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EFFECTS OF SEMIACTIVE DAMPING ON THE RESPONSE OF BASE-ISOLATED BUILDINGS

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Abstract

Passive base isolation systems are one of the most successful and widely implemented technologies for seismic hazard mitigation. However, recent changes to the building codes have made the design requirements such that some of the potential gains of such systems may not be realized. This paper investigates the effects of using controllable semiactive dampers, such as magnetorheological fluid dampers, in a base isolation system. A two degree-of-freedom model of a base isolated building is used, with linear viscous, active, and semiactive supplemental damping devices in the isolation layer. Using an H_2/LQG design, semiactive and active devices are able to achieve a notable decrease in base drifts, compared to the optimal linear passive designs, with no accompanying increase in accelerations imparted into the superstructure.

Introduction

Recent years have seen a number of occurrences of catastrophic structural failures due to severe, impulsive, seismic events. One of the most widely implemented and accepted seismic protection systems is base isolation. The fundamental concept is to isolate a structure from ground motion, especially in the frequency range where the building is most affected. The goal is to reduce interstory drifts and floor accelerations to limit damage to the structure and its contents in a cost-effective manner.

Despite the direct benefits of seismic isolation technology, some researchers (*e.g.*, Hall *et al.*, 1995) have raised concerns as to its efficacy. These results, based on observations from the 1994 Northridge earthquake, suggest that base-isolated buildings are vulnerable to strong impulsive ground motions generated at near-fault locations. Additionally, the most recent revisions to the Uniform Building Code (ICBO, 1997) have made the requirements for base-isolation systems more stringent, rendering the additional complexity and cost of such structures less economically justified (Kelly, 1999). The code-mandated accommodation of larger base displacements and larger Maximum Capable Earthquakes (MCE) has suggested the need for supplemental damping devices (*e.g.*, Asher *et al.*, 1996). However, additional damping may also increase the internal motion of the superstructure as well as increase accelerations, thus defeating many gains for which base isolation is intended.

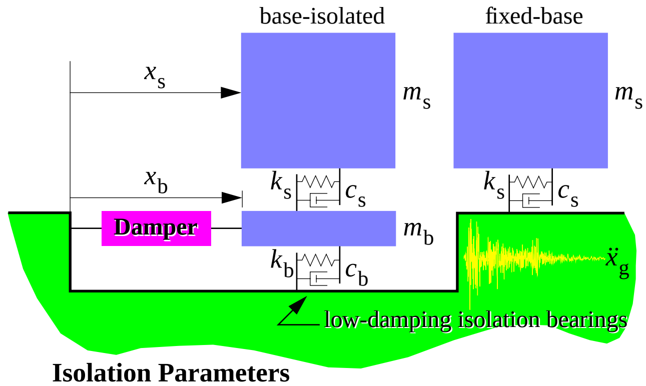
Several active base control systems have been proposed and studied (*e.g.*, Reinhorn *et al.*, 1987; Kelly *et al.*, 1987; Yoshida *et al.*, 1994; Yang *et al.*, 1996), with the goal of supplementing passive base-isolation with active control devices to limit base drift. Reinhorn and Riley (1994) performed several small-scale experiments to verify the effectiveness found in the simulation studies. Active control devices, however, have yet to be fully embraced by engineers, in large part due to the challenges of large power supplies (that will not be interrupted during an earthquake), concerns about stability and robustness, and so forth.

This paper investigates the improvements that may be achieved by replacing supplemental linear viscous damping devices in base isolation with semiactive dampers (*e.g.*, magnetorheological dampers). A study of a family of controllers for a semiactive damper is used to find an optimal isolation system for several design earthquakes (El Centro, Kobe, Northridge, and Hachinohe) that further decrease the base drift compared to the optimal linear viscous damper but without increasing the accelerations imparted into the superstructure. A linear, two degree-of-freedom (2DOF), lumped mass model of a base-isolated building is used as the testbed for this study. The isolation layer parameters were fixed such that the fundamental mode has a period of 2.5 seconds and 1% of critical damping. It is demonstrated that linear viscous dampers have an optimal damping level, over the suite of ground motions considered, for minimum peak accelerations (though the level is dependent on characteristics of the seismic excitation such as magnitude and frequency spectrum). It may be concluded that a "smart" damper would be a most effective alternative for a broad class of earthquakes including near-field events.

