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Acceleration Feedback Control of Hysteretic Base-Isolated Structures: Application to a Benchmark Case ⋆

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Abstract: The main objective of applying robust active control to base-isolated structures is to protect them in the event of an earthquake. Taking advantage of discontinuous control theory, a static discontinuous active bang-bang type control is developed using as a feedback only the measure of the velocity at the base. Moreover, due to that in many engineering applications, accelerometers are the only devices that provide information available for feedback, our velocity feedback controller could be easily extended by using just acceleration information through a filter. The main contributions of this paper are the development and application of (a) a static velocity feedback controller design, and (b) a dynamic acceleration feedback controller design, to a benchmark problem which is recognized as a state-of-the-art model for numerical experiments of seismic control attenuation. The performance indices show that the proposed controller behaves satisfactorily and with a reasonable control effort. *Copyright© 2008 IFAC*

1. INTRODUCTION

Base isolation has been widely considered as an effective technology to protect flexible structures up to eight storeys high against earthquakes. The conceptual objective of the isolator is to produce a dynamic decoupling of the structure from its foundation so that the structure ideally behaves like a rigid body with reduced inter-story drifts, as demanded by safety, and reduced absolute accelerations as related to comfort requirements. Although the response quantities of a fixed-base building are reduced substantially through base isolation, the base displacement may be excessive, particularly during near-field ground motions (Yang and Agrawal, 2002). Applications of hybrid control systems consisting of active or semi-active systems installed in parallel to base-isolation bearings have the capability to reduce response quantities of base-isolated structures more significantly than passive dampers (Rammalo et al., 2002; Yang and Agrawal, 2002).

In this paper, two versions of a robust active bang-bang type control (Sonnetorn and Van Vleck, 1964) are developed and applied to a benchmark base-isolated building model. The first controller uses the velocity at the base of the structure as feedback information, and it is analyzed via Lyapunov stability techniques as proposed in Luo et al. (2001). Due to the fact that, in civil engineering applications, accelerometers are the most practically available sensors for feedback control, the second controller is an extension of the first one where just acceleration information is used. Performance of the proposed controllers, for seismic attenuation, are evaluated by numerical simulations using the smart base-isolated benchmark building (Narasimhan et al., 2006). Narasimhan et al. (2006) developed this benchmark problem to provide systematic and standardized means by which competing control strategies –including devices, algorithms, sensors, etc.– can be evaluated. Moreover, analytical benchmark problems are an excellent alternative to expensive experimental benchmark test structures.

This paper is structured as follows. Section 2 is dedicated to designing the robust active control and it is divided in three Subsections: Subsection 2.1 describes the problem formulation. The solution to the problem statement using just velocity measurements is described in Subsection 2.2, meanwhile the solution employing only acceleration information is presented in Subsection 2.3. The smart base-isolated structure which serves as a benchmark problem for numerical testing is presented in Section 3. Numerical simulations to analyze the performance of the proposed controllers are presented in Section 4. Final comments are given in Section 5.

2. SYSTEM DESCRIPTION AND CONTROL DESIGN

Consider a nonlinear base-isolated building structure as shown in Figure 1. For control design and because the

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mathematical model of the benchmark structure is very complicated and cannot be used directly for control purposes (Erkus and Johnson, 2006), a dynamic model composed of two coupled subsystems, namely, the main structure or superstructure (S_r) and the base isolation (S_c) (Skinner et al., 1992), is employed:

$$\begin{aligned} S_r &: \mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = -\mathbf{M}\mathbf{J}\ddot{x}_g + \bar{\mathbf{C}}\dot{\tilde{\mathbf{r}}} + \bar{\mathbf{K}}\tilde{\mathbf{r}}, \quad (1)\\ S_c &: m_0\ddot{x}_0 + c_0\dot{x}_0 + k_0 x_0 = \\ &\quad c_1\dot{r}_1 + k_1 r_1 - \Phi(x_0,t) - m_0\ddot{x}_g + u, \quad (2)\end{aligned}$$

