing to reduce serious problems like auto-excitation of the structure caused by the resonance frequencies of the building. In particular, implementation of piezoelectric stack actuators (PZT) in civil engineering is a decent alternative to monitor and measure the movement or damage of buildings, when they are excited by exogenous forces. Some works are related with the applications of PZT devices as sensors, using three schemes to evaluate the damages in concrete civil structures.

Basically, this PZT stack actuators are mounted on steel bars of reinforced concrete, included inside the concrete mass and concrete surfaces of the construction [2]. There are also some works related with experimental applications of the PZT actuators. For instance [3], presented a civil structure consisting of a four-story building with a total weight of 2000 kg and a height of about 3.7 m. The authors considered PZT actuators mounted on the H-section steel of each floor, including the use of PZT actuators to provide the bending moment to the columns in the overall system. The active control $\mathbf{H}^{\infty}$ is applied through the PZT actuators using the bending moment as a shearing force, reducing the vibration of the structure.

In recent years, the technological advances of PZT *actuators* are so notable that it is possible to find actuators able to move high loads of several tons, in particular the PZT actuators manufactured with high voltage ceramics designed with larger cross-sections of civil structures [4].

The use of modal control schemes for active vibration control is an interesting area of Experimental Modal Analysis (EMA), being of great interest the topic of Operational Modal Analysis (OMA). For instance, some works are related with the application of modal control to attenuate vibrations in a building-like structure using Positive Position Feedback (PPF), combined with Sliding Mode Control (SMC), perturbed at the base by harmonic external forces [5, 9]. The authors show experimental results including an extension of PPF control through a Multiple Positive Position Feedback (MPPF).

The remainder of this paper proceeds as follows. Section 2, presents a preliminary analysis of the platform-setup used with the PZT actuator, describing their mechanical characteristics and interfaces. In this section the authors present a simplified mathematical model of the system and an experimental modal analysis, which shows us the first three resonance frequencies of the building-like structure. Section 3, presents the design of the PPF control scheme, establishing the matrix of stability $\widehat{K}$ from of values of gains g and ω_f of the PPF control. Section 4, shows the experimental results of the PPF control applied to the system through the PZT actuator designed to reduce the amplitude of the first lateral resonant frequency of the building-like structure. Section 5, presents a study of the optimization of the parameters of the PPF control, using a metaheuristic method known as Differential Evolution Method showing numerical results with interesting responses. Concluding comments are given in Section 6.

2 Fundamental Study

The application of structural control for civil engineering to reduce the displacements of the structures due to vibrations when the overall system is excited at the base by external forces can be implemented using one of three typical methodologies, these are known as: passive, semi-active and active vibration control [17, 18]. In this paper, our goal is to show the advantages of active vibration control using a PZT actuator mounted on the column of a building-like structure.

The objective is to reduce the vibrations in several resonant frequencies of the system using the feedback of a sensor placed at a specific section of the structure. In general, adding an actuator will increase the degrees of freedom of the original system, but it can substantially improve the stability of the structure in closed-loop.

2.1 Building-Like Structure using a Smart Actuator Mounted on a Column

Figure 1, shows the experimental setup, which consists of a building model with three-floors, with a height of 450 mm and a rectangular base of 150 × 100 mm^2, with a distance between floors of approximately 150 mm. The building-like structure is composed of an aluminum alloy considering an equivalent stiffness of $k_i = 12EI/L^3$, where E is Young´s module, I the moment of inertia and L is the height of the i-th column between each floor of the overall system [4].

The base or ground borne of the structure is perturbed through external forces applied using an electromagnetic shaker manufactured by *Labworks*® model ET-139. This rectangular base is mounted over a mechanical rail supported by a set of viscous ball bearings which allows limited lateral movements of the structure.

The electromagnetic shaker allows working with harmonic components of frequencies between 0 to 120 Hz and is controlled via a linear power amplifier manufactured by *Labworks*® model PA-138. The response and force applied by the electromagnetic shaker to the structure is measured through the impedance head placed at the stinger of the shaker using a cable connected to the NI-CompactDAQ data acquisition system of *National Instruments*®. This system is integrated with a NI-DAQ-9172 chassis and a NI-9133 module to feedback information of the accelerometers mounted in the floors of the structure. The NI-CompactDAQ is connected via USB to a computer using software programmed in *Labview*® and an external interface with *Matlab/Simulink*® associated to a *Sensoray*® card running *Windows 7*®.

