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Adaptive active output controller to suppress mechanical vibrations on building-like structures

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Abstract: Suppression of mechanical vibrations is becoming an active field in seismic engineering. The suppression is solved by either semi-active and active controllers based on nonlinear dampers or pneumatic actuators. This study describes an adaptive control design for suppressing mechanical vibrations on a simulated building-like structure. The adaptive method is selected considering that energy can be saved when the suppression should be done. A simple building structure was modelled as an interconnected system and it is considered for evaluating the controller proposal. Therefore, the controller scheme is designed as a decentralized structure. Each adaptive controller is based on an time varying gain proportional derivative scheme. The adaptive gain structure is determined using a kind of controlled Lyapunov function. The adaptive law uses an estimation of velocity based on a robust exact differentiator (RED) implemented as a variation of the super-twisting algorithm. The adaptive proportional derivative controller is evaluated on a simulated three floor building-like structure. The set of simulations considered the presence of an external perturbation forced by a non-regular movement of the building basement. The controller shows to be efficient to counteract the effect of external mechanical vibrations. The effect of the vibrations amplitude on the controller performance is also evaluated. The performance of the proposed controller was superior to the standard proportional derivative controller as it is proven in this study.

Keywords: Suppression of mechanical vibrations; Adaptive PD control; Active controller; Seismic structures; Interconnected systems

1. INTRODUCTION

Nowadays, relevant earthquakes have occurred all over the world. Some of them have been catastrophic because a large number of persons have died. Moreover, a big number of civil structures have been destroyed or at least severely damaged. This condition has enforced the development of systems that can counteract the oscillations provoked by earthquakes. Based on the previous idea, the emerging of new methods in civil engineering has provided reliable, secure and energy efficient system that can compensate some degree of oscillations Fisco and Adeli (2011b), Fisco and Adeli (2011a).

Even when there are some passive solutions to counteract the effect of earthquake oscillations, they only can actuate within a very narrow interval of oscillation's amplitude and frequency Lu and Lin (2009). The most famous solution offered by the technique is the so-called timed mass damper (TMD). This solution proposed for the first time the idea of interconnecting elements of the civil structure using a virtual spring-damper system. This was considered as the most representative solution of the so-called passive controllers of civil structures. Despite the contribution offered by TMD, the single frequency where this device can oscillate produces a serious limitation over the performance of this passive controller.

In 1988, Clark proposed the concept of multiple timed mass damper (MTMD) to control structural vibrations in a wider frequency range Housner et al. (1997). Since that moment, a big number of results were proposed using the concept of MTMD Guo and Chen (2007). The major issue when MTMD is considered is the constrain on the model structure which should be discrete . This solution is still using a semi-active framework.

In the beginnings of 90's, the concept of active control of building structures was introduced. Active timed mass damper (ATMD) was the first type of solution within the method. This system included an actuator between the building structure and the TMD. This actuator applies on-line force to compensate mechanical vibrations. This method was successfully implemented to regulate both lateral and rotation vibrations using the linear quadratic regulator control concept (LQR). Li proposed a distributed array of mini ATMD to compensate vibration in lateral sense. This strategy showed better result compared to the case when a single TMD was considered. Stancioiu Stancioiu and H.Ouyang (2012) proposed a sequence of synchronized TMD with central frequencies forming a discrete spectrum. This strategy produced a more effective and wider frequency range where the actuator was effective.

In 1990, the first actual application of ATM was developed by Ikeda et al. (2001). A real ten-floors building was instrumented with two ATM to control lateral and torsional vibrations. The control algorithm used the same LQR mentioned in Hanagan and Murray (1997). In average, this controlled building was 26 % less affected by hurricane winds and earthquakes mechanical vibrations. The same scheme was implemented but considering the instrumentation of multiple mini ATMD and it was compared with the single ATMD system. The superior performance of multiple actuated system was evidenced.

Fuzzy logic (FL) and proportional derivative (PD) controllers applied over instrumented buildings were compared in Nomura et al. (2007). FL controller was more efficient considering that similar oscillations were equally suppressed but using less energy. This condition was achieved as consequence of the state dependent gain scheme which is natural in the FL control method.

