Hybrid Control of a 3-D Structure by using Semi-Active Dampers

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Abstract

A base isolated three story 3-D building is semi-actively controlled to not exceed the maximum allowable base displacement. Large displacements are likely to cause failure in the isolation system, and hence, failure in the superstructure is expected. Generally, base isolated structures are designed only if their location is far from an earthquake fault, but the possibility of a new forming fault nearby the structure always exists and design considerations should be made accordingly. In case of nearby seismic action, the isolated building should be smart enough to modify its isolation impedance to resist against large ground displacement and velocities. For this study, an isolated three story building model together with four dampers, which are all placed at the base level, is considered. The dampers have controllable orifices (damping coefficients) and the magnitudes of these damping coefficients are assigned by using a linear quadratic regulator (LQR). During an earthquake excitation, the story displacements and velocities are used as feedback in the calculation of the optimal control force that is producible by viscous dampers, at each time step. This force, however, is applied only at times when critical displacements and/or velocities occur. The performance of the set of controllers is presented via time simulations of the system for three recorded earthquakes. In addition, these records are time shifted five folds to see the effect of near field action. The results indicate that the control effectively reduces the maximum displacements of the isolation system, while maintaining a reasonable isolation to the superstructure.

Keywords: *semi-active control, hybrid control, optimum damping, earthquake excitation*

1 Introduction

Semi-active dampers are foolproof control devices, which makes them being widely accepted in structural control. Dampers are utilized to absorb energy from the structure. Thus, the larger the damping, the less will be the relative velocity and displacement. The accelerations, however, will increase. If the latter behavior is not detrimental, then the act of controlling a damper appears to be useless. Since the maximum damping yields the best response, there would be no need to place a controller into the system. For building type structures, the only case at which the control of dampers would be feasible seems to be the case at which buildings are seismically isolated. The role of the dampers in these type of structures is to limit the displacement of the dampers so that they don't rupture. The presence of a damper in parallel to a base isolation system obviously decreases the effectiveness of the structures earthquake isolation. Nevertheless, it will keep the elastomeric bearings from being driven into large displacements, thus securing the base isolation system.

A number of research has been conducted to model and implement variable orifice dampers. Kurata et al. (1999) designed a full scale building that is controlled by semi active dampers. The damper used in his design is capable of producing a 1000 kN damping force, while only 70 Watt electric energy is consumed for this purpose. Wongprasert and Symans (2005) used variable-orifice fluid dampers to enhance the response of a base isolated 1:4 scale three story frame model. They simulated the response of the system both with software and on an earthquake simulator. Aldemir and Bakioğlu (2000) designed a time varying controller for a damper in a single degree of freedom system. They showed that the maximum displacement of the controlled response is about 18% less than the passive response. Çetin et al. worked on a six story building that was to be controlled via a Magneto rheological damper at the floor level. Although the device is different than a variable orifice damper, the principal remains the same. They modeled the structure as a single degree of freedom system and designed a robust Hinf controller.

2 Three Story 3-D Building Model

A three story building type model is considered for analysis in this study. Elastomeric base isolators are used at the base and four dampers are connected to two opposite corners of the building (see Figure 1). The building is modeled by using 3-D steel beam elements (columns: 17.5mm x 17.5mm, beams: 90 x 90 x 5). The story heights are 80cm, the structures cross sectional dimensions are 100cm (x-dir) by 60cm (y-dir). The structure is constraint at the ground level and in the vertical direction. The remaining degrees of freedoms (dof) except for the lateral dofs at and above the damper connections are statically condensed. The resulting system is a second order differential equation with 12 dof for the fixed base building, and 16 dof for the isolated building. The building without base isolation and dampers has periods denoted by T_0, and the periods with isolators are denoted by T_i . See Table 1 in which the major modes of vibration are shortly described. Note that the first three modes of the isolated building occur mostly in the base, which are the isolation modes. Modes 13 through 16 of the isolated building have high frequencies, which correspond to a skew deformation in the denoted story level only. Since high frequency modes have a relatively small effect on the structural displacements and velocities, they are removed from the system.

The fixed building has a fundamental period of 0.67 seconds. Figure 2 shows the influence of the chosen earthquakes onto the building. In order to isolate the building from the effect of these earthquakes, the elastomeric bearing stiffness is appropriately chosen as 1200N/m (For comparison purposes, the columns have a stiffness of 36600N/m). Thus, the fundamental period of the isolated building is increased to 3.19 seconds and as it can be seen on Figure 2, the expected absolute acceleration of the isolated building is significantly decreased.

