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Civil structures semi-active control with limited measurements

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Abstract— A control scheme to protect civil structures against earthquake induced damage that uses magnetorheological dampers as control devices is presented. The design of the scheme is based on a LuGre's dynamic friction model adapted to better describe the behavior of magnetorheological dampers and an adaptive observer that estimates the damper parameters and the structure stories positions and velocities, based on acceleration and force measurements. A linear matrix inequality approach is used to design the adaptive observer, while the design of the structure motion controller is developed with Lyapunov techniques. Seismic attenuation with respect to the case of non-controlled structures is demonstrated by numerical simulations.

I. Introduction

Semi-active control is a relatively new approach for protecting civil structures against seismic induced damage [1], [2], [3], [4], [5]. A semi-active controller modulates in real-time the energy dissipation rate of the structure. According to [1], [6] and [7] these techniques can achieve a performance that is better than that achieved by passive isolation systems and comparable with that of active control systems.

One of the best actuator candidates to implement semi-active control strategies are the magnetorheological (MR) dampers, due to their high ability to dissipate energy and their low power requirements [8]. In [9] a Bouc-Wen friction model is used to describe the MR damper behavior. However, the resulting model is difficult to use in real-time control applications as it has a significant number of parameters that need to be tuned. This difficulty motivated the work in [10] that introduces a LuGre dynamic friction model to describe the MR damper behavior. This model has a simpler structure than that in [9] and its parameters, together with the parameters that define the structure behavior, can be identified in real-time [11], [12].

In [13] control laws to protect structures by means of a MR damper placed between ground and the first story are presented. To derive these laws it is assumed that the parameters of the structure and damper are known and that the accelerations, velocities and displacements of the stories are available. The internal state of the LuGre dynamic friction model is estimated with a nonlinear observer. Controllers design is achieved using Lyapunov based techniques. The analysis and simulation results show that these laws achieve seismic effect attenuation, when compared with the non-controlled case.

In this paper some of the assumptions in [13] are relaxed. It is now assumed that most of the damper parameters are unknown and that the velocities and displacements of the structure stories are not measured. It is still assumed that the structure parameters and the stories acceleration, together with the force at the damper, are available. An adaptive observer is designed based on linear matrix inequalities techniques, and it allows to estimate both the damper parameters and the structure state. The control law to attenuate the motion of the structure is designed based on standard Lyapunov techniques and has the same structure as in [13] .

The results presented in this paper are obtained from a numerical simulation of a three-degrees-of-freedom structure subject to seismic excitation. They indicate a good performance of the controller and adaptive observer and confirm the analytical results that lead to the design of the control scheme.

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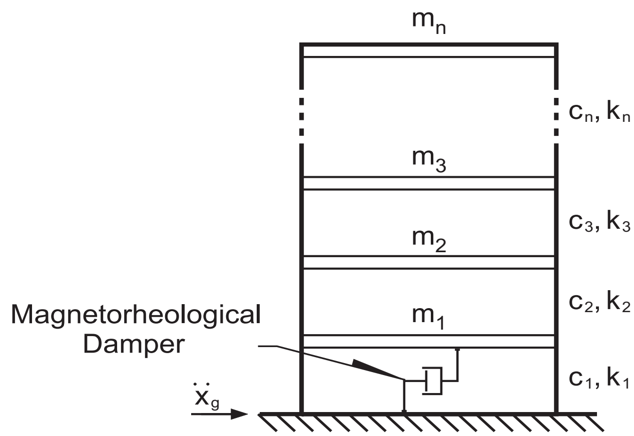

Fig. 1. Structure model.

II. Mathematical model

In this paper a planar three-degrees-of-fredom structure is considered to illustrate the development of the control algorithms and the adaptive observer. The structure has a MR damper installed between the first story and ground (see Fig. 1). The design procedure can be easily extended to control algorithms for structures with more degrees-of-freedom.

