A COMPARATIVE STUDY FOR ADVANCED SEISMIC VIBRATION CONTROL ALGORITHMS

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Această lucrare prezintă un studiu comparativ al algoritmilor de control al vibrațiilor seismice. În timp ce obiectul condus este neliniar, are intrări și ieșiri multiple, deseori prezentând mai multe grade de libertate, o importanță crescută în reglare o constituie alegerea și proiectarea elementului de execuție. Această lucrare studiază două tipuri de elemente de execuție pentru controlul vibrațiilor seismice, utilizând diverși algoritmi de control și sub acțiunea a diferite perturbații seismice. Autorii arată superioritatea algoritmilor avansați de control.

This paper presents a comparative study for seismic vibration control algorithms. While the controlled object is nonlinear, has multiple inputs and multiple outputs, often with multiple degrees of freedom, a high importance in control comes to actuator choice and design. This paper studies two types of actuators for seismic control, with various control algorithms and under various seismic disturbances. The authors show the superiority of advanced control algorithms.

Keywords: seismic vibration control, fuzzy control, genetic algorithms, optimal control

1. Introduction

Research of the last three decades addressed the limitations of structural engineering design, as the inherent structural ability to dissipate earthquake energy was no longer sufficient. Although structural seismic design has overcome difficulties in structural vibration control, modeling uncertainties, aging of buildings and economic factors have contributed to the necessity of developing additional damping strategies. Evolution of these strategies from passive to active and semi-active architectures is due to advances in seismic design (new materials and new technologies) and information technology (computer assisted design, simulation and data processing).

One form of vibration control to be implemented was the passive dissipative control in which an inertial mass comes to oppose the external

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disturbance force [1-5]. In [1] the authors performed a successful reduction for multi-modal seismic responses of high-rise structures by tuned liquid dampers: two rectangular water tanks on top of a three story test structure connected to a shaking table. The limitations of the passive control systems is addressed in [5], as the authors present a hybrid passive/semi-active seismic isolation system, consisting of passive isolation and semi-active fluid damping devices.

Another type of structural vibration control (active control) emerges, in which the necessary control forces are synthesized based on sensory information and fed into the structure (closed loop) [6-12]. The major drawback for this form of damping is given by strict requirements for large auxiliary power sources. Nevertheless, efficiency in dissipating harmful seismic energy is well acknowledged. In [6], structural vibration control is performed using a neural network controller and an active mass-damper as actuator. Results show an 80% random vibration suppression and considerable robustness. Regarding active dampers, a major downsize is brought by the large installation and maintenance costs, altogether with low reliability and high constructive complexity. A combination of passive and active control is proposed in [12]. Here, the authors used the advantages of a base isolation system in order to reduce the large control forces otherwise required. A robust control, strategy was accepted by means of a modified skyhook regulator. Active control forces were applied solely to the first story. Simulations revealed that base isolation will keep the structure stationary relative to the ground, thus reducing the large active control forces.

Out of various forms of hybrid strategies, a new concept emerged: semi-active control, with an overall ingenious procedure - as long as the structural vibration remains in certain specified limits, the damping system behaves as a passive one; otherwise, the control is active [13-19]. Following this line, advantages show low costs and little need for auxiliary power sources. Semi-active dampers generate the necessary control forces based on the information received from the transducer distribution and can efficiently respond with equal precision, to both strong wind and damaging earthquakes. The performance levels are comparable to the ones offered by active control strategies, without their major drawbacks and with minimal risk to generate unstable behavior of the structure.

An analysis of a seismic response of structures using semi-active MR (magnetorheologic) and ER (electrorheologic) bracing systems is performed in [20]. The authors showed that placing dampers near the base of a structure, as opposed to the upper levels, gives a better response reduction. The control method used here is a linear generation of the control forces based on ground acceleration. In [21] the authors bring an experimental testing and analytical modeling of semi-active fluid dampers, emphasizing on the advantages and the fail-safe mechanism naturally ensued by this strategy. To that extent, a command law was extracted from experimental data, resulting a command voltage dependent on the desired

damping coefficient that was then applied to a servo-valve. In [22], a semi-active control system configuration with MR fluid dampers is discussed. A damper controller is used to generate and adjust the command voltage to track the desired damping force determined by the system controller based on the desired and the actual damping forces. A classic control strategy using semi-active fluid dampers is presented in [23], where the response reductions achieved with the proposed control system were comparable to those obtained with a high damping passive control system. A clear advantage is in the form of a time delay reduction by the use of digital filters. An on/off semi-active energy-based algorithm for a steel frame equipped with MR dampers is presented in [24], experimentally confirming that semi-active control not only reduces maximum values of displacement, but also improves the entire time history.