Table 1. Vibrational Modes

Mode #	Fixed		Isolated	
	Mode	**T_0 (sec)**	**Mode**	**T_i (sec)**
1	Trans - x	0.674	Trans-x	3.198
2	Trans - y	0.666	Trans - y	3.111
3	Twist - xy	0.593	Twist - xy	2.897
4	Trans - x	0.239	Trans - x	0.369
5	Trans - y	0.236	Trans - y	0.000
6	Twist - xy	0.210	Twist - xy	0.000
7	Trans - x	0.000	Trans - x	0.199
8	Trans - y	0.162	Trans - y	0.000
9	Twist - xy	0.144	Twist - xy	0.173
10	Trans - x	0.008	Trans - x	0.000
11	Trans - y	0.0076	Trans - y	0.1500
12	Twist - xy	0.0074	Twist - xy	0.1330
13			skew - B	0.0110
14			skew - 2	0.0109
15			skew - 1	0.0103
16			skew - 3	0.0089

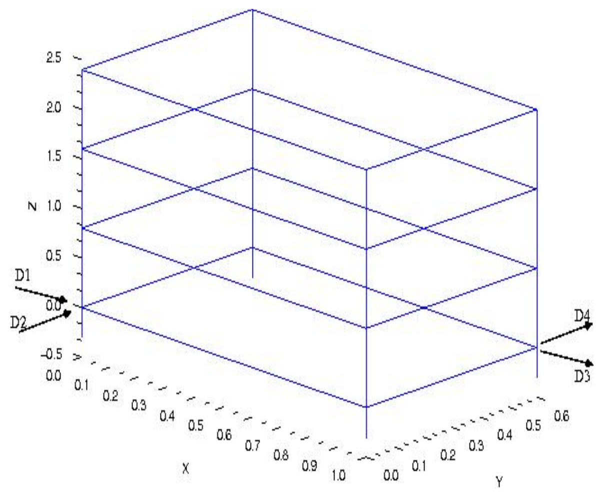


Figure 1. 3-D Building, modeled by frame (line) elements

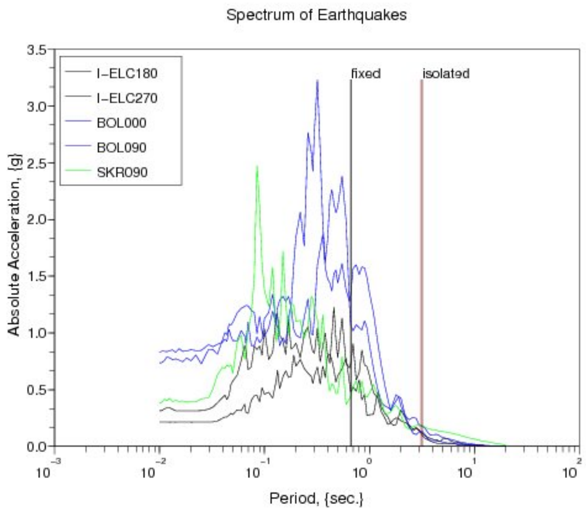


Figure 2. Earthquake Spectra and the influence onto the first vibrational mode of the fixed and isolated buildings, respectively.

3 Semi Active Damper

A piston is modified by a pipe that interconnects its two chambers and a stepper motor controlled valve is placed in series with this pipe. Figure 3 shows the modified piston.

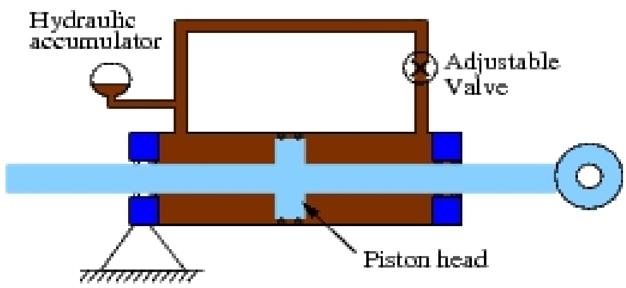


Figure 3. Cross section of the used semi active damper.