The differential equation that governs the structure's motion is

$$M\ddot{x} + C\dot{x} + F_A + Kx = -M\,l\ddot{x}_g \quad (1)$$

where M, C y K are the inertia, damping and stiffnes matrices, respectively; $x = [x_1,\ x_2,\ x_3]$ is the vector of displacements of each story; $\ddot{x}_g$ is the ground aceleration, $l = [1\ 1\ 1]^{\mathrm{T}}$ and $F_A = [f\ 0\ 0]^{\mathrm{T}}$ is the damper's force which is modeled by the following modified LuGre dynamic friction model [14], [11]

$$\dot{z} = \sigma_1\dot{x}_1 - \sigma_0 a_0|\dot{x}_1|(1 + a_1 v)z \quad (2a)$$

$$\begin{aligned} f &= \dot{z} + \frac{\sigma_0}{\sigma_1}zv + \sigma_2\dot{x}_1 \\ &= \sigma_1\dot{x}_1 + \frac{\sigma_0}{\sigma_1}zv - \sigma_0 a_0|\dot{x}_1|z - \sigma_0 a_0 a_1|\dot{x}_1|zv + \sigma_2\dot{x}_1\ , \end{aligned} \quad (2b)$$

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where a_0, a_1, σ_0, σ_1 and σ_2 are constant parameters; v is the voltage applied to the damper; $\dot{x}_1$ is the velocity of the first story; and z is an internal friction state. If the parameters σ_1 and σ_2 are assumed to be known[1], then the force equation can be rewritten as

$$\begin{aligned} f &= \begin{bmatrix} zv/\sigma_1 & -|\dot{x}_1|z & -|\dot{x}_1|zv \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix} + (\sigma_1+\sigma_2)\dot{x}_1 \\ &= U\Theta + (\sigma_1+\sigma_2)\dot{x}_1 \end{aligned} \quad (3)$$

where $U = \begin{bmatrix} zv/\sigma_1 & -|\dot{x}_1|z & -|\dot{x}_1|zv \end{bmatrix}$ and $\Theta^T = \begin{bmatrix} \theta_1 & \theta_2 & \theta_3 \end{bmatrix} = \begin{bmatrix} \sigma_0 & \sigma_0 a_0 & \sigma_0 a_0 a_1 \end{bmatrix}$. Defining the state vector as

$$\zeta = \begin{bmatrix} x_1 \; x_2 \; x_3 \; \dot{x}_1 \; \dot{x}_2 \; \dot{x}_3 \; z \end{bmatrix} , \quad (4)$$

and using equations (1) and (2a-b) the original system can be arranged as follows

$$\dot{\zeta} = A_1\zeta + B_1\Psi(\zeta)\Theta + B_2\ddot{x}_g + B_3 z , \quad (5)$$

where the system matrices are

$$A_1 = \begin{bmatrix} O_3 & I & O \\ -M^{-1}K & -M^{-1}C - \Lambda & -\Sigma \\ O^{\mathrm{T}} & \sigma_1 \; 0 \; 0 & -\alpha \end{bmatrix} ,$$

$$B_1 = \begin{bmatrix} & O_3 & \\ -1/m_1 & 1/m_1 & 1/m_1 \\ & O^T & \\ & O^T & \\ 0 & -1 & -1 \end{bmatrix},$$

$$B_2 = \begin{bmatrix} O \\ -l \\ 0 \end{bmatrix}, \; B_3 = \begin{bmatrix} O \\ \Sigma \\ \alpha \end{bmatrix}, \; \Psi(\zeta) = \begin{bmatrix} zv/\sigma_1 & 0 & 0 \\ 0 & |\dot{x}_1|z & 0 \\ 0 & 0 & |\dot{x}_1|zv \end{bmatrix},$$

$$\Sigma = \begin{bmatrix} \alpha \\ 0 \\ 0 \end{bmatrix} . \quad \Lambda = \begin{bmatrix} \frac{\sigma_1+\sigma_2}{m_1} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} , \quad O = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} .$$

O_3 is a 3×3 matrix having all its entries equal to zero, I is the identity matrix of third order and α is an arbitrary constant greater than zero which guarantees that A_1 is Hurwitz.