Problem Formulation

System Model

The structure model used in this study is a single degree-of-freedom model that has mass and fundamental modal frequency and damping ratio equal to that of the five-story building model given in Kelly *et al.* (1987). With the addition of an isolation layer, the model has two degrees of freedom. The fixed-base and isolated structure models are shown in Fig. 1 with the structural parameters. The isolation layer gives a fundamental mode with period 2.5 seconds and 1% of critical damping. This low-damping, long period, isolation system fits into the "*Class (ii): lightly damped, linear isolation system*" category of Skinner *et al.* (1993). Letting $\mathbf{x} = [x_b \;\; x_s]^T$ denote the displacements relative to the ground, and assuming the structural motion is sufficiently moderate that nonlinear effects may be neglected, the equation of motion of the base-isolated system may be written as



Isolation Parameters
$m_b = 6800$ kg
isolation period 2.5 secs $\Rightarrow k_b = 232$ kN/m
isolation damping ratio 1% $\Rightarrow c_b = 1.87$ kN·s/m

Structure Parameters
$m_s = 29485$ kg
structure period 0.3 secs $\Rightarrow k_s = 11912$ kN/m
structure damping ratio 2% $\Rightarrow c_s = 23.71$ kN·s/m

Figure 1: Two degree-of-freedom (2DOF) model.

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{\Lambda} f - \mathbf{M}\mathbf{1}\ddot{x}_g \tag{1}$$

where $\mathbf{\Lambda} = [1 \;\; 0]^T$ gives the position of the supplemental damper, f is the force exerted by the damper, and $\mathbf{1}$ is a vector whose elements are all unity. Rewriting in state-space form, with states $\mathbf{q} = [\mathbf{x}^T \;\; \dot{\mathbf{x}}^T]^T$, outputs to be regulated $\mathbf{z} = [x_b \;\; x_b - x_s \;\; \ddot{x}_b^a \;\; \ddot{x}_s^a]^T$ including interstory drifts and floor accelerations, and sensors $\mathbf{y} = [x_b \;\; \ddot{x}_b^a \;\; \ddot{x}_s^a]^T + \mathbf{v}$ measuring base drift and absolute floor accelerations ($\mathbf{v}$ are independent, Gaussian white sensor noises), gives

$$\begin{aligned} \dot{\mathbf{q}} &= \mathbf{A}\,\mathbf{q} + \mathbf{B}\,f + \mathbf{E}\ddot{x}_g \\ \mathbf{z} &= \mathbf{C_z}\mathbf{q} + \mathbf{D_z} f \\ \mathbf{y} &= \mathbf{C_y}\mathbf{q} + \mathbf{D_y} f + \mathbf{v} \end{aligned} \qquad \mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{\Lambda} \end{bmatrix} \quad \mathbf{E} = \begin{bmatrix} \mathbf{0} \\ -\mathbf{1} \end{bmatrix}$$
$$\mathbf{C_z} = \begin{bmatrix} \mathbf{\Delta} & \mathbf{0} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix} \quad \mathbf{D_z} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{\Lambda} \end{bmatrix} \tag{2}$$
$$\mathbf{C_y} = \begin{bmatrix} 1 \;\; 0 & 0 \;\; 0 \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix} \quad \mathbf{D_y} = \begin{bmatrix} 0 \\ \mathbf{M}^{-1}\mathbf{\Lambda} \end{bmatrix} \quad \mathbf{\Delta} = \begin{bmatrix} 1 & 0 \\ -1 & 1 \end{bmatrix}$$