The force exerted onto the damper is assumed to have a linear relation with the piston heads velocity as shown in Equation 1.

$$F_d = -c_d \ \dot{x}_d \tag{1}$$

F_d is the damper force, $\dot{x}_d$ is the damper velocity, and c_d is the damping coefficient. The dampers constant is evaluated to be in the range of 5000 to 25000 $N\,s\,/\,m$. The upper limit is selected so that the pistons capacity of 5000 N is not exceeded, whereas the lower limit corresponds to the valve being completely open.

4 Control Design

A hybrid control method, namely Gain Scheduling, is utilized in this study. The isolated building model is constructed with each damper valve opening possibility. The damping constants of the four dampers are each varied by 5000 $N\,s\,/\,m$ increments, resulting in 5 possible damping positions for each damper, and 625 damping positions for the structure with four dampers. Feedback gains are designed for each of these possible configurations by using the linear quadratic regulator (LQR) scheme. During an earthquake simulation, the required force is calculated, and closest damping constants for all four devices are selected such that the dampers are able to produce the required control forces.

4.1 Linear Quadratic Regulator (LQR) Design

Equation 2 shows the differential equation of the isolated building with damping control forces and earthquake effect.

$$M\,\ddot{x} + C\,\dot{x} + K\,x = -M\,\Gamma_{eq}\,\ddot{x}_g + \Gamma\,F_c \tag{2}$$

Here, M, C, and K are the structural mass, damping and stiffness matrices, respectively, and x is the structural displacement with respect to the ground. $\ddot{x}_g$ Is the ground acceleration, Γ_{eq} is the ground acceleration application matrix, Γ is the damper force application matrix, and F_c is the damping force vector of the four dampers, which is constructed as follows

$$F_c = \left\{ F_d^{(1)}, F_d^{(2)}, F_d^{(3)}, F_d^{(4)} \right\}^T \tag{3}$$

Since F_c is a force vector of passive devices and is linearly related to the structural velocity, it can be moved to the left hand side of Equation 2.

$$M\,\ddot{x} + \left(C + \Gamma\,C_d\,\Gamma^T\right)\dot{x} + K\,x = -M\,\Gamma_{eq}\,\ddot{x}_g \tag{4}$$

Equation 4 is transformed to a first order differential equation by introducing a variable transformation of $q = \left\{x, \dot{x}\right\}^T$, which is the system state.

$$\dot{q} = A\,q + B_1\,\ddot{x}_g + B_2\,u \tag{5}$$

The matrices A, B_1, and B_2 are defined below, and the variable u is the optimal control force vector to be evaluated.

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}\left(C + \Gamma\,C_d\,\Gamma^T\right) \end{bmatrix} \quad , \quad B_1 = \begin{bmatrix} 0 \\ \Gamma_{eq} \end{bmatrix} \quad , \quad B_2 = \begin{bmatrix} 0 \\ M^{-1}\Gamma \end{bmatrix} \tag{6}$$

The aim, is to design a controller so that the base displacements in the x and y directions are minimized. This is established by making use of the linear quadratic regulator formulation in which the cost function to be minimized is as follows

$$V(q)=\int_0^\infty q^T Q q + u^T R u \quad dt \tag{7}$$

where Q and R are positive semi definite weighting matrices. Q is arranged to be an identity matrix – all displacements at the base level have the same weight. The matrix R is taken as an identity matrix (same weights for all dampers) with a common multiplier of 1e-8. This common multiplier is the relative weight among the matrices Q and R. The optimal control effort that minimizes Equation 7 requires that

$$u^o = -R^{-1} B_2^T \bar{P} q^o \;=\; K_c\, q^o \tag{8}$$

where K_c is the feedback gain matrix, q^o and u^o are the optimum results of the state and control force, respectively. $\bar{P}$ is the symmetric matrix that is the solution to the Riccati equation

$$A^T \bar{P} + \bar{P} A + Q - \bar{P} B_2 R^{-1} B_2^T \bar{P} = 0 \tag{9}$$

Equations 6 thru 9 are evaluated for all 625 damping constant possibilities, resulting in 625 K_c matrices. These matrices are stored as a hyper matrix (3 dimensional) and they are recalled during the simulation when needed.

4.2 Upper Controller (Gain Scheduling)

An upper controller is designed to switch between the 625 feedback control gains during earthquake simulations. At each time step, the optimal control force is calculated based on the feedback gain for the system with damping constants that are calculated in the previous step. The force that is required for the i'th device is divided by the i'th dampers velocity to obtain the optimum damping constant (See Equation 1). Then the closest damping constant within [5000 to 25000 Ns/m at increments of 5000] is selected for the next time step.