If accelerometers are placed at each story, the output equation is

$$y = \begin{bmatrix} \ddot{x} + \ddot{x}_g \end{bmatrix} = E\zeta + Df \quad (6)$$

where

$$E = \begin{bmatrix} -M^{-1}K & -M^{-1}C - \Lambda & O \end{bmatrix} , \quad D = \begin{bmatrix} -1/m_1 \\ 0 \\ 0 \end{bmatrix}$$

III. Adaptive Observer Design

To undertake the design of an adaptive observer for the dynamic system in Eqs. (5)-(6) the following assumption is required

Assumption 1:

i. Matrices A_1, B_1, E in Eqs. (5)-(6) are known.
ii. Parameters σ_1 and σ_2 in Eq. (3) are known.
iii. Force f in Eq. (6) can be measured.

Using assumption 1, the following observer is proposed for the dynamic system in Eqs. (5)-(6)

$$\dot{\hat{\zeta}} = A_1\hat{\zeta} + B_1\Psi(\hat{\zeta})\hat{\Theta} + B_2\ddot{x}_g + B_3\hat{z} + L\left(y - \hat{y}\right) + B_1 g, \quad (7)$$

[1]Through, for example, an independent identifier for the parameters of the structure, as the one suggested in [12]

where $\hat{\zeta}$ is the estimated state, $\hat{\Theta}$ is the current damper parameters estimate, whose adaptation law will be discussed later, $\hat{z}$ is the last component of $\hat{\zeta}$, g is a tunning function to be defined later on, L is the observer gain matrix, and finally, $\hat{y}$ is the estimated output defined by

$$\hat{y} = E\hat{\zeta} + Df \quad (8)$$

To prove the convergence of the adaptive observer, one additional assumption is required

Assumption 2:

i. The pair (A_1, B_1) is controllable and the pair (A_1, E) is observable.
ii. The matrix $\Psi(\zeta)$ in Eq. (5) satisfies $\|\Psi(\zeta)\| < \rho_0 < \infty$.
iii. The unknown parameter vector Θ is also bounded, i.e., $\|\Theta\| \preceq \rho_3$.
iv. The map $w \mapsto \xi$ of the system

$$\begin{aligned} \dot{\zeta} &= (A_1 - LE)\zeta + B_1 w \\ \xi &= E\zeta \end{aligned}$$

with $(A_1 - LE)$ Hurwitz, is strictly passive; moreover, $\exists \rho_1 > 0$, a constant, and a matrix $P_1 = P_1^T > 0$ such that

$$(A_1 - LE)^T P_1 + P_1(A_1 - LE) + (\rho_1 + \rho_2)I < 0$$

and

$$P_1 B_1 = E^T ,$$

where ρ_2 satisfies

$$\|E^T U_a \Theta + B_3\| < \frac{\rho_2}{2}$$

with $U_a = \mathrm{diag}\begin{bmatrix} v & |\dot{x}_1| & |\dot{x}_1|v \end{bmatrix}$.

Theorem 1: Under assumptions 1 and 2 there exists a parameter adaptation law and a choice of tunning function g such that

$$lim_{t\to\infty}\hat{\zeta} = \zeta$$

for the systems in Eqs. (5)-(6) and (7)-(8); moreover the estimated force $\hat{f} \to f$ as $t \to \infty$.

Proof: Define the following error signals $\tilde{\zeta} = \zeta - \hat{\zeta}$, $\tilde{y} = y - \hat{y}$, $\tilde{\Theta} = \Theta - \hat{\Theta}$ and $\tilde{z} = z - \hat{z}$, then the error dynamics for $\tilde{\zeta}$ is given by

$$\dot{\tilde{\zeta}} = (A_1 - LE)\tilde{\zeta} + B_1\left(\Psi(\zeta)\Theta - \Psi(\hat{\zeta})\hat{\Theta}\right) + B_3\tilde{z} - B_1 g . \quad (9)$$