Recently, distributed actuators have been considered to compensate mechanical vibrations in building systems. The first proposal where multiple distributed actuators were considered used a computational model. The controller was designed using the LQR structure. This controller showed to be very efficient when mechanical vibrations appeared in lateral and torsional directions. This distributed controller design was also tested to reduce the mechanical vibrations induced by walking over a business building structure.

Optimal distribution of actuators was proposed in Saleh and Adeli (1998) to compensate mechanical vibrations. The controller implemented to regulate each actuator was LQR. This solution also showed that a reduced number of actuators cannot be sufficient to compensate mechanical vibrations but a new problem appeared, the actuator saturation which is still a matter of concern. This condition happened when the actuator has to apply big amounts of energy. One option to overcome the actuator saturation used the acceleration feedback.

The necessity of reducing energy when the mechanical vibration must be suppressed and considering the eventual presence of actuator saturation enforce the application of adaptive controller instead of robust strategies. This conditions was confirmed indirectly when a class of sliding mode controller was implemented/compared with integral and LQR controllers.

Model predictive control (MPC) has been also evaluated to compensate mechanical vibrations. This kind of controller was useful when the optimization problem was the main objective. However, this controller strategy also required big amounts of energy that cannot be applied in real building structures. However, MPC showed a 43 % reduction for root mean square of acceleration compared with the conventional LQR controller. A similar controller based on active tendons was evaluated and confirmed a better performance.

All the previous controllers considered the position and velocity feedback of beams forming the building structure Symans and Constantinou (1999). This conditions can be hardly hold it in real buildings. Therefore, an output based controller must be considered when the mechanical vibrations of real building structures should be suppressed. At this moment, there are just a few of studies considering the output based controller for suppressing mechanical vibrations. The main issue that must be solved when the output based controller is applied regards to the necessity of estimating velocity within a fixed period of time.

The aim of this work is to evaluate the application of the output based controller based on the adaptive PD controller supplied with the super-twisting structure to estimate velocity in finite time Levant (1993), Levant (1998).

The rest of the paper is organized as follows, in Section 2 the Notation section is described. The section 3 describes the state space representation of the building structure. After that, the STA working as a RED is described. In the same section, the extended system that incorporates the STA to estimate the derivative of the error signal in closed loop with the twisting controller is given. In section 3 the main result is introduced. Numerical results are presented in section 4 and finally in section 5, some conclusions are given.

2. NOTATION

The following notation was used in this study: $\mathbb{R}^n$ represents the vector space with n-components. $\top$ is used to define the transpose operation. $\|z\|$ is used to define the euclidean norm of $z \in \mathbb{R}^n$. $\|z\|_H^2 := z^\top Hz$ is the weighted norm of the real-valued vector $z \in \mathbb{R}^n$ with weight matrix $H > 0$, $H = H^\top$, $H \in \mathbb{R}^{n\times n}$. The matrix norm labelled as $\|D\|_2$, $D \in \mathbb{R}^{n\times n}$ is defined as the maximum eigenvalue of the matrix D. If two matrices $N \in \mathbb{R}^{n\times n}$ and $M \in \mathbb{R}^{n\times n}$, fulfils $M > N$ ($\geq$), that means that $M - N$ is a positive definite (semidefinite) matrix. The symbol $\mathbb{R}^+$ represents the positive real scalars. The symbols $I_{n\times n}$ and $0_{n\times n}$ were used to represent the identity matrix $I \in \mathbb{R}^{n\times n}$ and the matrix formed with zeroes of dimension $n \times n$.

3. STATE SPACE FORMULATION OF SEISMIC STRUCTURES

Consider a multiple-storey seismic structure equipped with variable friction dampers as shown in Fig. 1. The notations m_i, k_i and $x_i(t)$ in Fig. 1 represent the mass, stiffness, and relative-to-the-ground displacement of the i-th floor, while k_b,i and $N_i(t)$ denote the stiffness of the bracing and the controllable clamping force of the i-th friction damper, respectively. When subjected to a seismic force, the motion of the structure may be formulated in a state space equation, i.e.