2.2 PZT Actuator

Figure 2, shows the PZT actuator used in the experimental setup manufactured by *Dynamic Structures & Materials*® model FPA-0500E P-1036-150-SS-1M3 110, which consists of a mechanical arrangement with springs, which is used to increase the longitudinal motion from the transversal PZT material expansion. The electrical characteristics of the piezoelectric actuator are given in Table 1. The voltage control of the device is carried out through the interface with a *Sensoray*® card, establishing the implementation of active schemes of control in the building-like structure. The active control force from the PZT actuator is applied directly to the first floor of the structure to reduce or minimize the vibrations at the third floor of the structure, establishing a scheme of control for an under-actuated system.

2.3 Analytical Model

In order to analyze the PZT mounted in one beam-column of the first floor of the system, we show in Figure 3, a simplified model of the building-like structure excited at the base by an external force.

The simplified mathematical model of the system is represented as follows:

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

where $y = [y_1,\ y_2,\ y_3]^T \in\ R^3$denotes the vector of generalized coordinates of relative displacement for each floor with respect to the fixed frame of reference. M_3, C_3, K_3 are 3×3 real matrices which represent mass, damping and stiffness respectively. The vector $e_3 = [1,1,1]^T$ is the influence vector, which relates to the effect of ground motion at the base of the structure to each floor. The external force used as excitation at the base of the structure in terms of the acceleration is denoted as $\ddot{z}(t) = Z_a \sin(\omega t)$, where Z_a is the amplitude and ω the frequency, which is in an interval of 0 to 60 Hz. Finally, the vector $B_f = [1\ 0\ 0]^T$ is the input of the external active control force into the structural dynamics and $u_{pzt} \in R$ is

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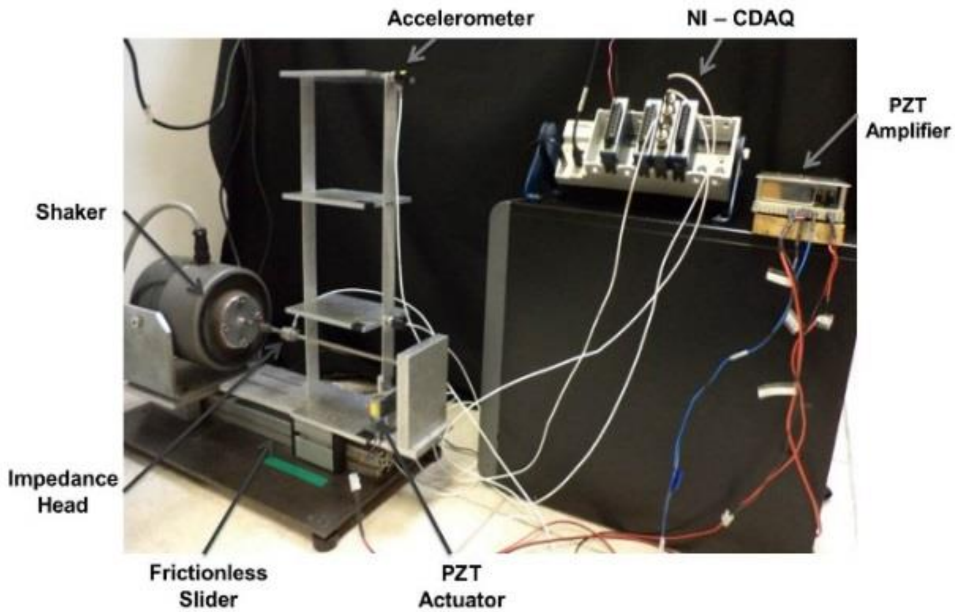

Fig. 1. Complete experimental setup with the PZT actuator.