Introduce the Lyapunov function candidate

$$V = \frac{1}{2}\tilde{\zeta}^T P_1\tilde{\zeta} + \frac{1}{2}\tilde{\Theta}^T\Gamma^{-1}\tilde{\Theta} , \; \Gamma = \Gamma^{\mathrm{T}} > 0 \quad (10)$$

Taking the time derivative of Eq. (10) and using Eq. (9) it follows

$$\begin{aligned} \dot{V} =& \frac{1}{2}\tilde{\zeta}^T\left((A_1 - LE)^T P_1 + P_1(A_1 - LE)\right)\tilde{\zeta} \\ &+ 2\tilde{\zeta}^T P_1 B_1\left(\Psi(\zeta)\Theta - \Psi(\hat{\zeta})\hat{\Theta}\right) \\ &+ 2\tilde{\zeta}^T P_1 B_3\tilde{z} - 2\tilde{\zeta}^T P_1 B_1 g + \tilde{\Theta}^T\Gamma^{-1}\dot{\tilde{\Theta}} \end{aligned} \quad (11)$$

Decomposing $\Psi(\zeta)\Theta - \Psi(\hat{\zeta})\hat{\Theta} = \Psi(\hat{\zeta})\tilde{\Theta} + (\Psi(\zeta) - \Psi(\hat{\zeta}))\Theta$ and using Assumption 2.*iv*, Eq. (11) can be rewritten as

$$\begin{aligned} \dot{V} =& \frac{1}{2}\tilde{\zeta}^T\left((A_1 - LE)^T P_1 + P_1(A_1 - LE)\right)\tilde{\zeta} \\ &+ 2\tilde{\zeta}^T P_1 B_1\left(\Psi(\zeta) - \Psi(\hat{\zeta})\right)\Theta + 2\tilde{\zeta}^T P_1 B_3\tilde{z} \\ &- 2\tilde{\zeta}^T P_1 B_1 g + \tilde{\Theta}^T\left(2\Psi(\hat{\zeta})\tilde{y} + \Gamma^{-1}\dot{\tilde{\Theta}}\right) \end{aligned} \quad (12)$$

Choosing the parameter adaptation law as

$$\dot{\hat{\Theta}} = 2\Gamma\Psi(\hat{\zeta})\tilde{y} \tag{13}$$

and decomposing $\Psi(\zeta) - \Psi(\hat{\zeta})$ as

$$\Psi(\zeta) - \Psi(\hat{\zeta}) = \begin{bmatrix} v & 0 & 0 \\ 0 & |\dot{x}_1| & 0 \\ 0 & 0 & |\dot{x}_1|v \end{bmatrix} \tilde{z}$$
$$+ \begin{bmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -v \end{bmatrix} \mathrm{sign}(\dot{\hat{x}}_1)\hat{z}\dot{\tilde{x}}_1 = U_a\tilde{z} + U_b\hat{z}\dot{\tilde{x}}_1 \tag{14}$$

it is possible to rewrite Eq. (12) as

$$\begin{aligned} \dot{V} =& \frac{1}{2}\tilde{\zeta}^T\left((A_1 - LE)^T P_1 + P_1(A_1 - LE)\right)\tilde{\zeta} \\ &+ 2\tilde{\zeta}^T\left(E^T U_a\Theta + B_3\right)\tilde{z} \\ &+ 2\tilde{\zeta}^T E^T U_b\Theta\hat{z}\dot{\tilde{x}}_1 - 2\tilde{y}^T g \end{aligned} \tag{15}$$