One of the implementations of actuators for this control strategy is the one using smart fluids (MR or ER). These are fluids with controllable viscous behavior, given a small electric or magnetic input [25].

2. Earthquake Induced Vibration of Civil Structures

In real structures, all their defining characteristics become variant in time, due to degradation phenomena. This must be taken into account when dealing with large scale systems, as civil structures. Given a building, the only way to ensure a valid design model is to operate such approximations that the entire behavior conforms to reality. The response of real structures when subjected to a large dynamic input often involves significant non-linear behavior, that includes the effects of considerable displacements and non-linear material properties. These conditions would generate large strains in all members of the structure.

A structure is usually described (in vibration control) in accordance to its dynamic response, composed of three major elements: inertial, damping and stiffness. First element deals with masses and suffers variations throughout the structure's life. What actually determines the dynamic of the structural response is the latter two. The damping component defines an elastic type of behavior in structures, while the stiffness element defines a plastic component. Nevertheless, no structural response is deficit of neither one of the three.

In vibration analysis it is often assumed that the three structural characteristics can be modeled as a finite number of discrete elements. In reality, inertial, elastic and dissipative effects are found continuously distributed in all dimensions, possessing an infinite number of mass elements integrated with connecting flexibility and energy dissipation elements. Thus, each small mass element will move somewhat independently from the other mass elements, meaning that the structure will have an infinite number of degrees of freedom that will require an infinite number of coordinates for motion representation. In other

words, a structure is a distributed parameter system. Due to high structural complexity and the considerable number of necessary variables, modeling and analysis of structural behavior is consuming of resources and computational effort. The general time model of a structure has the following form [26]:

$$M\ddot{x} + C\dot{x} + Kx = -F_u - MEa \qquad (1)$$

where x is the displacement, $\dot{x}$ and $\ddot{x}$ are the velocity and acceleration, respectively; M, C and K are mass, damping and stiffness matrix coefficients, respectively; F_u is the vector of control forces; a is the earthquake induced ground acceleration and E is a vector of ones.

The EH (electrohydraulic) damper (figure 1) taken into consideration in this paper, has the following model:

$$\alpha_{EH} \cdot \frac{dp(t)}{dt} + \beta_{EH} \cdot \sqrt{p(t)} \cdot u(t) = A_{EH} \cdot v(t) \qquad (2)$$

where $p(t)$ [kgm/s^2] is the pressure in the cylinder, $v(t)$ [m/s] is the ground velocity, A_{EH} [m^2] is the surface of the piston, α_{EH} [m^{4}s^2/kg] and β_{EH} [m^3/Vs(ms^2/kg)$^{1/2}$] are constants, and $u(t)$ [V] is the command voltage. To be noted the non-linearity in the model, as described by the presence of the square root of pressure. The control force is proportional to the output pressure, by the size of A_{EH}.

The hydraulic cylinder is comprised of two chambers filled with viscous fluid, between which a piston moves freely. The two chambers are interconnected through a channel with variable opening. The opening of the connecting channel is controlled by the command voltage, generating higher or lower pressure in the cylinder's chambers.