where $\ddot{x}_g$ is the absolute ground acceleration, $\mathbf{x} = [x_1, x_2, \ldots, x_8]^{\mathrm{T}} \in \mathbb{R}^8$ represents the horizontal displacements of each floor with respect to the ground. The mass, damping and stiffness of the ith storey is denoted by m_i, c_i and k_i, respectively, $\tilde{\mathbf{r}} = [x_0, \mathbf{r}^{\mathrm{T}}]^{\mathrm{T}} \in \mathbb{R}^9$ and $\mathbf{r} = [r_1, \ldots, r_8]^{\mathrm{T}} \in \mathbb{R}^8$, represents the horizontal displacements of the i-th floor relative to the $(i-1)$-th storey. The base isolation is described as a single degree of freedom with horizontal displacement x_0. It is assumed to exhibit a linear behavior characterized by mass, damping and stiffness m_0, c_0 and k_0, respectively, plus a nonlinear behavior represented by a hysteretic restoring force $\Phi(x_0,t)$. The matrices $\mathbf{M}, \mathbf{C}, \mathbf{K}, \bar{\mathbf{C}}$ and $\bar{\mathbf{K}}$ of the structure have the following form

$$\begin{aligned} \mathbf{M} &= \mathrm{diag}(m_1, m_2, \ldots, m_8) \in \mathbb{R}^{8\times 8},\\ \mathbf{C} &= \mathrm{diag}(c_1, c_2, \ldots, c_8) \in \mathbb{R}^{8\times 8},\\ \mathbf{K} &= \mathrm{diag}(k_1, k_2, \ldots, k_8) \in \mathbb{R}^{8\times 8},\\ \mathbf{J} &= [1, \ldots, 1]^{\mathrm{T}} \in \mathbb{R}^8,\end{aligned}$$

$$\bar{\mathbf{C}} = (\bar{c}_{ij}) \in \mathbb{R}^{8\times 9},\ \bar{c}_{ij} = \begin{cases} c_i, & i \le j \\ c_{i+1}, & j - i = 2 \\ 0, & \text{otherwise} \end{cases},$$

$$\bar{\mathbf{K}} = (\bar{k}_{ij}) \in \mathbb{R}^{8\times 9},\ \bar{k}_{ij} = \begin{cases} k_i, & i \le j \\ k_{i+1}, & j - i = 2 \\ 0, & \text{otherwise} \end{cases}.$$

The restoring force Φ can be represented by the Bouc-Wen model (Ikhouane et al., 2005; Ikhouane and Rodellar, 2007) in the following form:

$$\Phi(x_0,t) = \alpha K x_0(t) + (1-\alpha) D K z(t) \quad (3)$$

$$\dot{z} = D^{-1}\left(A\dot{x}_0 - \beta|\dot{x}_0||\dot{z}|^{n-1}z - \lambda\dot{x}_0|z|^n\right) \quad (4)$$

where $\Phi(x_0,t)$ can be considered as the superposition of an elastic component $\alpha K x_0$ and a hysteretic component $(1-\alpha) DKz(t)$, in which the yield constant displacement is $D > 0$ and $\alpha \in [0,1]$ is the post- to pre-yielding stiffness ratio. $n \ge 1$ is a scalar that governs the smoothness of the transition from elastic to plastic response and $K > 0$.

Finally, u is the control force supplied by an appropriate actuator.

The model in (1)-(2) is used to design an appropriate control law. The applicability and efficiency of the proposed controller will be then shown using a more realistic and complex model through the benchmark presented in Section 3.

It is well accepted that the movement of the superstructure S_r is very close to the one of a rigid body due to the base isolation (Skinner et al., 1992). Then it is reasonable to assume that the interstory motion of the building will be much smaller than the relative motion of the base (Luo et al., 2001; Pozo et al., 2008). Consequently, the following simplified equation of motion of the base can be used in the subsequent controller design:

$$\tilde{S}_c\ : m_0\ddot{x}_0 + c_0\dot{x}_0 + k_0x_0 = -\Phi(x_0,t) - m_0\ddot{x}_g + u. \quad (5)$$

The feasibility of this simplification is justified in a more detailed way in Pozo et al. (2008).