Damper Models Considered

In this study, three types of supplemental damping devices are considered, which can be classified as

- *Passive linear viscous damper*: the force generated by the damper is proportional to the velocity across the damper, *i.e.*, $f_L = -c_L \dot{x}_b$;
- *Active damper*: a fully active controllable device capable of exerting any force f_A required by a particular control algorithm;
- *Semiactive damper*: a controllable damper (*e.g.*, variable orifice dampers, controllable fluid dampers, etc.) that may exert only dissipative forces, *i.e.*, $f_{SA}\dot{x}_b \le 0$ where f_{SA} is the force and $\dot{x}_b$ is the velocity across the damper.

Control Strategies

Active Control

Several studies have focused on the use of active control devices in parallel with a base-isolation system (Spencer and Sain, 1997). Herein, an H_2/LQG control design methodology (Spencer *et al.*, 1998) is adopted. A shaping filter is incorporated into the model of the structure so as to better inform the controller of the spectral content of the excitation. The Kanai-Tajimi filter (Soong and Grigoriu, 1993) used herein is shown in Fig. 2 along with the spectra of four adopted design earthquakes.

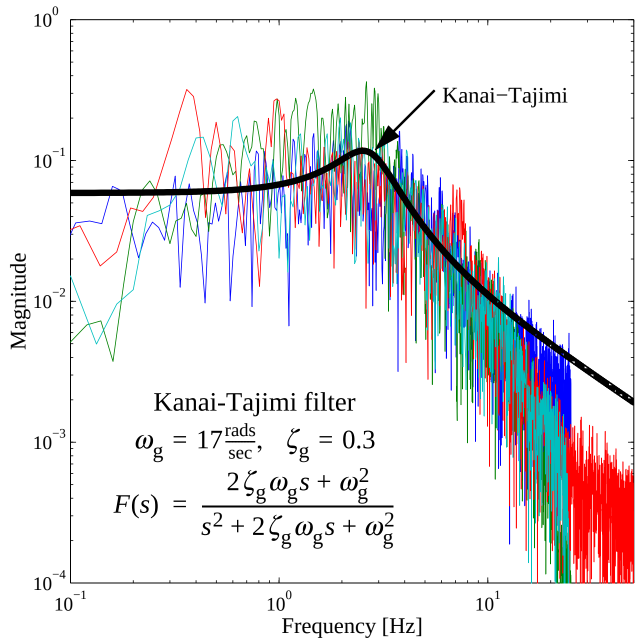


Figure 2: Frequency content of design earthquakes and adopted Kanai-Tajimi shaping filter.

The ground excitation and measurement noises are assumed to be independent. The system outputs, absolute accelerations and interstory drifts, are weighted so as to minimize interstory drifts and floor accelerations using the cost function

$$J = \lim_{\tau \to \infty} \frac{1}{\tau} E\left[\int_0^{\tau} (\mathbf{z}^{\mathrm{T}}\mathbf{Q}\mathbf{z} + f^2)\,dt\right] \qquad \mathbf{Q} = \begin{bmatrix} q_{\text{drifts}}\mathbf{I} & \mathbf{0} \\ \mathbf{0} & q_{\text{accels}}\mathbf{I} \end{bmatrix} \tag{3}$$

An H_2/LQG control may then be designed using one of several convenient tools (*e.g.*, the Control Toolbox in MATLAB®) to solve two Riccati equations. The resulting optimal compensator $\mathbf{K}(s)$ is dynamic and of order equal to the sum of the orders of the structure and the shaping filter.