$$M\frac{d^2q(t)}{dt^2} + C\left(q(t), \frac{dq(t)}{dt}\right)\frac{dq}{dt} + G(q(t)) + \Sigma(q(t), \frac{dq(t)}{dt}, t) = u(t)$$

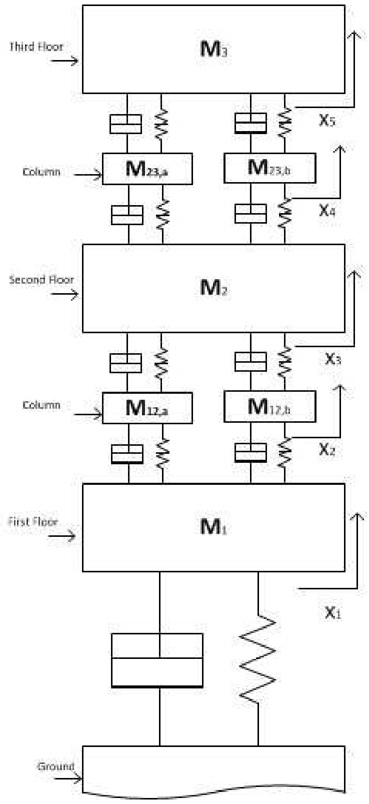

Fig. 1. Mechanical representation for one vertical section of the building structure. It shows the presence of an active damper place between the building and earth. Each vertical column used to construct the building structure is also represented as an natural damper placed in parallel to a passive spring. This section of the system is used to consider the energy accumulation (stiffness)obtained as consequence of building torsion.

where the vector q represents the state of the structure which contains the relative-to-ground velocities and displacements of all floors; u denotes the vector of the controllable forces provided by the variable friction dampers; w is the vector of the ground accelerations; M denotes the system matrix that is composed of the structural mass, damping and stiffness matrices; C, G and E represent the distribution matrices of the Coriolis, gravitational and external exciting forces, respectively. It must be pointed out that although (1) looks similar to that of a typical active control system, the control forces in u are essentially passive (resistant) friction forces. The structural members of the building system are modelled as a classical longitudinal rod for the axial wave motion, a Timoshenko beam for flexural waves, and a classical torsional shaft for the torsional mode. A small deformation is assumed so that the linear theory is valid and all three types of wave motions are uncoupled from each other for a single structural member. The effect of viscous damping, which was not considered in the original version of RMM, is included as an extension. A uniform treatment of joints of structures is suggested to keep the number of unknowns in the formulation of the RMM for structures with MTMDs the same as that without MTMDs. It is noted that the current formulation is presented in a way that is particularly convenient for programming.

Using the state variable representation of the mechanical structure (1), the second order nominal model presented above can be represented as follows:

$$\begin{aligned} \frac{d}{dt}x_a^i(t) &= x_b^i(t) \\ \frac{d}{dt}x_b^i(t) &= f(x^i(t)) + g\left(x^i(t)\right)u^i(t) \\ &+\zeta^i(x^i(t), x^{i+1}(t), x^{i-1}(t), t) \end{aligned} \tag{1}$$

The vector x_a^i represents the three coordinate position of each column's centre of gravity. The associated vector x_b^i is the corresponding velocity of those three coordinates. Finally, the function ζ^i represents the uncertainties and perturbations produced by the presence of earthquake, the movement of the neighbour columns, wind flows, etc. In this paper, it is assumed that

$$\left\|\zeta^i(x^i, x^{i+1}, x^{i-1}, t)\right\|^2 \leq \eta_0^i + \eta_1^i \left\|x^i\right\|^2, \ \ \eta_0^i, \eta_1^i \in \mathbb{R}^+$$

The control structure was proposed following the adaptive PD scheme. This class of control model obeyed

$$u(t) = \left(g(x(t))^{-1}\right)\left(k_p(t)e(t) + k_d(t)\frac{d}{dt}e(t)\right)$$

where

$$x = \left[e^\top, \frac{de}{dt}^\top\right]^\top, \ \ e = [x_a^1, x_a^2, \cdots, x_a^n]^\top$$
$$\frac{de}{dt} = [x_b^1, x_b^2, \cdots, x_b^n]^\top$$

The mechanical nature of building structure is used here to consider that a nonlinear system described by a feasible distributed second order nonlinear differential equation can be used for representing it mathematically.