The actuator receives a command voltage between 0 and 10V, for which: 0 means shutdown, 1 is the maximum command and 10 is the minimum (passive) command.
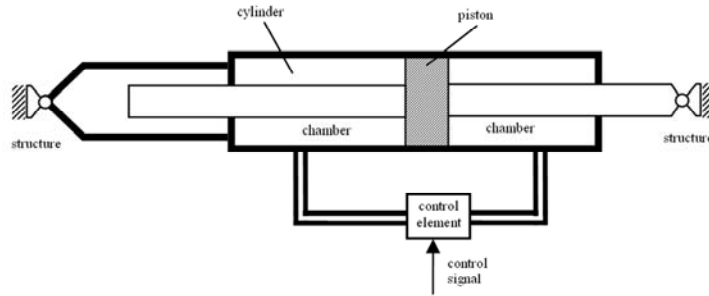

Fig. 1. Electrohydraulic damper

A MR (magnetorheological) damper is also analyzed (figure 2). An approximation of the damper model is obtained by means of experimental data.

The behavior of the semi-active MR damper is given by the mechanical model of the MR damper proposed by Spencer et al. [27]:

$$f = c_1(i)\dot{y} + k_1(x - x_0) \tag{3}$$

$$\dot{z} = -\gamma \cdot |\dot{x} - \dot{y}| \cdot z \cdot |z|^{n-1} - \beta(\dot{x} - \dot{y}) \cdot |z|^n + A(\dot{x} - \dot{y}) \tag{4}$$

$$\dot{y} = \frac{1}{c_0(i) + c_1(i)} [\alpha(i)z + c_0(i)\dot{x} + k_0 \cdot (x - y)] \tag{5}$$

where f [N] is the output force of the damper, c_0 [Ns/m] is the viscous damping at large velocities, c_1 [Ns/m] is the viscous damping for force roll-off at low velocities, k_0 [N/m] is the stiffness at large velocities, k_1 [N/m] is the accumulator stiffness, x_0 [m] is the initial displacement of the spring, z is an intermediary variable. A [m^{-1}], γ [m^{-1}], β [m^{-1}] and n are constants. Parameters c_0, c_1 and α are dependent on the command current i [A] and have been determined experimentally. Details of this model are given in [26].
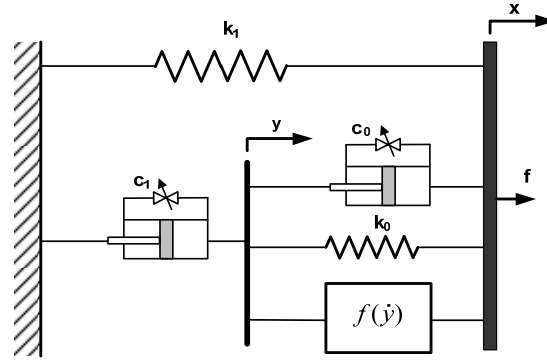

Fig. 2. Mechanical model of the MR Damper proposed by Spencer et al. [27]

The two dampers will be used as base isolation systems for a 3-story structure subjected to the seismic excitation of the Vrancea (1977) and Northridge (1994) earthquakes, under various control algorithms: bang-bang, optimal, fuzzy. In order to assure the correct desired output forces from both dampers, an internal negative feedback loop has been closed, using a PID controller, the tuning of which has been obtained by means of genetic algorithms. The dampers will be mounted at the base of the structure, their main objective being the decoupling of the structure from the ground motion. The PID controller has been chosen for control of the damper's output force in order to construct a control loop that will be used as an internal loop in a cascade configuration with advanced control algorithms for the structure displacement. As opposed to the conventional control algorithms (mainly PID and variants of on-off laws), advanced control includes algorithms such as state control, adaptive control, intelligent control systems.

Bang-bang control is an on-off type of control algorithm: if the relative displacement and the relative velocity are in the same direction, then the command force is maximum; else, the command force is minimum. Skyhook control is another on-off type of algorithm: if the relative velocity of the current story and the velocity of the earthquake induced ground motion are in the same direction, then the command force is maximum; else, the command force is minimum. These two algorithms are implemented as a comparison basis for the advanced controllers.