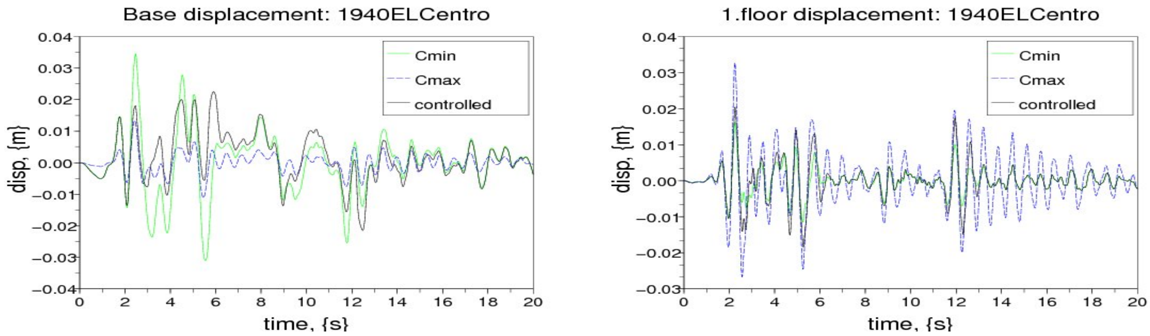
A passive device, as it is the case for dampers, may only absorb energy from the system. That is why the damping force can only act in the opposite direction of its velocity. Hence, if the calculated optimum damping constant has a negative sign, the required force will not be producible. In this case, the damping constant will take its minimum value (5000 Ns/m). Also note that, a numerical precaution is taken to prevent a "divide by zero" error – during the calculation of the optimum damper constant, the smallest absolute damper velocity is limited to 1 mm/s. This should not have a detrimental effect to the structural response, since the worst case causes a force of 25 Newtons, only.

The upper controller also decides when the optimum control forces should be applied. The control should only take affect when the isolators are in danger. Where "danger" in this study is defined as an isolator displacement of 15 mm or more. Once, an isolator exceeds this value, the controller is in action until a minimum or maximum displacement instance is reached that is less than 15 mm.

5 Simulations

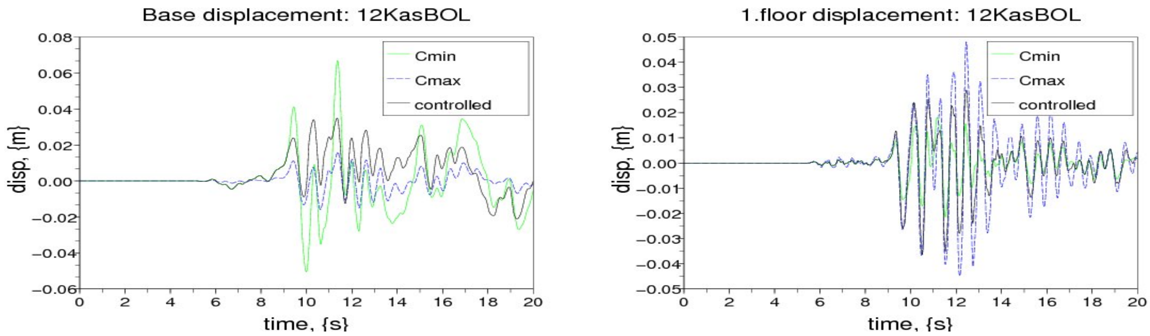
Three different earthquakes are selected for the simulation of the hybrid controlled isolated 3-D building. These are the 19.05.1940 Imperial Valley (El Centro Station), 12.11.1999 Düzce (Bolu Station), and the 17.08.1999 Kocaeli (Sakarya Station) earthquake acceleration records (http://peer.berkeley.edu). The North-South and the East-West components of the earthquake records are applied to the x and y-directions of the structure, respectively. Unfortunately, the North-south component of the Sakarya Station is not available, and therefore the East-West components of this earthquake are used in both directions. Note that this records first 30 seconds has no amplitude. In order not to waste any computing power, these 30 seconds are omitted.

The simulations are carried out for the first 20 seconds for all earthquakes. The major response is seen in this time frame, and it also allows for more detail in the illustrations. Newmark's β method (with constant acceleration approximation) is used as the solver for all simulations in this study.