2.1 Controller design

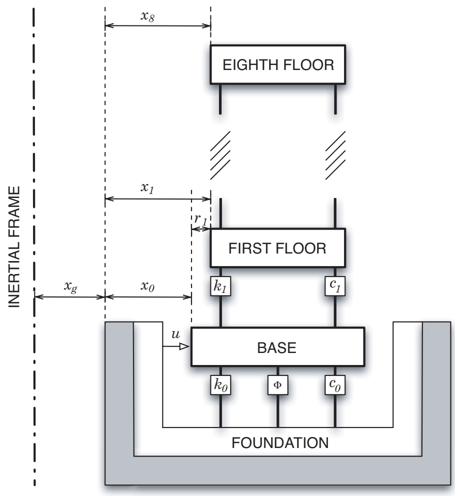

Fig. 1. Base-isolated structure with active control.

The following assumption is stated for system (3)-(5):

Assumption 1. The acceleration disturbance

$$f(t) = -m_0\ddot{x}_g$$

is unknown but bounded; *i.e.*, there exists a known constant F such that $|f(t)| \le F, \quad \forall t \ge 0$.

Assumption 1 is standard in control of hysteretic systems or base-isolated structures Ikhouane et al. (2005). Moreover, Theorem 1 in Ikhouane et al. (2005) guarantees the existence of a computable upper bound $\bar{\rho}_z$ on the internal dynamic variable $z(t)$, i.e., $|z(t)| \le \bar{\rho}_z,\ \forall t \ge 0$, *independently* on the boundedness of $x_0(t)$.

Control objective: Our objective is to design a robust controller for system (5) such that, under earthquake attack, the trajectories of the closed-loop remain bounded.

To this end, the theorems in the following sections satisfy this control objective.

2.2 Seismic attenuation using only velocity feedback

Theorem 1. Consider the nonlinear system (3)-(5) subject to Assumption 1. Then, the following control law

$$u = -\rho\,\mathrm{sgn}(\dot{x}_0) \quad (6)$$

solves the control objective if

$$\rho \ge (1-\alpha)DK\bar{\rho}_z + F. \quad (7)$$

Proof. See Pozo et al. (2008).

Remark 1. The signum function in the control law in Theorem 1 –common in sliding mode control theory– produces chattering (Utkin, 1982; Edwards and Spurgeon, 1998). One way to avoid chattering is to replace the signum function by a smooth sigmoid-like function such as

$$\nu_\delta(s) = \frac{s}{|s| + \delta},$$

where δ is a sufficiently small positive scalar (Edwards and Spurgeon, 1998).

Consequently, the following Corollary is stated:

Corollary 2. Consider the nonlinear system (3)-(5) subject to Assumption 1. Then, the following control law

$$u = -\rho \frac{\dot{x}_0}{|\dot{x}_0| + \delta} \tag{8}$$

solves the control objective if

$$\rho \geq (1 - \alpha) D K \bar{\rho}_z + F$$

and δ is a sufficiently small positive scalar.

2.3 Seismic attenuation using only acceleration feedback

Motivated by the fact that in many civil engineering applications accelerometers are the only devices that provide information available for feedback, Theorem 3 (below) presents a control law based on equation (6) where only acceleration information is required.

Theorem 3. Consider the nonlinear system (3)-(5) subject to Assumption 1. Then, the following control law

$$u = -\rho \operatorname{sgn}(\upsilon) \tag{9}$$

$$\dot{\upsilon} = \ddot{x}_0 \tag{10}$$

solves the control objective if

$$\rho \geq (1 - \alpha) D K \bar{\rho}_z + F.$$

Proof. This proof is straightforward by considering direct integration of equation (10). ∎

Remark 2. In the practical implementation of this control law, ν may drift due to unmodeled dynamics, measure errors and disturbance. To avoid this, the following σ-modification (Ioannou and Kokotović, 1983; Koo and Kim, 1994) can be used,

$$u = -\rho \operatorname{sgn}(\upsilon), \tag{11}$$

$$\dot{\upsilon} = -\sigma \nu + \ddot{x}_0, \tag{12}$$

where σ is a positive constant.