Optimal control is based on minimizing a performance index, that includes information about the requirements for the controlled system with weighting factors provided by a human expert. Given the structural state-space system:

$$\begin{cases} \dot{s} = As + BU \\ \quad y_s = Is \end{cases} \tag{6}$$

where s is the state vector $s = \begin{bmatrix} x & \dot{x} \end{bmatrix}^T$; y_s is the state space model output; $U = \begin{bmatrix} F_u & -Ea \end{bmatrix}^T$ containing a vector of damper output forces and a vector of earthquake accelerations; the state space matrixes are:

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \tag{7}$$

$$B = \begin{bmatrix} 0 & 0 \\ -M^{-1}D & I \end{bmatrix} \tag{8}$$

where D contains the control force distribution throughout the building, then the general structure of this cost function is:

$$J = \int_{t=0}^{\infty} \left(x^T Q_0 x + F_u^{\ T} R_0 F_u \right) dt \tag{9}$$

where Q_0 is a positive semi-definite diagonal constant matrix containing the restrictions of the state deviation from zero, R_0 is a cost matrix that weights the control signal in order to comply with energy consumption restrictions.

Thus, the optimal controller has the general form:

$$F_u = -K_0 x \tag{10}$$

where K_0 is the control matrix (as feedback gain) and is obtained by solving the Riccati equation:

$$A^T x_0 + x_0 A - x_0 B R_0^{-1} B^T x_0 + Q_0 = 0 \tag{11}$$

where x_0 is the unknown variable, used for computing the K_0 control matrix:

$$K_0 = -R_0^{-1} B^T x_0 \tag{12}$$

Fuzzy logic control has the advantage of not requiring a strict mathematical model for design. The nonlinearities of the plant are inherently included in the controller and little knowledge of the plant model is necessary. However, these controllers are usually based on human expertise.

Fuzzy logic is centred around linguistic terms and non-crisp coding of the process variables. Thus, each input and output variable is described in linguistic terms, as a human expert would. For the Mamdani fuzzy controller, the inputs need to pass through a fuzzification procedure, while the commands sent into the system need to be defuzzified, as the actuators currently used require numerical control signals (either discrete or continuous) [28].

The controller uses an inference mechanism to generate the control signal, as the consequence of a certain input and state. The entire rule set comprises the rule base of the fuzzy controller (figure 3). Every input and output of the FLC needs to be translated into a linguistic variable in order to be analyzed. Each linguistic variable is described by a set of membership functions: the linguistic terms and their distribution on the plant variable intervals.
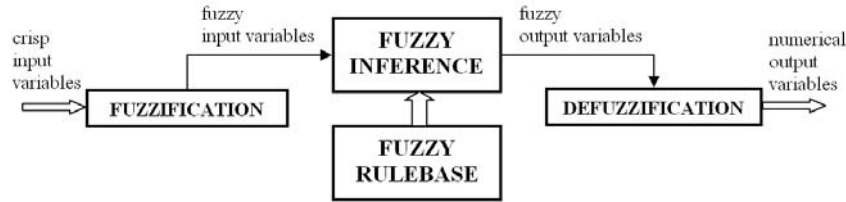

Fig. 3. Fuzzy Controller.

Genetic algorithms (GAs) are evolutionary optimization algorithms, also suited for searching problems, specifically when the solution pool is vast and the information is little. GAs are based on the survival of the fittest concept. The analytical requirements for the problem description are low, thus making the algorithm very attractive when dealing with modeling uncertainties or nonlinearities [29]. A fitness function models the objective of the algorithm, its purpose being the rejection of unfit/unwanted solutions from the gene pool.

3. Genetic Algorithms for PID Tuning

This paper considers an internal loop for control of the output actuator force, with a conventional PID control algorithm, with parameters obtained by means of genetic algorithms (figure 4). The fitness function minimizes the error between the desired control force (fed into the loop as a setpoint) and the output control force of the damper. The performance index is to be minimized, and the algorithm returns the best set of PID tuning parameters with the lowest performance index at the moment the stop condition for the algorithm is met.
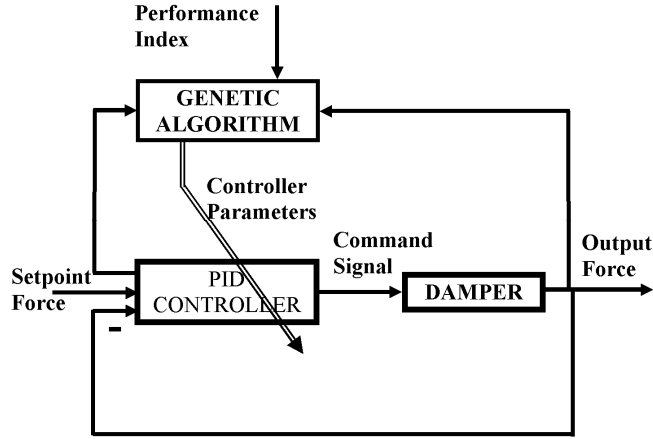
Fig. 4. Genetic tuning of PID controllers for dampers