The drift term $f : \mathbb{R}^{2n} \to \mathbb{R}^n$ is a Lipschitz function. The following assumption is considered valid in this study.

Assumption 1. The nonlinear system (1) is controllable.

Based on the previous fact, the input associated term $g : \mathbb{R}^n \to \mathbb{R}^{n \times n}$ satisfies.

$$0 < g^- \leq \|g(z)\|_F \leq g^+ < \infty, \quad \forall z \in \mathbb{R}^n \tag{2}$$

It is evident that matrix $g(z(t))$ is invertible $\forall t \geq 0$.

In this study, we considered that measurements of building displacements can be obtained on-line. Under these considerations, we proposed that exists a set of output signal $y \in \mathbb{R}^n$ which is given by $y^i = x_a^i$.

The following assumptions are assumed to be fulfilled in this study:

Assumption 2. The nonlinear function $f(\cdot)$ is unknown but satisfies the Lipschitz condition

$$\|f(x) - f(x')\| \leq L_1 \|x - x'\| \tag{3}$$

In the previous inequality, $x, x' \in \mathbb{R}^{2n}$ and $L_1 \in \mathbb{R}^+$.

4. PROBLEM FORMULATION

The problem considered in this paper was to compensate the presence of mechanical oscillations of the building-like structure. The previous statement can be reformulated as to design an output feedback controller such that $\|x_a^i(t)\| \leq v^+$ with v^+ a positive bounded scalar which represents the upper limit for internal building displacements before it could damaged. This condition must be hold it for any time and despite the presence of external perturbations that can include the appearing of earthquakes, faster winds, etc. This problem can be considered a class of stabilization problem.

5. CONTROLLER STRUCTURE

5.1 Design of the Adaptive PD controller

In general, a PD controller is designed using the assumption regarding $e(t)$ and $\frac{de}{dt}(t)$ are measured simultaneously where e is the tracking or the regulation error. This is not the regular case in real building mechanical structure represented in Figure 1. Otherwise, an important resources investment is required. Therefore, in classical literature, one can find two important solutions: to construct an observer or using a first order filter to approximate the error derivative. The first one requires the system structure (that is in this paper is assumed to be unknown because the presence of external perturbations and internal uncertainties) and in the second case, the derivative approximation is usual poor, specially if the output information is contaminated with noises. One additional option is considering a class of RED that can provide a suitable and accurate approximation of the error derivative. Super Twisting Algorithm (STA) has demonstrated to be one of the best RED in several times.

5.2 Super-Twisting Algorithm

In counterpart of some others second order sliding modes algorithms, the STA can be used with systems having relative degree one with respect to the chosen output Levant (1993). The STA application as a RED is described as follows. If $w_1(t) = r(t)$ where $r(t) \in \mathbb{R}$ is the signal to be differentiated, $w_2(t) = \frac{dr}{dt}(t)$ represents its derivative and under the assumption of $\left|\frac{dr}{dt}(t)\right| \leq r^+$, the following auxiliary equation is gotten $\frac{dw_1}{dt}(t) = w_2(t)$ and $\frac{dw_2}{dt}(t) = \frac{d^2r}{dt}(t)$. The previous set of differential equation is a state representation of the signal $r(t)$.

The STA algorithm to obtain the derivative of $r(t)$ looks like

$$\begin{aligned} \frac{d}{dt}\bar{w}_1(t) &= \bar{w}_2(t) - \lambda_1 |\tilde{w}_1(t)|^{1/2} \operatorname{sign}(\tilde{w}_1(t)) \\ \frac{d}{dt}\bar{w}_2(t) &= -\lambda_2 \operatorname{sign}(\tilde{w}_1(t)) \\ \tilde{w}_1 := \bar{w}_1 - w_1 \quad & d(t) = \frac{d}{dt}\bar{w}_1(t) \end{aligned} \tag{4}$$

where $\lambda_1, \lambda_2 > 0$ are the STA gains. Here $d(t)$ is the output of the differentiator Levant (1998).