As in the previous Section, a smooth version of the control law in equations (11)-(12) is considered in the following Corollary.

Corollary 4. Consider the nonlinear system (3)-(5) subject to Assumption 1. Then, the following control law

$$u = -\rho \frac{\upsilon}{|\upsilon| + \delta} \tag{13}$$

$$\dot{\upsilon} = -\sigma \upsilon + \ddot{x}_0 \tag{14}$$

solves the control objective if

$$\rho \geq (1 - \alpha) D K \bar{\rho}_z + F,$$

where $\sigma > 0$ and δ are sufficiently small positive scalar.

3. SMART BASE-ISOLATED BENCHMARK BUILDING

The smart base-isolated benchmark building (Narasimhan et al., 2006) is employed as an interesting and more realistic example to further investigate the effectiveness of the proposed design approach. This benchmark problem is recognized by the American Society of Civil Engineers (ASCE) Structural Control Committee as a state-of-the-art model developed to provide a computational platform for numerical experiments of seismic control attenuation (Ohtori et al., 2004; Spencer and Nagarajaiah, 2003).

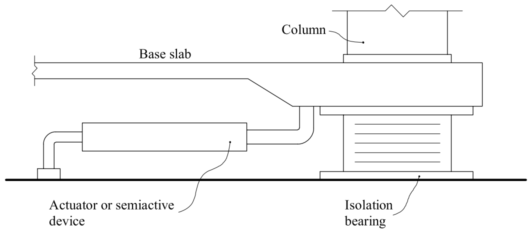

Fig. 2. Elevation view with devices.

The benchmark structure is an eight-storey frame building with steel-braces, 82.4 m long and 54.3 m wide, similar to existing buildings in Los Angeles, California. Stories one to six have an L-shaped plan while the higher floors have a rectangular plan. The superstructure rests on a rigid concrete base, which is isolated from the ground by an isolator layer, and consists of linear beam, column and bracing elements and rigid slabs. Below the base, the isolation layer consists of a variety of 92 isolation bearings. The isolators are connected between the drop panels and the footings below, as shown in Figure 2. See Figure 3 for a representative figure of the benchmark structure.

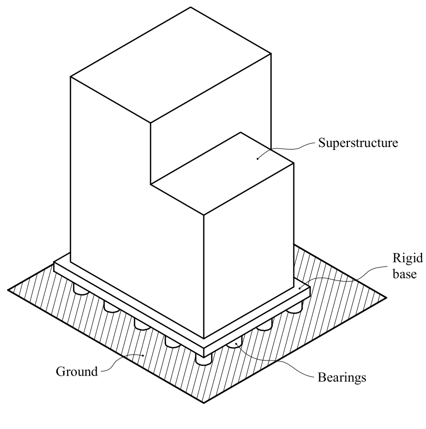

Fig. 3. A representative figure of the benchmark structure.

4. NUMERICAL RESULTS

The results of the robust active control in equations (13)-(14) of the benchmark problem are summarized in Tables 1 and 2, for the fault normal (FN) component and the fault parallel (FP) components acting in two perpendicular directions. The results are also compared with the performance indices in Erkus and Johnson (2006). The evaluation is reported in terms of the performance indices described in the Appendix. The controlled benchmark structure is simulated for seven earthquake ground accelerations defined in the benchmark problem (Newhall, Sylmar, El Centro, Rinaldi, Kobe, Ji-Ji and Erzinkan). All the excitations are used at the full intensity for the evaluation of the performance indices. The performance indices larger than 1 indicate that the response of the controlled structure is bigger than that of the uncontrolled structure. These quantities are highlighted in bold.