Using Assumption 2, from Eq. (15) it follows that

$$\begin{aligned} \dot{V} \preceq& \frac{1}{2}\tilde{\zeta}^T\left((A_1 - LE)^T P_1 + P_1(A_1 - LE)\right)\tilde{\zeta} \\ &+ \rho_2\|\tilde{\zeta}\|^2 + 2\rho_3\|\tilde{y}\||\hat{z}||\dot{\tilde{x}}_1| - 2\tilde{y}^T g \\ =& \frac{1}{2}\tilde{\zeta}^T\left((A_1 - LE)^T P_1 + P_1(A_1 - LE)\right)\tilde{\zeta} + \rho_2\|\tilde{\zeta}\|^2 \\ &- \rho_2\left(|\dot{\tilde{x}}_1| - \frac{\rho_3}{\rho_2}\|\tilde{y}\||\hat{z}|\right)^2 \\ &+ \rho_2|\dot{\tilde{x}}_1|^2 + \frac{\rho_3^2}{\rho_2}\|\tilde{y}\|^2|\hat{z}|^2 - 2\tilde{y}^T g \end{aligned} \tag{16}$$

Choosing the tunning function g as

$$g = \frac{1}{2}\frac{\rho_3^2}{\rho_2}|\hat{z}|^2\tilde{y} \tag{17}$$

and using again Assumption 2, Eq. (16) can be expressed as

$$\dot{V} \preceq -\rho_1\|\tilde{\zeta}\|^2 - \rho_2\left(|\dot{\tilde{x}}_1| - \frac{\rho_3}{\rho_2}\|\tilde{y}\||\hat{z}|\right)^2 \preceq 0 \tag{18}$$

Eq. (18) assures that the equilibria $\tilde{\zeta} = 0$ and $\tilde{\Theta} = 0$ is stable and that $\tilde{\zeta}$ and $\tilde{\Theta}$ are bounded. Using Barbalat's Lemma [15] it is also possible to state that $lim_{t\to\infty}\tilde{\zeta} = 0$.

To prove that $\hat{f} \to f$ as $t \to \infty$, define

$$\begin{aligned} \tilde{f} = f - \hat{f} &= U\Theta - \hat{U}\hat{\Theta} + (\sigma_1 + \sigma_2)\dot{\tilde{x}}_1 \\ &= \tilde{U}\Theta + \hat{U}\tilde{\Theta} + (\sigma_1 + \sigma_2)\dot{\tilde{x}}_1 \end{aligned} \tag{19}$$

From $lim_{t\to\infty}\tilde{\zeta} = 0$ it follows that $lim_{t\to\infty}\tilde{f} = \hat{U}\tilde{\Theta}$.

Using Eq. (9) for the error dynamics of $\tilde{\zeta}$ and taking into account that a) Assumption 2.*iii* implies Θ is bounded and b) that $lim_{t\to\infty}\tilde{\zeta} = 0 \Rightarrow lim_{t\to\infty}\tilde{y} = 0$ and therefore $lim_{t\to\infty}g = 0$, according to the selection of g in Eq (17), it follows directly that $\dot{\tilde{\zeta}}$ is bounded. Using these facts and the previous results about the decomposition of $\Psi(\zeta)\Theta - \Psi(\hat{\zeta})\hat{\Theta}$, it also follows that $\ddot{\tilde{\zeta}}$ is bounded. From this, the uniform continuity of $\dot{\tilde{\zeta}}$ is proven and using Barbalat's Lemma again it can be shown that $lim_{t\to\infty}\dot{\tilde{\zeta}} = 0$.

Usign $lim_{t\to\infty}\dot{\tilde{\zeta}} = 0$ in Eq. (9) and again the decomposition of $\Psi(\zeta)\Theta - \Psi(\hat{\zeta})\hat{\Theta}$, it follows that

$$lim_{t\to\infty}B_1\Psi(\hat{\zeta})\tilde{\Theta} = 0 \tag{20}$$

By Eq. (3), the fourth row of $B_1\Psi(\hat{\zeta})$ can be written as $\frac{1}{m_1}\hat{U}$ and therefore it follows that

$$lim_{t\to\infty}\frac{1}{m_1}\tilde{f} = lim_{t\to\infty}\frac{1}{m_1}\hat{U}\tilde{\Theta} = 0 \ . \tag{21}$$

As usual, only if $\hat{U}$ is persistently exciting it is possible to achieve $\tilde{\Theta} = 0$.