In the previous equation,

$$\operatorname{sign}(z) := \begin{cases} 1 & if \quad z > 0 \\ \in [-1, 1] & if \quad z = 0 \\ -1 & if \quad z < 0 \end{cases} \tag{5}$$

5.3 PD controller with the Super-Twisting Algorithm

A single adaptive PD controller is applied over each section of the building-like mechanical structure. This is a class of ATMD. Each adaptive PD controller proposed in this study obeys the following structure

$$u_i(t) = -k_{1,i}(t)\, e_i(t) - k_{2,i}(t)\, d_i(t) \tag{6}$$

where e_i is x_a^i. The gains in the PD controller are determined by

$$\begin{aligned} k_{1,i}(t) &= g_i^{-1}(x_a(t)) \left(\bar{k}_{1,i}(t) + k_{1,i}^*\right) \\ k_{2,i}(t) &= g_i^{-1}(x_a(t)) \left(\bar{k}_{2,i}(t) + k_{2,i}^*\right) \end{aligned} \tag{7}$$

with $\bar{k}_{1,i}$ and $\bar{k}_{2,i}$ are time varying scalars adjusted by a special tracking error dependent adaptive law described by the following ordinary differential equations:

$$\begin{aligned} \frac{d}{dt}\bar{k}_{1,i}(t) &= -\pi_{1,i}^{-1} e_i(t) M_a^\top P_{2,i} E_i(t) \\ \frac{d}{dt}\bar{k}_{2,i}(t) &= -\pi_{2,i}^{-1} e_{i+n}(t) M_b^\top P_{2,i} E_i(t) \end{aligned} \tag{8}$$

where $\pi_{1,i}$ and $\pi_{2,i}$ are free parameters to adjust the velocity of convergence for the adjustable gains. In (7), the parameters $k_{1,i}^*$ and $k_{2,i}^*$ are positive constants. The matrices M_a and M_b are given by $M_a = [1 \;\; 0]^\top$ and $M_b = [0 \;\; 1]^\top$. Additionally, the term $E_i = [e_i \;\; e_{i+n}]^\top$. The matrix $P_{2,i}$ is positive definite and it is presented in the main statement of the main theorem of this article.

The variable $d_i(t)$ is obtained from the following particular application of the STA as RED:

$$\begin{aligned} \frac{d}{dt}\bar{x}_a^i(t) &= \bar{x}_b^i(t) - \lambda_{1,i} |\tilde{x}_a(t)|^{1/2} \operatorname{sign}(\tilde{x}_a(t)) \\ \frac{d}{dt}\bar{x}_b^i(t) &= -\lambda_2 \operatorname{sign}(\tilde{x}_a(t)) \\ \tilde{x}_a^i &= x_a^i - \bar{x}_a^i \end{aligned} \tag{9}$$

Considering that displacements on building-like structures are small and considering the assumption 1 and 2, it is easy to get that $|\frac{d}{dt}x_b^i(t)| \leq h^*$ where h^* is a finite positive scalar.

The following extended system describes the complete dynamics of the error signal in close-loop with an adequate implementation of (4) and the controller proposed in (6):

$$\begin{aligned} \frac{d}{dt}x_a^i(t) &= x_b^i(t) \\ \frac{d}{dt}x_b^i(t) &= f(x^i(t)) - \bar{k}_{1,i}(t)\, e_i(t) - \bar{k}_{2,i}(t)\, d_i(t) \\ &\quad + \zeta^i(x^i(t), x^{i+1}(t), x^{i-1}(t), t) \\ \frac{d}{dt}\tilde{x}_a^i(t) &= \tilde{x}_b^i(t) - \lambda_{1,i} |\tilde{x}_a(t)|^{1/2} \operatorname{sign}(\tilde{x}_a(t)) \\ \frac{d}{dt}\tilde{x}_b^i(t) &= -\lambda_2 \operatorname{sign}(\tilde{x}_a(t)) - \frac{d}{dt}x_b^i(t) \\ \frac{d}{dt}\bar{k}_{1,i}(t) &= -\pi_{1,i}^{-1} e_i(t) M_a^\top P_{2,i} E_i(t) \\ \frac{d}{dt}\bar{k}_{2,i}(t) &= -\pi_{2,i}^{-1} e_{i+n}(t) M_b^\top P_{2,i} E_i(t) \end{aligned} \tag{10}$$

The following section shows the main result of this paper. The theorem introduced in that section gives a constructive way to adjust the gains of the STA and it provides the applicability of using the adaptive gains for the PD controller.