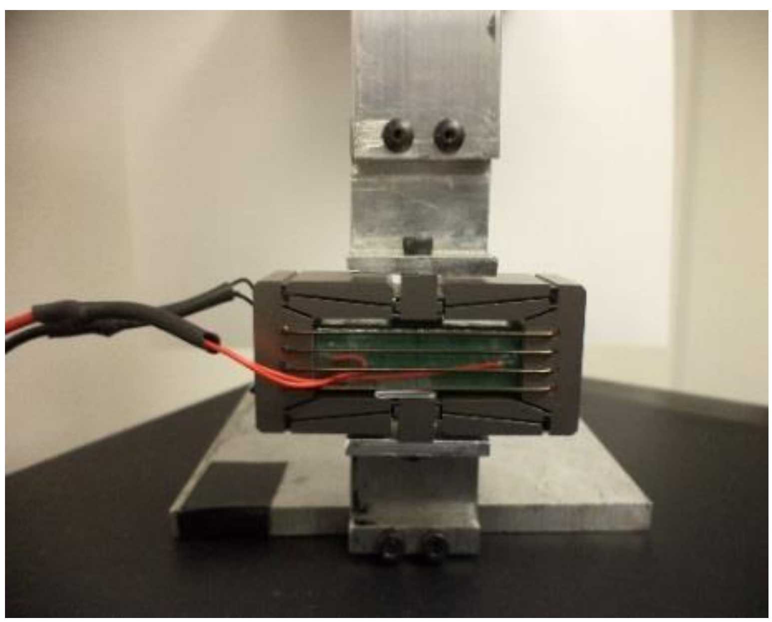

Fig. 2. PZT actuator model FPA-0500E P-1036-150-SS-1M3 110 manufactured by the *Dynamic Structures & Materials®*

the active control force in terms of the voltage applied to the system through the PZT actuator.

The mass, damping and stiffness matrices for the building-like structure shown in Figure 3 are given by:

$$M_3 = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix},$$
$$C_3 = \begin{bmatrix} c_1 + c_2 & -c_2 & 0 \\ -c_2 & c_2 + c_3 & -c_3 \\ 0 & -c_3 & c_3 \end{bmatrix}, \quad (2)$$
$$K_3 = \begin{bmatrix} k_1 + k_2 & -k_2 & 0 \\ -k_2 & k_2 + k_3 & -k_3 \\ 0 & -k_3 & k_3 \end{bmatrix}.$$

In particular, the damping matrix can be expressed in terms of the Rayleigh or proportional damping, which are related with the mass and stiffness matrices expressed as $C_3 = a_0 M_3 + b_0 K_3$, where a_0 and b_0 are coefficients expressed in terms of the resonant frequencies and the damping proportion of the structure, respectively [6].

In a PZT actuator the equivalent stiffness k_{pzt} is much greater than the equivalent stiffness of one single column-beam k_c (e.g., right side between base and first floor), which is $k_{pzt} \gg k_c$. Resulting in an equivalent stiffness in a series expressed as

$$k_{eq} = \left(\frac{1}{k_c} + \frac{1}{k_{pzt}}\right)^{-1} \approx k_c \ , \quad (3)$$

Therefore, the PZT actuator can be used in the implementation of several schemes of control without affecting the dynamics of the experimental setup with an axial force $F_{axpzt} \approx k_c \delta_{pzt}$. For more details related with the operation of the PZT actuator the interested reader is referred to [4].

2.4 Modal Analysis

In this section we present a study to obtain the experimental resonant frequencies of the structure considering a harmonic external force at the rectangular base of the system. This force is generated using an electromagnetic shaker in an interval between 0 to 60 Hz. The experimental Frequency Response Function (FRF) is studied using the *Peak Picking* method (for more details see [6]).

In Figure 4, we show the experimental frequency response of the structure, specifically the three dominant modes of the system. In this study we have interest in the lateral displacement of the structure, computed using information provided by the accelerometer placed on the third floor of the system.

Table 1. Fundamental characteristics of the PZT actuator

Parameters	Values
Maximum displacement	$\delta_{max} = 523.7\mu$m
Equivalent stiffness	$k_s = 0.934$ N/ μm (unloaded)
Resonant frequency	440 Hz
Blocking force	375 N
Operation voltage	-30 to +150 V
External control input	-2 to 8 V
Restrictive voltage of physical limits	± 30 V