■

Theorem 1 is inspired in the results presented in [16]. It is straightforward to prove that Assumption 2.*i* $\to$ *iii* holds. To prove Assumption 2.*iv* a linear matrix inequality package, as the one in [17], can be use to find the feasability of a given observer gain matrix L.

IV. Seismic response reduction algorithms

The purpose of the semi-active control algorithms is to reduce the dynamic response of a structure under seismic excitation. It is assumed that the structure is built to code in such a way that under nominal seismic excitation its displacements are below the maximum safety limit. Adding control to the structure will reduce the magnitude of these displacements. The control goal is to maintain the system as close as possible to the equilibrium point $\zeta = 0$.

To illustrate the performance of the adaptive observer introduced in the previous section, one of the control laws presented in [13] is used. For that purpose, the system in Eqs. (5)-(6) is rewritten using the observed state $\hat{\zeta}$ instead of the real state ζ as

$$\dot{\hat{\zeta}} = A_1\hat{\zeta} + B_2\ddot{x}_g + C_1\hat{z} + C_2\hat{z}v \ , \tag{22}$$

where

$$C_1 = \begin{bmatrix} O \\ \frac{1}{m_1}\hat{\theta}_2|\dot{\hat{x}}_1| \\ 0 \\ 0 \\ -\hat{\theta}_2|\dot{\hat{x}}_1| + \alpha \end{bmatrix}, C_2 = \begin{bmatrix} O \\ \frac{\hat{\theta}_1}{\sigma_1 m_1} + \frac{\hat{\theta}_3}{m_1}|\dot{\hat{x}}_1| \\ 0 \\ 0 \\ -\hat{\theta}_2|\dot{\hat{x}}_1| \end{bmatrix},$$

The voltage in the damper $v \in [0, \bar{v}]$, the control signal in this case, is chosen according to

$$v = \mathrm{sat}(\gamma_1\hat{\zeta}^{\mathrm{T}}P_2C_2\hat{z}) \ , \ \gamma_1 > 0 \ , \tag{23}$$

where

$$\mathrm{sat}(y) = \begin{cases} 0, & \text{if } y \geq 0; \\ |y|, & \text{if } -\bar{v} < y < 0; \\ \bar{v}, & \text{if } y \preceq -\bar{v}. \end{cases} \tag{24}$$

The control law in Eq. (23) is derived from a Lyapunov based approach in which the Lyapunov function is

$$V_2 = \hat{\zeta}^{\mathrm{T}}P_2\hat{\zeta} \ , \ P_2 = P_2^{\mathrm{T}} > 0 \ . \tag{25}$$

Matrix P_2 is a solution to the Lyapunov equation $\left[P_2A_1 + A_1^{\mathrm{T}}P_2\right] = -Q_2; Q_2 = Q_2^T > 0$. The complete stability proof for this control law can be found in [13]. In general lines it leads to prove that $\hat{\zeta}$ is ultimately bounded. The Lyapunov function V_2 in Eq. (25) is independent of the convergence of ζ to $\hat{\zeta}$. The stability proof of Theorem 1 guarantees that $\hat{\zeta}$ is bounded and therefore, that it has no possibility to escape in finite time.

V. Simulation Results

The adaptive observer designed in the previous section together with the control law in Eq. (23) were tested with a numerical simulation. The test consist of applying the N-S component of the El Centro earthquake (see Fig. 2) to the three degrees-of-freedom structure. The seismic excitation signal was applied first to the structure with no magenetorheological damper and then to the same structure with the magnetorheological damper operated using the estimated states and parameters from the adaptive observer and the seismic attenuation control law described in the previous sections.