5.4 Convergence of the adaptive PD controller

The stability of the $e =$ is justified by the result presented in the following theorem:

Theorem 1. Consider the nonlinear system given in (1), supplied with the control law (6) adjusted with the gains given in (7) and the derivative of the error signal obtained by means of equation (9), if there exist a positive scalar α_i and if the gains are selected as $\lambda_{1,i} > 0$, $\lambda_{2,i} > 0$, the next Lyapunov inequalities always have a positive definite solution $P_{1,i}$,

$$A_{1,i}^{\top} P_{1,i} + P_{1,i} A_{1,i} \leq -Q_{1,i}$$

$$A_{1,i} = \begin{bmatrix} -\lambda_{1,i} & 1 \\ -2\lambda_{2,i} & 0 \end{bmatrix}, \quad Q_{1,i} = Q_{1,i}^{\intercal} > 0, \quad Q_{1,i} \in \Re^{2\times 2} \tag{11}$$

then for every positive value of L_1 satisfying equation (3) and positive value of h^+, there exist positive gains $\bar{k}_{1,i}$, $\bar{k}_{2,i}$ such that if the Riccati equations given by

$$P_{2,i}\left(A_{2,i} + \alpha_i I\right) + \left(A_{2,i} + \alpha_i I\right)^{\intercal} P_{2,i} + P_{2,i} R_{2,i} P_{2,i} + Q_{2,i} \leq 0 \tag{12}$$

have positive definite solution $P_{2,i}$ with

$$A_{2,i} = \begin{bmatrix} 0 & 1 \\ -k_{1,i}^{*} & -k_{2,i}^{*} \end{bmatrix}, \quad R_{2,i} = \Lambda_{a,i} + \Lambda_{b,i}$$
$$Q_{2,i} = 4\lambda_{\max}\left\{\Lambda_{b,i}^{-1}\right\} I_{2\times 2} + \bar{\Lambda}_{a,i}, \quad \bar{\Lambda}_{a,i} = L_1 \Lambda_{a,i},$$
$$\Lambda_{a,i}, \Lambda_{b,i} > 0 \text{ and symmetric}, \quad \Lambda_{a,i}, \Lambda_{b,i} \in \mathbb{R}^{2\times 2} \quad \alpha_i \in \mathbb{R}_{+} \tag{13}$$

and if the adaptive gains of the PD controller are adjusted by (8), thus the trajectories of $E^{\intercal} = \left[x_1^a, ..., x_n^a, x_1^b, ..., x_n^a\right]$ are globally ultimately bounded with bound

$$\overline{\lim_{t\to\infty}} E^{\top}(t) P_2 E(t) \leq \sum_{i=1}^{n} \frac{\gamma_i}{\alpha_i} \tag{14}$$

where

$$P_2 = \begin{bmatrix} P_{2,1} & 0_{2\times 2} & \cdots & 0_{2\times 2} \\ 0_{2\times 2} & P_{2,2} & \cdots & 0_{2\times 2} \\ \vdots & \vdots & \ddots & \vdots \\ 0_{2\times 2} & 0_{2\times 2} & \cdots & P_{2,n} \end{bmatrix} \tag{15}$$

and $\gamma_i = 2\lambda_{\max}\left\{\Lambda_{b,i}^{-1}\right\}\left(h_i^{+} + 2\zeta_{+}^{*} + \eta_{0,i}\right)$

Proof. The complete proof of this theorem is skipped. However, the main tool to prove that the controller enforces the mechanical oscillations compensation is the following Lyapunov-like function.

$$V\left(\xi, E, \bar{k}_1, \bar{k}_2\right) = \sum_{i=1}^{n} V_i\left(\xi_i, E_i, \bar{k}_{1,i}, \bar{k}_{2,i}\right)$$
$$V_i\left(\xi_i, E_i, \bar{k}_{1,i}, \bar{k}_{2,i}\right) = V_{1,i}\left(\xi_i\right) + V_{2,i}\left(E_i\right) + V_{3,i}\left(\bar{k}_{1,i}, \bar{k}_{2,i}\right)$$

with $V_{1,i}(\xi_i) = \xi_i^{\top} P_{1,i} \xi_i$, $V_{2,i}(x_i) = x_i^{\top} P_{2,i} x_i$ and $V_{3,i}\left(\bar{k}_{1,i}, \bar{k}_{2,i}\right) = \pi_{1,i}\bar{k}_{1,i}^2 + \pi_{2,i}\bar{k}_{2,i}^2$.