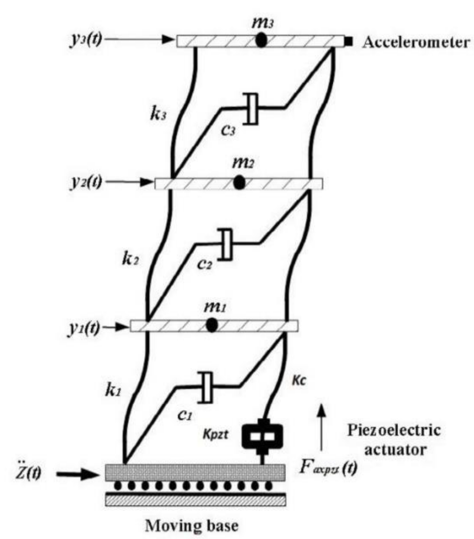

Fig. 3. Schematic diagram of building-like structure

Table 2. Resonant frequencies of the studied system

Mode i	Numerical Frequency ω_i [Hz]	Experimental Frequency ω_i [Hz]	Experimental Damping ζ_i
1	9.58	9.2775	0.02690
2	26.86	27.3442	0.00074
3	38.82	37.6287	0.00053

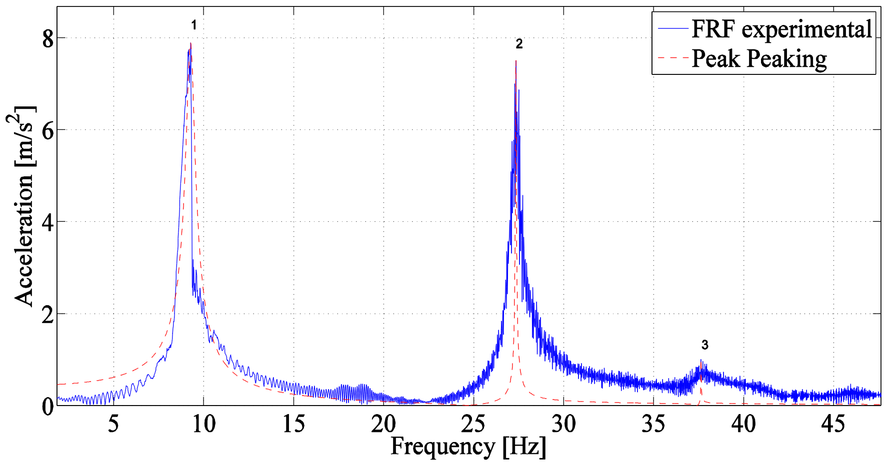

Fig. 4. Experimental Frequency Response Function (FRF)

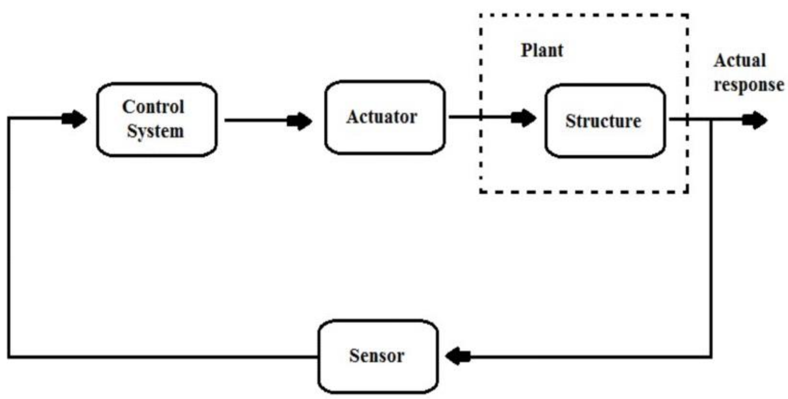

Fig. 5. Block diagram of the active structure

A comparative analysis of the resonant frequencies in numerical and experimental form of the building-like structure is presented in Table 2. Table 2 allows us to validate the simplified mathematical model used to represent the building-like structure, which shows a minimal variation between the first three principal resonant frequencies of the system.

3 Design of the Controller

For the implementation of modal control such as PPF, it is necessary to establish a relationship between the resonant frequencies of the system and the suppression frequency designed in the controller.

This control scheme adds an additional degree-of-freedom to the dynamics of the system in close-loop, which is known as a *virtual passive absorber* or *second order low-pass filter*.

Basically, this control considers the values of the natural frequency to minimize ω_n and the value of the damping factor ζ, establishing a performance of the system in several cases, such as: under damping, damped critical and overdamped form [7, 8].