Semiactive Device

In previous studies of semiactive dampers, including generalized semiactive as well as magnetorheological fluid dampers, in seismic protection systems (*e.g.*, Dyke *et al.*, 1996a,b; Johnson *et al.*, 1999), one control strategy that performed well, a *clipped-optimal control*, was to assume an "ideal" active control device, use H_2/LQG control theory to design an appropriate controller for this active device, and then, using a secondary bang-bang-type controller, make the semiactive damper replicate the same forces the active device would have exerted on the structure. Since the force generated by a semiactive damper is dependent on the structure and its motion, it is not always possible to produce the "desired" force. For the general semiactive device herein, the secondary control strategy is given by

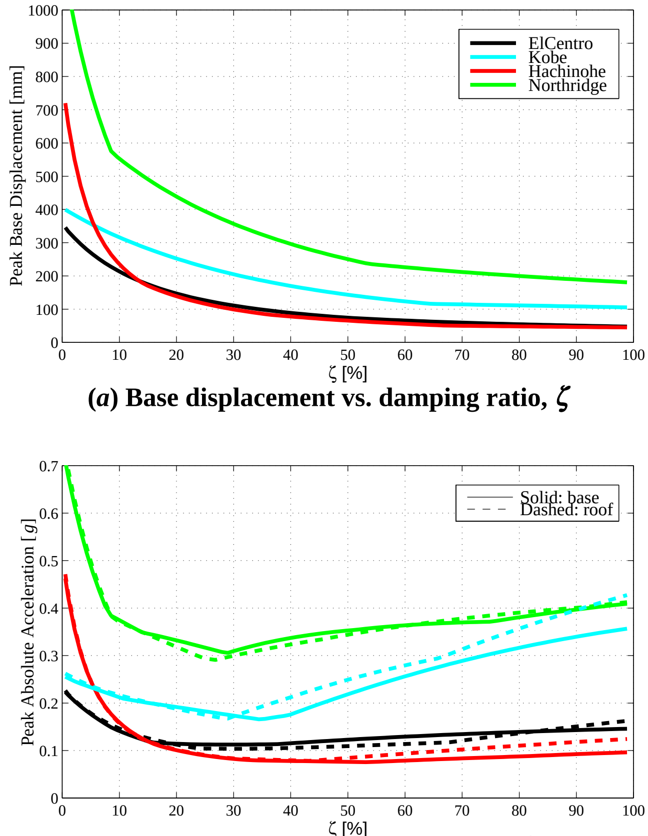
$$f_{SA} = \begin{cases} f_A, & f_A \dot{x}_b < 0 \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

where $\dot{x}_b$ is the velocity across the damper (in this case it is the base velocity). Since the semiactive damper is an *energy dissipation* device and cannot add mechanical energy to the structural system, care must be taken in the design of the primary controller (here, the H_2/LQG design) so that the "desired" force f_A is dissipative the majority of the time history of a seismic event.

Numerical results

Passive Linear Viscous Damper

For a fair comparison of semiactive dampers with the passive linear viscous variety, one should compare with a passive damper that is “optimal” in some sense. To choose the “optimal” damper to be used herein, the damper coefficient c_L is varied such that the damping in the isolation mode spans the range from 1% to 99% of critical damping. The natural period and inherent viscous damping of the isolation layer are kept fixed at 2.5 seconds and 1%, respectively. With this range of linear dampers, the system was simulated using 4 different earthquakes: 1940 El Centro, 1995 Kobe, 1994 Northridge, and 1968 Hachinohe. This set of ground motions was selected to encompass a broad array of plausible seismic characteristics, some of which are quite rare events. The peak base drift and peak absolute accelerations are depicted in Fig. 3. Although base drift is substantially decreased up to about 50-60% damping, the levels of acceleration have their minimum values around 25% to 35% of critical damping, depending on the particular earthquake. In the current study, the optimal damping ratio of 27% is chosen from Fig. 3. The performance of active and semiactive damping strategies will be compared to the performance of this optimal passive linear viscous damping system with 27% of critical damping.



(*a*) Base displacement vs. damping ratio, ζ

(*b*) Acceleration vs. damping ratio, ζ

Figure 3: Response of base-isolated building with supplemental linear viscous damper (T_1 = 2.5 sec, ζ_1 = 1%).