The nominal parameters for the structure were obtained from [2] and the parameters for the MR damper from [11]. They are shown below and in Table I

$$M = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix} (\mathrm{kg}) \ ,$$

$$C = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix} \left(\frac{\mathrm{N} \cdot \mathrm{s}}{\mathrm{m}} \right) \ ,$$

$$K = 10^5 \begin{bmatrix} 12 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix} \left(\frac{\mathrm{N} \cdot \mathrm{s}^2}{\mathrm{m}} \right)$$

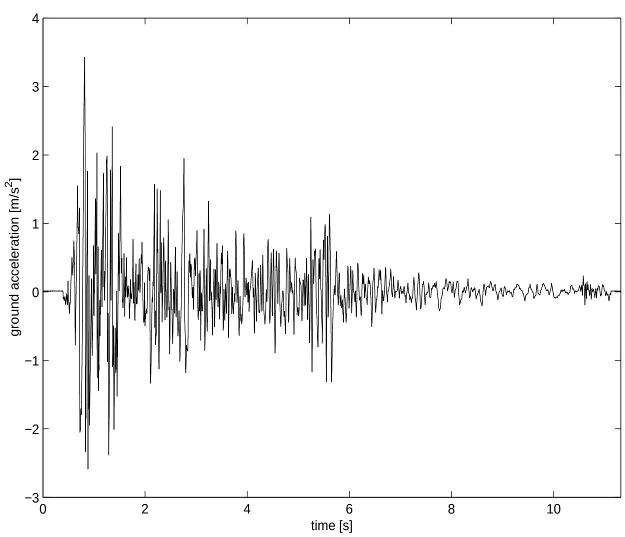

Fig. 2. N-S component of El Centro earthquake.

TABLE I
Parameters for the MR damper.

Parameter	value)
σ_0	$1.059e6$
σ_1	5700
σ_2	2300
a_0	.0030
a_1	-0.1444

Fig. 3 shows the displacement of the third story during the duration of the simulated earthquake. It can be easily appreciated that the use of the control law together with the adaptive observer provides a significat reduction on the magnitude of the displacement of this story. A plot of the control voltage applied to the MR damper is presented in Fig. 4. Figs. 5 and 6 show the norm evolution of the state estimation errors and force estimation errors, respectively. In both cases the estimation errors go to zero. Finally, Table II is a summary of the results for the three stories. It shows the relative reductions attained with the chosen control law in the three stories displacements, velocities and accelerations, when compared to the nominal case of no control law. It can be noted that the results in Fig. 3 corresponds to the worst case in terms of attenuation. Even for this worst case, there is a 67% reduction in the absolute displacements.

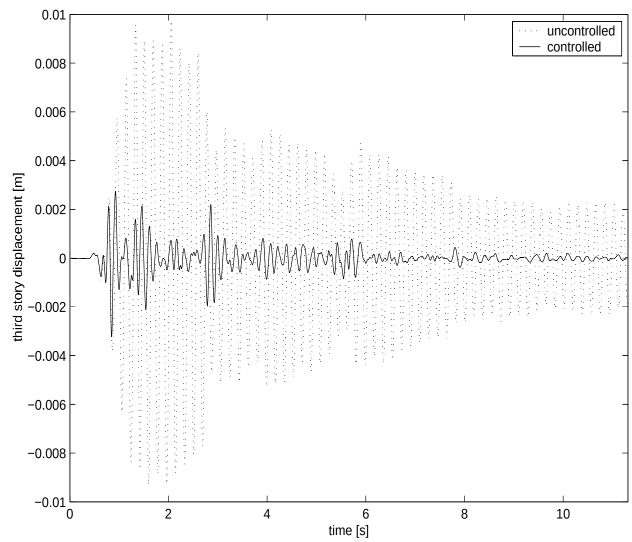

Fig. 3. Third story displacement using control law and adaptive observer.

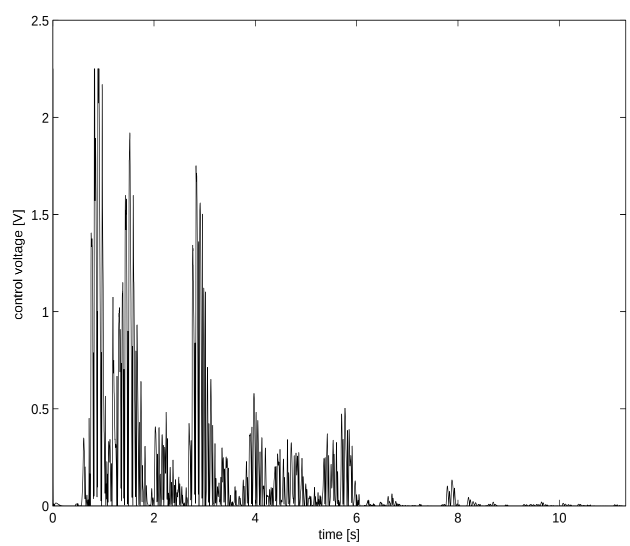

Fig. 4. Applied control voltage.