In this paper, the controllers are assumed to be fully active. They are placed in eight specific locations, including the corners and center of mass of the base. At each location, there are two controllers –one in the x- and the other in the y-direction. These actuators are used to apply the active control forces to the base of the structure. In this control strategy most of the response quantities are reduced substantially from the uncontrolled cases.

The base and structural shears are reduced between 22 and 55% in a majority of earthquakes (except El Centro and Ji-ji). The reduction in base displacement is between 11 and 60% in all cases except Ji-ji. Reductions in the inter-storey drifts between 12 and 49% are achieved in a majority of earthquakes (except Ji-ji and El Centro-FN) when compared to the uncontrolled case. The floor accelerations are also reduced by 8-32% in a majority of earthquakes (except Rinaldi and Ji-ji).

The benefit of the active control strategy is the reduction of base displacements (J_3) and shears (J_1, J_2) of up to 50% without increase in drift (J_4) or accelerations (J_5). The reduction of the peak base displacement J_3 of the base-isolated building is one of the most important criteria during strong earthquakes. Moreover, the index J_6 in the proposed scheme reach to small values, which means that the force generated by all control devices with respect to the base shear of the structure is acceptable.

For the base-isolated buildings, superstructure drifts are reduced significantly compared to the corresponding fixed-buildings because of the isolation from the ground motion. Hence, a controller that reduces or does not increase the peak superstructure drift (J_4), while reducing the base displacement significantly (J_3), is desirable for practical applications (Xu et al., 2006). In this respect, the proposed robust active controller performs well.

4.1 Time-history plots

Figures 5-7 show the time-history plots of various response quantities for the uncontrolled building, and the building with robust active controllers using the Erzinkan FP-x, FN-y earthquake. Figure 4 shows the ground acceleration for this earthquake. More precisely, Figure 5 presents the plots for the displacement of the center of the mass of the base in both the x and y direction. The plotted quantities in Figure 6 are the eighth floor absolute acceleration in the x direction and in the y direction, for both the uncontrolled and the controlled situations. Finally, the interstory drift between the eighth and the seventh floor in the x direction is depicted in Figure 7. It is observed from these Figures that the controlled response quantities can be effectively reduced compared with the uncontrolled case.

4.2 Comparison

For comparison, the results of a linear quadratic Gaussian (LQG) controller for the same base-isolated benchmark structure in Erkus and Johnson (2006) are also presented in Tables 1 and 2. This LQG controller, which is applied in each active controller, is an eighth order dynamic system requiring position measurements for its implementation. Moreover, this LQR design is based on an iterative method employing an equivalent lineal model (ELM) structure of the benchmark scheme along with an augmented representation of the model which is also modified using a Kanai-Takimi filter to shape the excitation. This procedure is strongly dependent on the linear model and therefore, in order to acquire a good performance, an iterative procedure is asked. So, the iterative-LQR technique presented in Erkus and Johnson (2006) is extremely complex (in architecture and computation) with respect to our controller, which is based on just one feedback measurement (velocity or acceleration) and it is static for the velocity feedback case, and of one order for the acceleration feedback event. Moreover, from Tables 1 and 2, it can be seen that the performance indices in the proposed robust active control case are better than in the LQG controller in almost all earthquakes of the benchmark. The robust controller with acceleration information feedback deserves a special attention because most of the sensors installed in structures are accelerometers. As a summary, our robust controller that employs only acceleration information is viewed as an important contribution.