The term labelled ξ_i is given by $\xi_i = \left[|\delta_{1,i}|^{1/2} sign\left(\delta_{1,i}\right) \quad \delta_{2,i}\right]^{\top}$. Finally, $\xi = [\xi_1, \cdots, \xi_n]^{\top}$.

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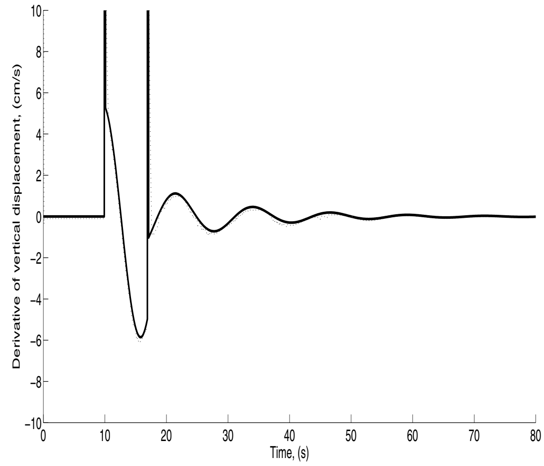

Fig. 2. Estimation of velocity of center of mass for one selected column based on the STA applied as RED. The estimated velocity is compared with the measured velocity obtained form the model exported to Matlab. A similar behaviour was obtained for the remainder columns.

6. NUMERICAL RESULTS

When the adaptive PD controller is computed for the system, the derivative obtained by the STA brings some advantages. The robustness of STA applied as differentiator forced a better performance for any controller applied on second order systems when the only available information is the output signal.

Then, the first part of the numerical simulations is devoted to evaluate the performance of the STA as RED. The derivative of building like positions is compared with the information provided by the measurements obtained directly form the simulation of the system presented in Figure 1 and the derivative of reference signal. The differentiation of the error signal is shown in Figure 2. In this figure, one can observe how the estimation process is accurate when the STA is applied to the velocity estimation of the some selected section of the building structure.

The simulation results for the stabilizing performance of x-displacement of one column of the building system are depicted in Figure 3 and 4. In this figure, all the states never leave the predefined region proposed in the theorem. This condition confirmed the performance of the controller proposed in this study. Moreover, the fast convergence obtained of the tracking error prevents important damage on the building structure.

The x-displacement of the center of mass for the same selected column returned to its equilibrium point within fifteen seconds after the simulated earthquake (Fig. 3). The same condition was obtained for the y-displacement that also converged within the firsts fifteen seconds of simulation (Fig. 4). This condition was considered acceptable of one takes into account that seismic alarms can provide information regarding the presence of seismic waves 40 second prior they could have any influence over the building.

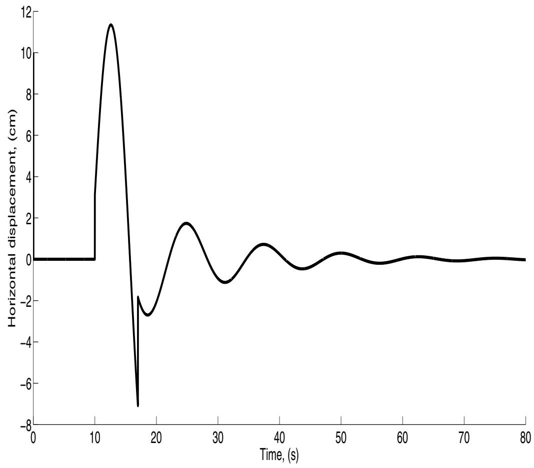

Fig. 3. Evaluation of the x displacement for the same center of mass for one selected column based on the adaptive PD controller. The controller forced the returning to the equilibrium point of the building structure