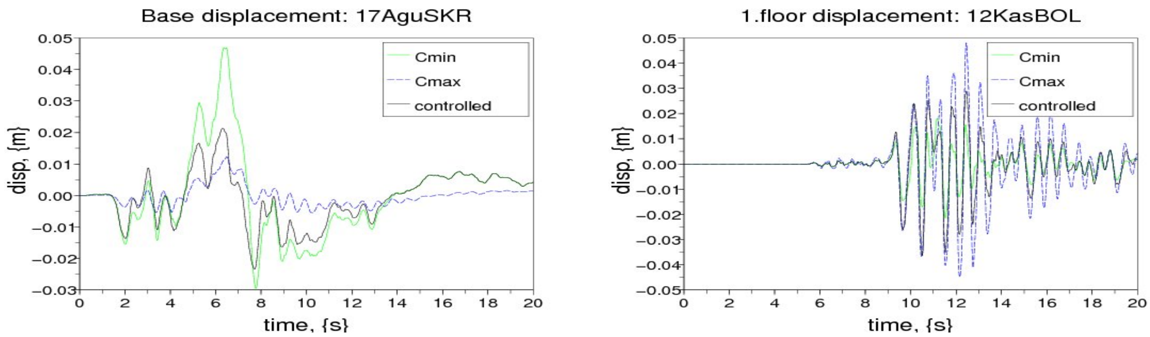
a) Base displacement (node 3, x-dir.) b) 1.Floor displacement (node 5, x-dir.)

Figure 4. El Centro Simulation Response



a) Base displacement (node 3, x-dir.) b) 1.Floor displacement (node 5, x-dir.)

Figure 5. 12KasBOL Simulation Response



a) Base displacement (node 3, x-dir.) b) 1.Floor displacement (node 5, x-dir.)

Figure 6. 17AguSKR Simulation Response

Figures 4, 5, and 6 show earthquake simulation responses of the isolated building. Each figure shows the response of the isolated building with damping at minimum stage, damping at maximum stage, and optimally controlled damping. Recall that the aim is to have the least amount of displacements at the superstructure (first floor) and the isolators displacement should be limited to avoid damage. For the superstructures point of view the case with minimum damping, or even further, no damping at all, would be the most feasible situation. On the other hand, from the isolation systems point of view the highest damping case would be beneficial.

Table 2. Simulation Results

	displacement	C_{min}	C_{max}	$C_{Controlled}$	$\frac{C_{Controlled} - C_{min}}{C_{min}}$
El Centro	Base {m}	0.035	0.013	0.022	-35 %
	1st Floor {m}	0.016	0.033	0.020	26 %
Bolu	Base {m}	0.067	0.016	0.035	-48 %
	1st Floor {m}	0.022	0.048	0.036	69 %
Sakarya	Base {m}	0.047	0.012	0.023	-50 %
	1st Floor {m}	0.0076	0.0126	0.0106	39 %

Table 2 presents the base and the first floor drifts for all three situations. The last column shows the percentile reductions by the controlled damping (compared to the minimum damping case). In other words, the optimal control of the damper constants saves the isolator system from too large displacements, while the superstructures response is less affected when compared to the minimal damping case.

Conclusions

In this study, a seismically isolated 3 story and 3 dimensional building is controlled by four dampers. A set of optimal controllers is designed for each possible damping of the structure. These controllers are utilized into the feedback of the structure by an upper controller, which picks the controller that corresponds to the current state of the building response (displacement and velocity). Simulations of this system shows that this hybrid control application is capable to save the isolation system from too large displacements, while maintaining a reasonable amount of isolation to the superstructure.

References

Aldemir, Ü., and Bakioğlu, M. (2000). Semiactive Control of Earthquake-Excited Structures. Turk J Engin Environ Sci, Vol. 24, pp.237-246.

Çetin, S., Sivrioğlu, S., Zergeroğlu, E., and Yüksek, İ. (2009). Semi-Active Hinf Robust Control of Six Degree of Freedom Structural System using MR Damper. Otomatik Kontrol Türk Milli Komitesi Otomatik Kontrol Ulusal Toplantısı, YTÜ, İstanbul.

Kurata, N., Kobori, T., Takahashi, M., Niwa, N. and Midorikawa, H. (1999). Actual Seismic Response controlled building with semi-active damper system. Earthquake Engng. Struct. Dyn., Vol. 28, pp. 1427-1447.

Wongprasert, N. and Symans, M.D. (2005). Experimental evaluation of adaptive elastomeric base-isolated structures using variable-orifice fluid dampers