4. Fuzzy Controller for Base Isolation

The fuzzy controller implemented in this paper is of Mamdani type and is part of the control strategy presented in figure 5, where: x is the displacement of the structure; $\dot{x}$ and $\ddot{x}$ are the velocity and acceleration of the structure, respectively; F is the control force; u_{FLC} is the desired control force, u is the command signal (either voltage or current), ε is the control error of the inner loop; a and v are the earthquake induced ground acceleration and velocity, respectively.

The controller input variables are the displacement and velocity of the structure and the output is the command voltage or current used for the dampers, respectively. The discourse universes for each input variable are normalized to the interval [-1, 1], while the output is generated in the normalized interval [0, 1]. The scaling factors used were obtained by analyzing the structure output.

Table 1

Rulebase of the fuzzy controller

Displacement Velocity	ELN	EMN	ESN	EZ	ESP	EMP	ELP
DLN	CPL	CPL	CPL	CPS	CPS	CZ	CZ
DMN	CPL	CPL	CPS	CPS	CZ	CZ	CZ
DSP	CPL	CPS	CPS	CZ	CZ	CZ	CPS
DZ	CPS	CPS	CPS	CZ	CPS	CPS	CPS
DSP	CPS	CZ	CZ	CZ	CPS	CPS	CPL
DMP	CZ	CZ	CZ	CPS	CPS	CPL	CPL
DLP	CZ	CZ	CPS	CPS	CPL	CPL	CPL

The input and output variables are presented in table 1, for which all membership functions are triangular, with a 50% overlap. The linguistic terms are coded as follows: E - displacement (deviation from zero), D - velocity (derivative of first input), C - command (output), N - negative, P - positive, L - large, M - medium, S - small, Z - zero. Table 1 also presents the rule base.
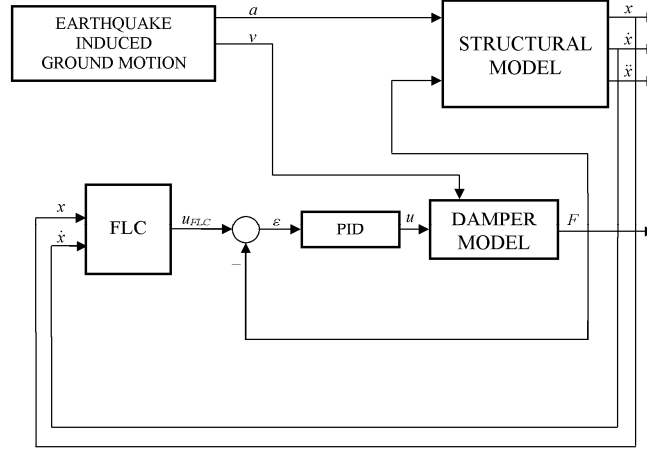

Fig. 5. Fuzzy control strategy

A second fuzzy controller (FLC) was implemented in order to obtain better reduction of the structural displacement. While the triangular membership functions are widely used, they sometimes lack in precision. When the considered plant is sensible to small variations of input, then a higher resolution in generating the control signal is required. The second FLC in this paper was designed by assigning gaussian membership functions to the linguistic variables, while using the same rulebase (table 1).

5. Comparative Study

The control methods described above have been simulated together with a 3-story structure, the two dampers, and subjected to two different earthquakes.

The three story building has the following parameters:

$$M = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix} [kg] \tag{13}$$

$$C = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix} [Ns/m] \tag{14}$$

$$K = 10^5 \begin{bmatrix} 12 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix} [N/m] \tag{15}$$

Details of this model are given in [30].