Active and Semiactive Devices in Isolation Layer

In order to determine appropriate H_2/LQG weighting matrices, an in-depth parameter study was performed. A family of controllers were obtained that decreases base drift and absolute accelerations (compared to the optimal passive system) for both active and semiactive dampers. Preliminary parameter studies showed that the output weight ranges

$$q_{\text{drift}} \in [10^9, 10^{10.5}] \qquad (5)$$
$$q_{\text{accels}} \in [10^8, 10^9]$$

made improvements in both base drift and accelerations. Fig. 4 shows the region, using a semiactive damper, where the peak accelerations are not

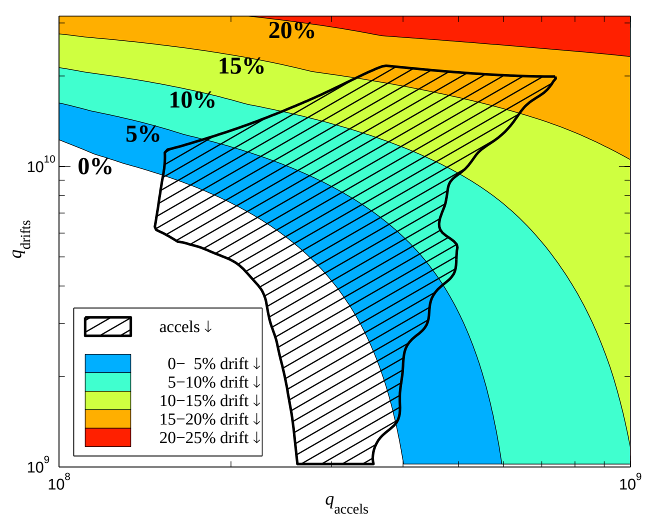


Figure 4: Regions of semiactive damper improvements.

increased for any of the four earthquakes (the hatched area) along with contour lines of improvements (*i.e.*, reductions) in base drift.

One particular point was chosen to demonstrate the gains that may be achieved with active and semiactive damping: $q_{\text{drifts}} = 2.07\times10^{10}$ and $q_{\text{accels}} = 5.31\times10^{9}$. Using these control weights, the peak drifts, accelerations, and damper forces due to the four earthquake excitations are shown in Table 1.

Table 1: Maximum drifts, accelerations, and damper forces.

Damper	El Centro	Hachinohe	Kobe	Northridge
	Peak Base Drift [mm]			
None	335.0	664.6	394.9	1060.4
Optimal Passive	122.0	111.1	220.4	383.5
Active	88.1	79.6	179.2	306.6
Semiactive	88.5	80.5	180.0	306.5
	Peak Base (Absolute) Acceleration [g]			
None	0.2173	0.4275	0.2525	0.6798
Optimal Passive	0.1128	0.0875	0.1803	0.3130
Active	0.0978	0.0749	0.1545	0.2708
Semiactive	0.1025	0.0754	0.1569	0.2767
	Peak Structural Drift [mm]			
(Fixed base)	25.3	20.4	57.8	77.5
None	5.3	10.6	6.3	16.9
Optimal Passive	2.5	2.2	4.2	7.1
Active	2.2	1.8	4.2	7.0
Semiactive	2.2	1.8	4.2	7.0
	Peak Structural (Absolute) Acceleration [g]			
Fixed base	1.0393	0.8438	2.3891	3.1791
None	0.2189	0.4349	0.2591	0.6942
Optimal Passive	0.1043	0.0886	0.1721	0.2920
Active	0.0906	0.0736	0.1720	0.2881
Semiactive	0.0907	0.0739	0.1718	0.2876
	Peak Applied Force [kN]			
Optimal Passive	18.96	17.84	47.98	66.19
Active	22.58	21.36	52.87	75.43
Semiactive	22.67	21.25	55.32	75.47