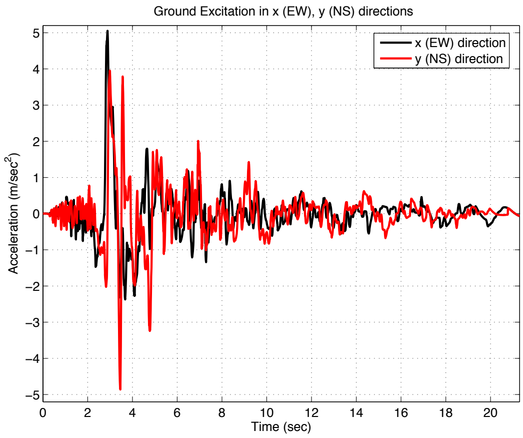

Fig. 4. 1992 Erzinkan earthquake, ground acceleration: EW and NS component excitations in the x-axis and y-axis direction, respectively.

5. CONCLUDING REMARKS

In this paper, two versions of a robust active bang-bang type control have been developed and applied to a benchmark base-isolated building model. The first controller uses the velocity at the base of the structure as feedback information, and it has been analyzed via Lyapunov stability techniques. The second controller is an extension of the first one where just acceleration information is used. The simulation results illustrate that the base and structural shears, the base displacement, the inter-story displacements and the floor accelerations have been significantly reduced by using the proposed robust active controllers as compared with the purely passive isolation scheme. One of the key points of the proposed control scheme is the simplicity of the control law. Moreover, the second version of this robust active control is specially interesting for practical implementations because it is based on acceleration feedback.

Table 1. Numerical results for the proposed robust active controller (RAC) (FP-x and FN-y) and the LQG regulator of Erkus and Johnson (2006)

Earthquake	Case	J_1	J_2	J_3	J_4	J_5	J_6	J_7	J_8	J_9
Newhall	Erkus *et al.*	0.902	1.070	0.949	0.869	0.734	0.341	0.926	0.818	0.190
	RAC	0.644	0.687	0.696	0.674	0.734	0.473	0.755	0.727	0.052
Sylmar	Erkus *et al.*	0.766	0.792	0.778	0.910	1.006	0.356	0.678	0.750	0.230
	RAC	0.645	0.589	0.655	0.622	0.821	0.387	0.476	0.696	0.018
El Centro	Erkus *et al.*	0.960	1.029	0.941	0.944	0.830	0.385	0.882	0.919	0.168
	RAC	0.949	**1.073**	0.602	0.737	0.766	0.321	0.983	0.700	0.208
Rinaldi	Erkus *et al.*	0.857	0.841	1.010	0.949	0.848	0.298	0.909	0.849	0.234
	RAC	0.687	0.668	0.895	0.840	0.978	0.323	**1.030**	0.827	0.125
Kobe	Erkus *et al.*	0.846	0.869	0.812	0.899	0.939	0.327	0.918	0.864	0.129
	RAC	0.729	0.780	0.638	0.884	0.924	0.225	0.767	0.794	0.148
Ji-ji	Erkus *et al.*	0.741	0.736	0.989	0.907	0.826	0.329	1.025	0.740	0.277
	RAC	**1.017**	**1.020**	0.941	**1.005**	0.996	0.086	0.948	0.893	0.239
Erzinkan	Erkus *et al.*	0.821	0.804	0.797	0.906	0.768	0.290	0.711	0.728	0.247
	RAC	0.443	0.493	0.424	0.613	0.818	0.668	0.437	0.817	0.232

Table 2. Numerical results for the proposed robust active controller (RAC) (FP-y and FN-x) and the LQG regulator of Erkus and Johnson (2006)