The control algorithms previously described have been implemented and simulated. The authors designed the control algorithms when considering the MR damper as an actuator. Inserting the EH damper has been regarded as a structural disturbance and the performance of the control algorithms was analyzed. Also, one more earthquake signal has been considered as external disturbance to test robustness of performances relative to exogenous seismic disturbances.

The performance indexes of the genetic algorithm tuning procedure for the two dampers were: 0.0036 for the MR damper and 0.0843 for the EH damper.

A set of evaluation criteria [31] has been chosen:

$$J_1 = \frac{\max |x_i(t)|}{x_{open}} \tag{16}$$

$$J_2 = \frac{\max |d_i(t)|}{d_{open}} \tag{17}$$

$$J_3 = \frac{\max |\ddot{x}_i(t)|}{\ddot{x}_{open}} \tag{18}$$

where $x_i(t)$ and $\ddot{x}_i(t)$ are the relative displacement and acceleration of the i-th story, while $d_i(t)$ is the interstory drift; the notation *open* designates the overall maximum absolute displacements, accelerations and drifts of the uncontrolled structure.

Table 2 presents the evaluation criteria (16)-(18) for the two dampers, for all algorithms designed in this paper and the two dampers. The following notations were considered: FLC-G is the fuzzy controller with gaussian membership functions and FLC-T is the fuzzy controller with triangular membership functions.

On the one hand, results show a very good reduction of displacement for the on-off algorithms, like Bang-bang, but with extremely degraded performances regarding acceleration reduction. On the other hand, the FLC-G fuzzy controller shows good reduction of both structural displacements and accelerations, maintaining the interstory drifts at low values. When faced with a sudden change in damping devices, the best overall performance is the one brought by the FLC-G controller. Figures 6 and 7 present the overall maximum displacements, interstory drifts and accelerations compared to the uncontrolled structure when subjected to the Northridge earthquake, while figure 8 shows the displacements of the top floor

for the two dampers and the FLC-G controller under the Northridge seismic excitations.

Table 2

Comparative numerical results

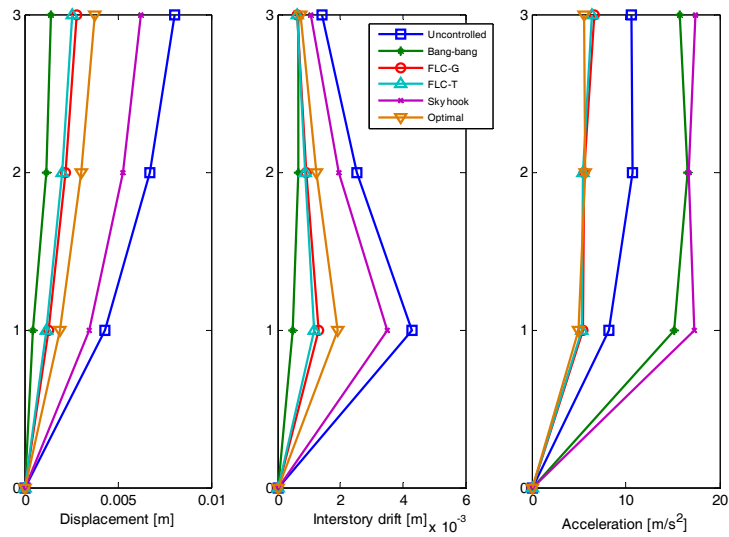| Damper	Control Method	J_1		J_2		J_3	
		Northridge	Vrancea	Northridge	Vrancea	Northridge	Vrancea
MR	Bang-bang	0.1770	0.1760	0.1570	0.1455	1.5442	1.3737
	FLC-G	0.3505	0.2671	0.3015	0.2815	0.6156	0.3490
	FLC-T	0.3172	0.2582	0.2717	0.2800	0.5955	0.3253
	Skyhook	0.7772	0.9076	0.8101	0.9540	1.6285	1.4363
	Optimal	0.4710	0.4244	0.4472	0.4372	0.5323	0.3235
EH	Bang-bang	0.2912	0.2659	0.2648	0.2895	1.2803	1.0616
	FLC-G	0.4829	0.3027	0.4275	0.3112	0.5655	0.4461
	FLC-T	0.8704	1.0068	0.7540	0.9494	1.2638	1.0612
	Skyhook	0.4176	2.2600	0.4341	2.4561	0.9453	1.9471
	Optimal	0.4864	0.4693	0.4884	0.5204	0.5540	0.3943