Table 2 shows the percent improvement for the active and semiactive systems compared to the optimal passive linear viscous system. Two primary observations may be made. First, the semiactive system is able to achieve nearly the same improvements as the fully active system. Second, the semiactive damper is able to decrease peak base drifts by 18 to 28% with simultaneous reductions in peak accelerations by 5–15%, all compared to the optimal passive system. The forces required by the semiactive damper are slightly larger than the optimal passive linear system, but still quite modest. (For example, a prototype 200kN semiactive magnetorheological fluid damper is being tested at the University of Notre Dame (Spencer and Sain, 1997).)

Some sample time histories for two earthquakes are shown in Fig. 5, for the optimal passive system (27%) and the semiactive damper with the control weights given above. The primary location where the semiactive damper performs better than the optimal passive is in the first couple of response peaks that are due to the initial seismic pulse. As the initial pulse response is typically the most difficult to control, it can be concluded that the semiactive damper is able to make real improvements in base isolation systems.

Conclusions

Table 2: Percent reduction using active/semiactive dampers.

	Peak Base Drift		Peak Absolute Accels.	
Earthquake	Active	Semiactive	Active	Semiactive
El Centro	27.8%	27.5%	13.3%	9.1%
Hachinohe	28.4%	27.5%	15.5%	14.9%
Kobe	18.7%	18.3%	4.6%	4.7%
Northridge	20.1%	20.1%	8.0%	8.1%
Worst-case	18.7%	18.3%	4.6%	4.7%

A comparison study of two “intelligent” base isolation systems, fully active and semiactive dampers, was performed. The response to several earthquake excitations were computed. The semiactive damper was able to accomplish nearly as much as the fully active damper. With the semiactive damper, the peak base drifts were decreased by at least 18.3% compared to the optimal passive linear damper with simultaneously reduction in the peak accelerations by at least 4.7%. The least improvement was seen for the Kobe earthquake, and the best for Hachinohe. This study suggests that semiactive dampers, such as magnetorheological fluid dampers, show significant promise for use in base isolation applications with greatly reduced power requirements as compared to the active systems.

Acknowledgments

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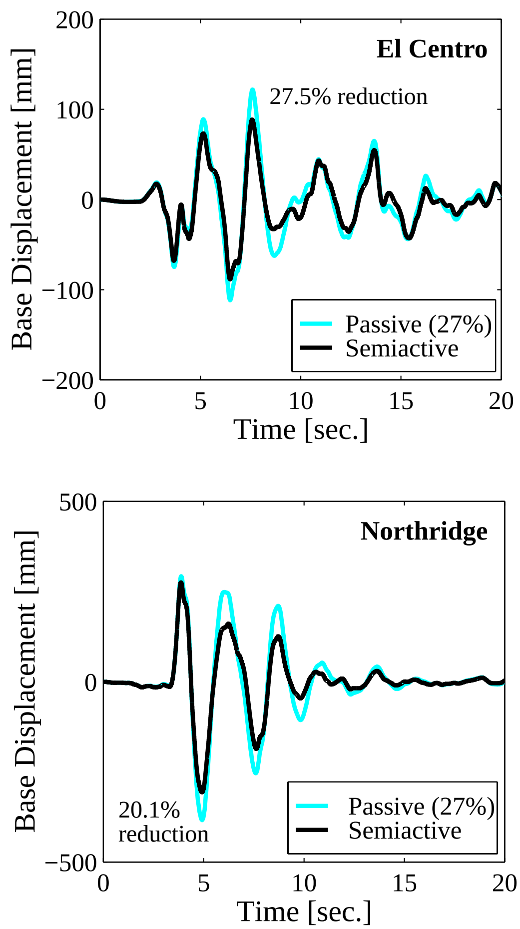

Figure 5: Base drifts with supplemental dampers for two historical earthquakes (T_1 = 2.5 sec, ζ_1 = 1%).

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