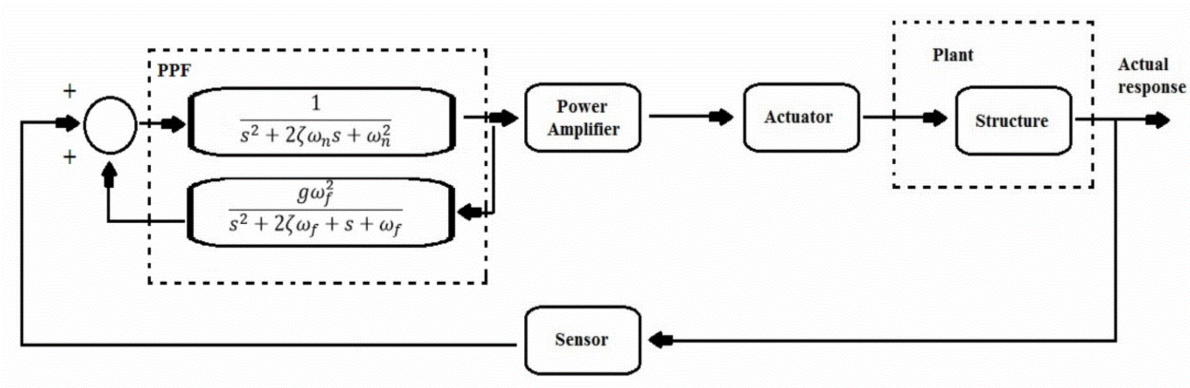

Fig 6. Block diagram of the PPF control

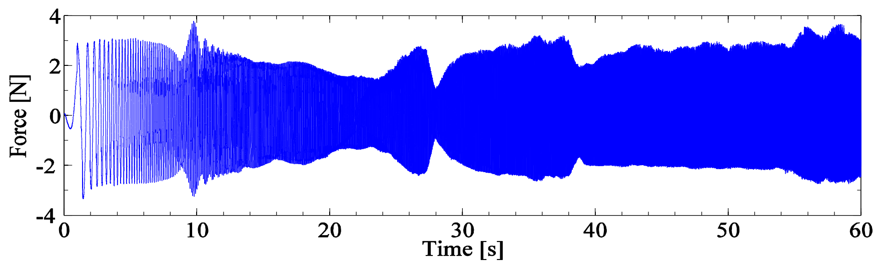

Fig. 7. External force

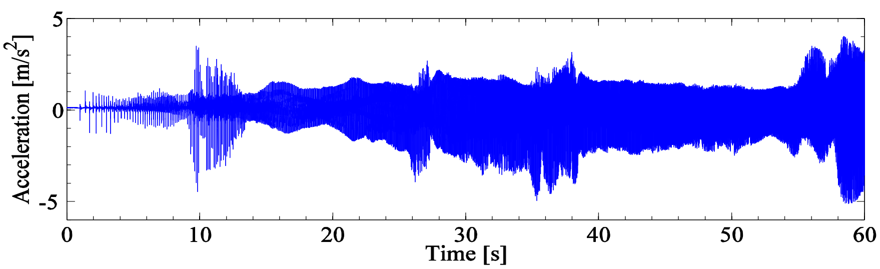

Fig. 8. Acceleration at the base of the building-like structure

The values of the parameters in this modal control are obtained from experimental analysis, which is useful for many researchers and engineers in structural control. In particular, the methodology for the building-like structure uses the position feedback of the third floor to attenuate the amplitude of the resonant frequencies in terms of the lateral displacements of the overall structure.

To tune the parameters of the controller we use an empirical methodology considering a specific damping factor ζ and adjusting the parameter of gain g, such that poles and zeros of the system are stable [6, 14].

A general schematic diagram of the active control and PPF controller are shown in Figure 5 and 6.

A simplified mathematical model of the building-like structure with the PZT actuator and the input control in terms of PPF, when excited in the rectangle base by harmonic external forces, is expressed as

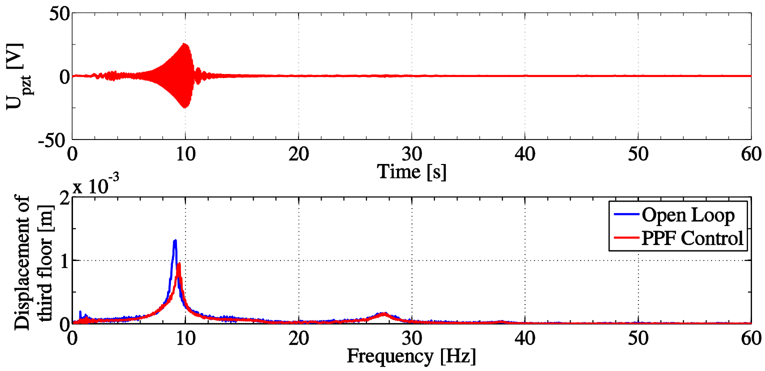

Fig. 9. Experimental control effort of the PPF active control and frequency response