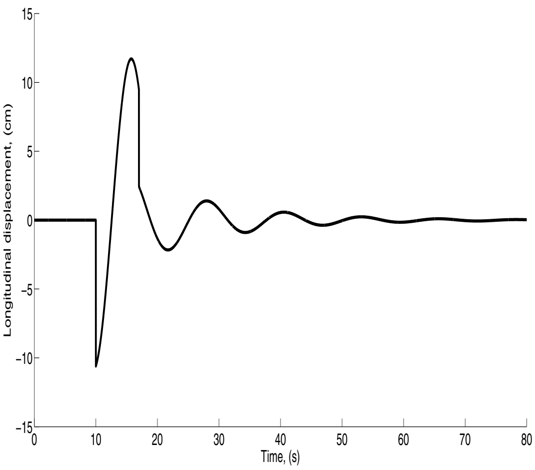

Fig. 4. Evaluation of the y displacement for the same center of mass for one selected column based on the adaptive PD controller. The controller forced the returning to the equilibrium point of the building structure

7. CONCLUSION

An adaptive output based controller based on the proportional derivative controller was implemented to force the regulation of a building structure. The controller was fed with the information of the building displacement as well as the velocity estimated by a RED based on the application of the super twisting algorithm. The closed loop controller forced the ultimate boundedness of the tracking errors to a region around the origin. A special class of Lyapunov function was the main tool for obtaining the adaptive gains of the PD controller as well as the convergence of the STA used as RED. The controller was successfully implemented to force the building to reject the effect of a simulated earthquake.

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REFERENCES

Fisco, N. and Adeli (2011a). Smart structures: part iihybrid control systems and control strategies. *Transaction A: Civil Engineering*, 18(3), 285295.

Fisco, N. and Adeli, H. (2011b). Smart structures: Part iactive and semi-active control. *Scientia Iranica*, 18(3), 275284.

Guo, Y. and Chen, W. (2007). Dynamic analysis of space structures with multiple tuned mass dampers. *Engineering Structures*, 29, 33903403.

Hanagan, L.M. and Murray, T.M. (1997). Active control approach for reducing floor vibrations. *Journal of Structural Engineering*, 123(11), 1497–1505.

Housner, G.W., Bergman, L.A., Caughey, T.K., Chassiakos, A.G., Claus, R.O., and Masri, S.F. (1997). Structural control: Past, present, and future. *ASCE Journal of Engineering Mechanics*, 123, 897–971.

Ikeda, Y., Sasaki, M., Sakamoto, M., and Kobori, T. (2001). Active mass driver system as the first application of active structural control. *Earthquake Engineering and Structural Dynamics*, 30(11), 1575–1595.

Levant, A. (1993). Sliding order and sliding accuracy in sliding mode control. *International Journal of Control*, 58(6), 1247–1263.

Levant, A. (1998). Robust exact differentiation via sliding mode tecnique. *Automatica*, 34(3), 379–384.

Lu, L.Y. Lin, G. and Lin, C. (2009). A unified analysis model for energy dissipation devices used in seismic-resistant structures. *Computer-Aided Civil and Infrastructure Engineering*, 24(1), 4161.

Nomura, Y., Furuta, H., and Hirokane, M. (2007). An integrated fuzzy control system for structural vibration. *Computer-Aided Civil and Infrastructure Engineering*, 22.(4), 306316.

Poznyak, A. (2008). *Advanced Mathematical Tools for Automatic Control Engineers: Volume 1: Deterministic Systems.* Elsevier Science.

Saleh, A. and Adeli, H. (1998). Optimal control of adaptive building structures under blast loading. *Mechatronics*, 8(8), 821–844.

Stancioiu, D. and H.Ouyang (2012). Structural modification formula and iterative design method using multiple tuned mass dampers for structures subjected to moving loads. *Mechanical Systems and Signal Processing*, 28, 542560.

Symans, M.D. and Constantinou, M.C. (1999). Semi-active control systems for seismic protection of structures: a state-of-the-art review. *Engineering Structures*, 21, 469487.