VI. Conclusions

A semi-active control strategy for the attenuation of seismic induced motion in civil structures is presented in this paper. The design used an adaptive observer to calculate the most important parameters of the magnetorheological damper, used as actuator, and to estimate the

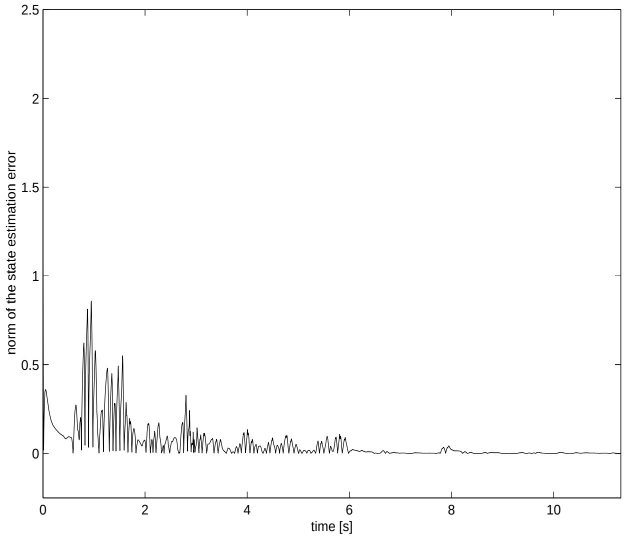

Fig. 5. Norm evolution of the state estimation error.

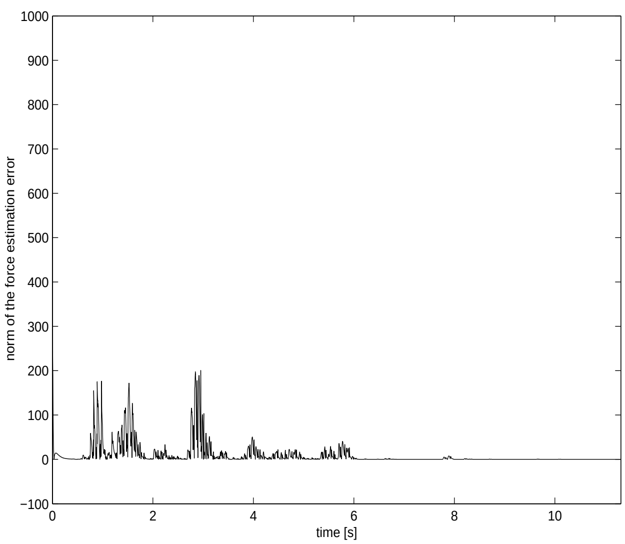

Fig. 6. Norm evolution of the force estimation error.

velocities and displacements of the structure stories, based on acceleration and force measurements. The convergence of the adaptive observer was proved using linear matrix inequalities techniques. The control law designed followed standard Lyapunov techniques and is based in previous work. Numerical simulation results showed that with the use of this control law it is possible to attain high reductions of the story structure displacements when subjected to a seismic excitation. The performance of the adaptive observer is also very good. Ongoing work is related to the integration of the estimation of all the parameters in the structure with the state observer.

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TABLE II

Comparison between free response and control law.

	story	free response	control law
x [%]	1	100	13.05
	2	100	26.21
	3	100	33.25
d [%]	1	100	13.05
	2	100	53.17
	3	100	52.85
a [%]	1	100	69.81
	2	100	62.69
	3	100	48.87

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