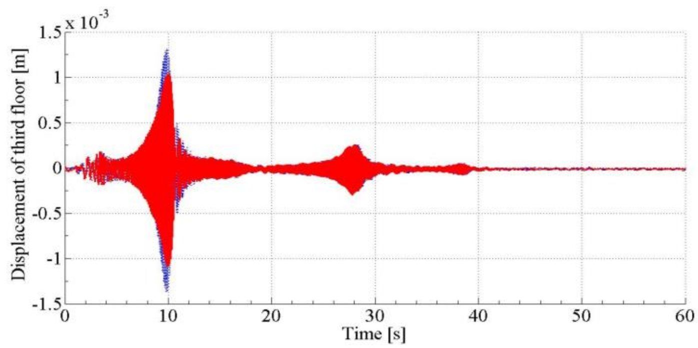

Fig. 10. Experimental displacement of the third floor

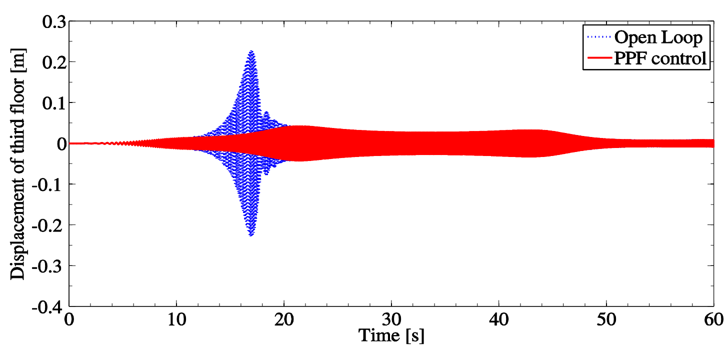

Fig. 11. Displacement of the third floor of the building-like structure using optimization methods

$$M_3\ddot{y}(t) + C_3\dot{y}(t) + K_3 y(t) = -M_3 e_3 \ddot{z}(t) + B_f u_{pzt}(t), \quad (4)$$

with $y \in R^3$, $u_{pzt} \in R$, where the PZT actuator is mounted in series with the column-beam on the first floor and the input control is applied directly through the first floor. However, it is important to notice that the sensor (accelerometer) for feedback in the control loop is placed on the third floor y_3, due to the maximum displacement of the building-like structure which occurs at the top floor. Therefore, the vibration problem is analyzed as a non-collocated sensor and actuator, resulting in a system completely controllable and observable with advantages of the robustness properties by PPF control [6].

The PPF control law for the three dominant modes of the structure considering the action of the PZT actuator is expressed as:

$$M_3\ddot{y}(t) + C_3\dot{y}(t) + K_3 y(t) = -M_3 e_3 \ddot{z}(t) + B_f u_{pzt}(t), \quad (5)$$

with $y \in R^3$, $u_{pzt} \in R$,

$$\ddot{\eta}(t) + 2\zeta_f \omega_f \dot{\eta}(t) + \omega_f{}^2 \eta(t) = g\omega_f{}^2 B_0^T y(t), \quad (6)$$

with $\eta \in R$, and

$$u_{pzt} = g\omega_f{}^2 \eta(t). \quad (7)$$

The secondary virtual system (passive absorber) described in Equation (6) is coupled to the primary system (building-like structure) through expression $g\omega_f{}^2 B_0^T y(t)$ and $g\omega_f{}^2 \eta(t)$, which described the PPF control law u_{pzt}.