Earthquake	Case	J_1	J_2	J_3	J_4	J_5	J_6	J_7	J_8	J_9
Newhall	Erkus *et al.*	0.902	1.070	0.949	0.869	0.734	0.341	0.926	0.818	0.190
	RAC	0.584	0.630	0.771	0.615	0.691	0.508	0.870	0.659	0.053
Sylmar	Erkus *et al.*	0.766	0.792	0.778	0.910	1.006	0.356	0.678	0.750	0.230
	RAC	0.651	0.576	0.619	0.698	0.847	0.376	0.437	0.693	0.009
El Centro	Erkus *et al.*	0.960	1.029	0.941	0.944	0.830	0.385	0.882	0.919	0.168
	RAC	0.825	1.000	0.704	0.949	0.807	0.342	**1.065**	0.703	0.202
Rinaldi	Erkus *et al.*	0.857	0.841	1.010	0.949	0.848	0.298	0.909	0.849	0.234
	RAC	0.693	0.643	0.858	0.740	0.985	0.317	0.962	0.791	0.110
Kobe	Erkus *et al.*	0.846	0.869	0.812	0.899	0.939	0.327	0.918	0.864	0.129
	RAC	0.759	0.721	0.602	0.812	0.767	0.216	0.741	0.826	0.116
Ji-ji	Erkus *et al.*	0.741	0.736	0.989	0.907	0.826	0.329	1.025	0.740	0.277
	RAC	**1.036**	**1.035**	0.943	**1.018**	**1.010**	0.083	0.959	0.876	0.235
Erzinkan	Erkus *et al.*	0.821	0.804	0.797	0.906	0.768	0.290	0.711	0.728	0.247
	RAC	0.506	0.456	0.398	0.510	0.635	0.574	0.360	0.644	0.257

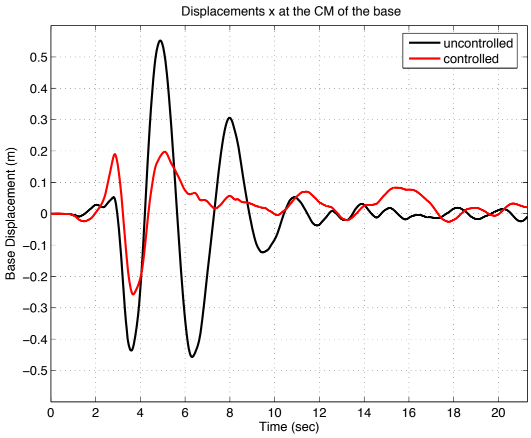

Fig. 5. Time-history of response of the isolated building under Erzinkan excitation. Displacement of the center of the mass (CM) of the base in the x direction, for both the uncontrolled (black) and the controlled (red) situations.

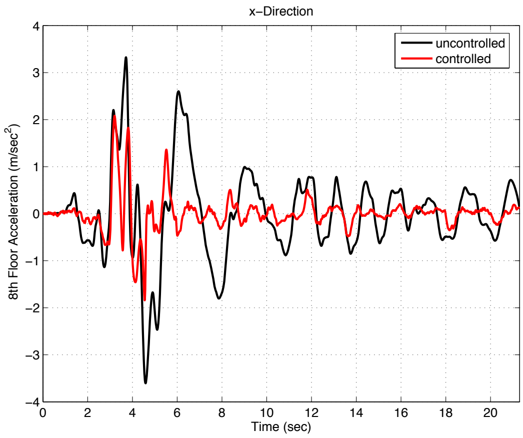

Fig. 6. Time-history of response of the isolated building under Erzinkan excitation. Absolute acceleration of the eighth floor in the x direction, for both the uncontrolled (black) and the controlled (red) situations.

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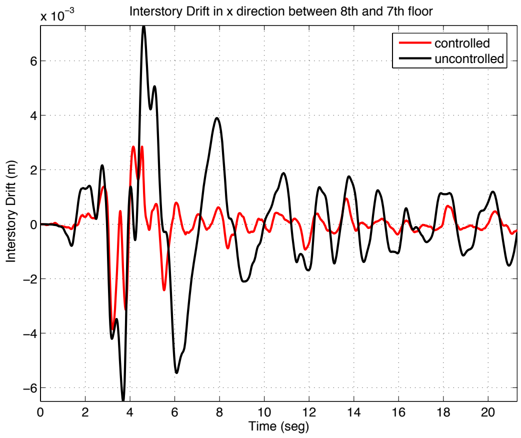

Fig. 7. Time-history of the isolated building under Erzinkan excitation. Interstory drift between eighth and seventh floor in the x direction, for both the uncontrolled (black) and the controlled (red) situations.

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