Fig. 6. Comparative displacements, interstory drifts and accelerations for the MR damper.
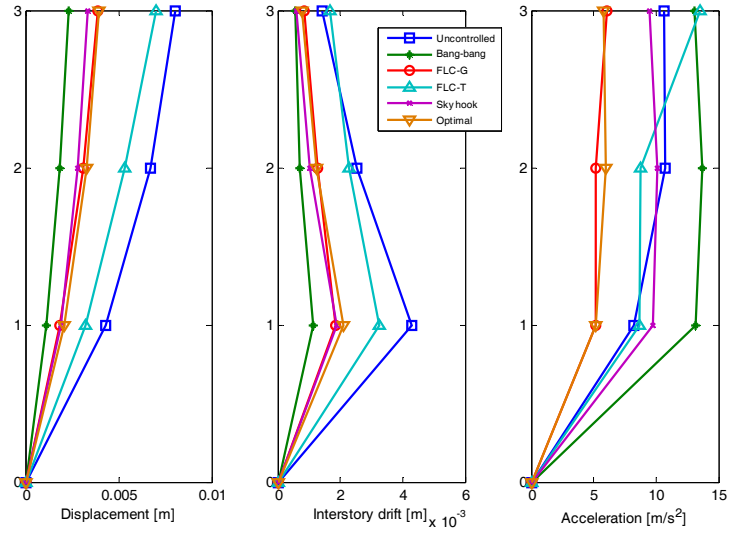
Fig. 7. Comparative displacements, interstory drifts and accelerations for the EH damper
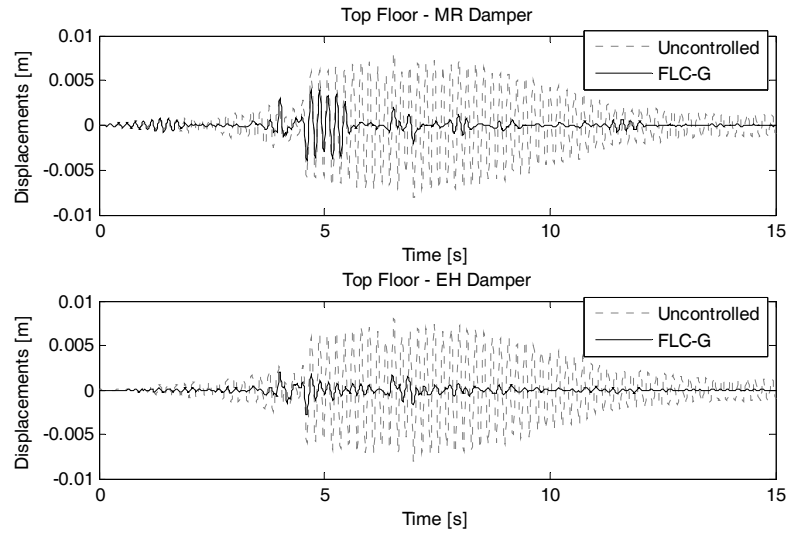

Fig. 8. Top floor displacements

6. Conclusions

Five control algorithms and two dampers have been tested, while considering two earthquake disturbances. Results show up to 74% seismic response reduction for the structure, considering displacements, interstory drifts

and acceleration in the case of a fuzzy controller with gaussian membership functions, regardless of the damper. Degraded performances for the other control algorithms prove the fuzzy controller more effective. An optimal control law has been implemented for testing purposes, showing a steady reduction of structural response of approximately half of the uncontrolled structure.

The analysis presented in this paper offers a basis for choosing control algorithms for seismic vibration control, according to the structural response component that is desired to be minimized.

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