A compact matrix form of the closed-loop system is given by:

$$\begin{bmatrix} M_3 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \ddot{y}(t) \\ \ddot{\eta}(t) \end{bmatrix} + \begin{bmatrix} C_3 & 0 \\ 0 & 2\zeta_f \omega_f \end{bmatrix} \begin{bmatrix} \dot{y}(t) \\ \dot{\eta}(t) \end{bmatrix} + \begin{bmatrix} K_3 & -B_f g\omega_f^2 \\ -g\omega_f^2 B_0^T & \omega_f^2 \end{bmatrix} \begin{bmatrix} y(t) \\ \eta(t) \end{bmatrix} = \begin{bmatrix} -M_3 e_3 \\ 0 \end{bmatrix} \ddot{z}(t). \quad (8)$$

The matrix M_3 is symmetric and positive definite, and the overall system is also symmetric and positive definite similar to the damping matrix C_3. The asymptotic stability of the overall system is associated to the definition of the stiffness matrix K_3, which depends of the values of constants g and ω_f in the PPF control. The close-loop stiffness matrix $\hat{K}$ is expressed as:

$$\hat{K} = \begin{bmatrix} K_3 & -B_f g\omega_f^2 \\ -g\omega_f^2 B_0^T & \omega_f^2 \end{bmatrix}. \quad (9)$$

4 Vibration Control Experiment

The experimental setup was tested with harmonic frequencies from 0 to 60 Hz. Figure 7 and 8, respectively show the components of force and acceleration applied at the rectangular base, which are measured using the impedance head of the shaker.

Table 3. Parameters of the DE method

Parameters	Values
Population size	50
Number of estimation	25
CR	0.8
F	0.95
Simulation time	60s

The experimental response of the system applying the active vibration PPF control is shown in Figure 9, where we can observe the control effort and frequency response in terms of the displacement, tuning the PPF control to reduce or minimize the first modal resonant frequency of the building-like structure. The parameters of control was selected as $\omega_f = \omega_1 = 9.2775$ Hz, $\zeta_f = 0.4$ and $g = 2.8$. Observe how the first dominant mode is reduced around 37%, employing small control efforts.

Finally, we can observe in Figure 10 the time response of the system in terms of the horizontal displacement.

Generally, in civil structures the maximum movements of a building excited at the base occurs at the top floor. Therefore, we show the analysis and response of the experimental response only at the third floor of the structure, which is partially reduced on the lateral displacement as observed in Figures 9 and 10.

The experimental response of the system can be improved using a better method of tuning for the parameters of the controller, which is possible through optimization methods. In particular, PPF control is a technique very useful in experimental form due to the ease of implementation and stability.

The drawback is that it is very complicated to obtain an acceptable tuning of the control parameters for this controller [13]. In particular the parameters for the gain and damping ratio in the filter have a strong relation and need fine tuning [13, 14]. Methods to help tune this type of modal control can be useful in practical and experimental applications of civil engineering for many types of systems [13].

For instance, the method described in [14] can be a slow process to obtain a group of tuned parameters for the controller. Some authors propose a fuzzy gain tuner to tune the gain in the PPF control and reduce the initial overshoot with quick vibration suppression in a long composite I-beam with piezoceramics patch sensors and actuators [15].

Finally, there are works related with implementation of meta-heuristic algorithms to optimize the controller using a single objective function by minimizing the mean square error of the observed vibration mode of a flexible beam system. In such methods, the control design does not require knowledge of the input/output characteristics of the overall structure [16].

5 Optimization in the Gains of PPF Control

In this work, we consider the integrated absolute tracking error as the objective e_{IAE} to optimize. The function e_{IAE} is defined as follows:

$$e_{IAE} = \int_0^{T_{ss}} |r(\hat{t}) - x(\hat{t})| d\hat{t}, \qquad (10)$$

where $r(t)$ is a reference input and T_{ss} is the time when the response is close to be in the steady state, resulting in $T_{ss} = 60$s for our experiments.

5.1 Differential Evolution Method

The method used to perform the optimization is Differential Evolution (DE) [10], which is a well-known metaheuristic for real valued black-box optimization, together with the Interior Point Algorithm [11], (this method comes within the *fmincon* function in *Matlab*®). In particular, we used the DE/rand/1/bin version implemented in *Matlab*® (the source code was taken from [12]).

This method consists in the initialization of a random population of n individuals. DE uses two operations to generate new solutions. The first operation consists in a mutation process, which

Table 4. Comparison between controllers

Variable	PPF / without Optimization Experimental results	PPF / with DE Optimization Numerical results
Modal frequency [Hz]	$\omega_f = 9.2775$	$\omega_f = 9.2775$
Damping factor	$\zeta_f = 0.4$	$\zeta_f = 0.4207$
Gain	$g = 2.8$	$g = 1.1999$
Control effort [V]	25.4	185.2
Percentage reduction	37%	97%

estimates n new individuals using three random individuals with the following equation:

$$v_{i,G+1} = x_{r1,G} + F\left(x_{r2,G} - x_{r3,G}\right), \qquad (11)$$

where r_1, r_2 and r_3 are random indexes, G is the current estimation and $F > 0$ and $x_{i,G}$ represent the x population of the algorithm considering i as the index of an individual. The next operation consists in a crossover operator, in DE used to increase diversity during the search. This search operator is expressed as:

$$u_{ji,G+1} = \begin{cases} v_{ji,G+1} \; if \; (rand(j) \leq CR) \; or \; j = rnbr(i), \\ x_{jiG} \; if (rand(j) > CR) or \; j \neq rnbr(i) \end{cases} j = 1,2,\cdots,D, \qquad (12)$$

where $rand(j)$ is a uniform random number in $[0,1]$, $CR \in [0,1]$ is the crossover constant and $rnbr(i) \in 1,2,\cdots,D$ is a randomly chosen index. Finally, to decide which individuals will be part of the next estimation $u_{i,G+1}$ is compared to $x_{i,G}$ and the one with the smallest fitness is retained for the next estimation.

The parameters used for the DE method are given in Table 3.

It is important to observe that DE was used to estimate a good initial solution. The best solution given by DE was then used as the initial point for the Interior Point Algorithm with $T_{ss} = 60$s. This approach allowed us to first explore the search

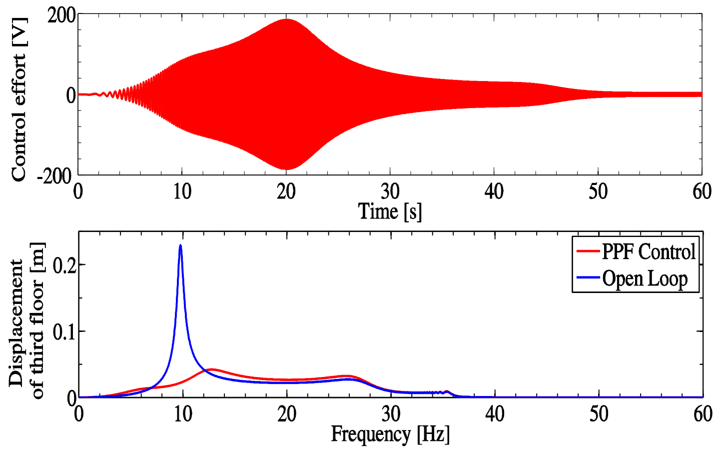

Fig. 12. Displacement of the third floor of the building-like structure using the optimization methods

space while keeping a low cost in terms of time, and once we have found a promissory region we used the local search to find the local optimum.

5.2 Numerical Response of the PPF Control

The numerical response of the system applying the active vibration control with the optimization method DE is shown in Figure 11, where the movement of the system is reduced significantly using as feedback the position of the third floor.

Figure 12, shows the control effort and frequency response in terms of the displacement, tuning the PPF control to reduce the first modal resonant frequency of the building-like structure. The parameters of control delivered by DE with the Interior Point Algorithm are $\omega_f = \omega_1 = 9.2775$ Hz, $\zeta_f = 0.4207$ and $g = 1.1999$. Observe how the first dominant mode is reduced by around 97%, using a particular control effort. The response of the system is much better compared with PPF control without optimization, as summarized in Table 4.

6 Conclusions

This paper presents a particular case of smart materials implemented in civil structures like buildings, using a PZT stack actuator. The active vibration control is a particular approach considered to reduce movements of the structures when they are perturbed at the base by exogenous forces. An experimental setup is presented, which consists in a building-like structure of three stories excited at the base by an electromagnetic shaker.

The active control scheme is a PPF, using the non-allocated sensor-actuator feedback the displacement of the third floor of the building-like structure. The experimental response of the overall system is attenuated up to 37% employing acceptable control efforts of the PZT actuator. Finally, an optimization analysis for the parameters of the PPF control is presented using metaheuristic methods and a local search, in particular DE and the Interior Point Algorithm.

The numerical results of the controller with optimization are shown to reduce the movement of the building-like structure by around 97%, with a control effort allowed by a PZT stack actuator.

For future works we consider the implementation of the optimized parameters obtained in the experimental platform of the building-like structure and validated by numerical simulations.

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