Performance Evaluation of Semi-Active Equipment Isolation for Seismic Protection Using MR Dampers

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SUMMARY:
Sensitive equipment, are vulnerable to strong earthquakes, and failure of these equipment may result in a heavy economic loss. To control the seismic response of the equipment, magnetorheological (MR) dampers are appropriate devices, because of their high adaptability and reliability. This paper presents the performance evaluation of passive and semi-active control in the equipment isolation system for earthquake protection. In order to reduce the vibration of the equipment, in a seismically excited steel frame building, an MR damper is placed in parallel with the sliding friction pendulum isolation system, between the equipment and the floor. For the MR damper, phenomenological model based on Bouc-Wen model is used. In the analysis, two semi-active control algorithms, clipped-optimal and the maximum energy dissipation, and two passive control algorithms, passive-on and passive-off are employed. Simulation results demonstrate that the control technique is effective in protecting vibration-sensitive equipment from both far-field and near-field earthquake excitations.

Keywords: MR damper, Sensitive equipment, Semi-active control, Earthquake excitation

1. INTRODUCTION

Because the performance of highly sensitive equipment in hospitals, communication centers, and computer facilities can be easily disrupted by moderate acceleration levels and even permanently damaged by higher excitations, efforts have turned toward the use of isolation for protection of a building's contents [1].

Passive isolation and damping systems have been shown to preserve structural integrity under demanding earthquakes [2]. Typically these equipment isolation systems are a friction-pendulum, or rolling-pendulum type [3]. Passive equipment isolation systems perform extremely well during low-level seismic events [4]. However, during high-amplitude, long-period, ground motions excessive isolator displacements could damage the isolators or overturn the equipment [5].

Seeking to develop isolation systems that can be effective for a wide range of ground excitations, hybrid control strategies, have been investigated by a number of researchers. The advantages of hybrid base isolation systems are high performance in reducing vibration, the ability to adapt to different loading conditions and control of multiple vibration modes of the structure. One class of hybrid base isolation systems employs semi-active control devices, often termed ''smart'' dampers. Semi-active control systems are unconditionally stable, have modest power requirements, and can reduce vibration transmissibility for long period excitations without increasing the transmissibility for short periods [6]. MR dampers are semi-active dampers in which the damping forces are controlled by magnetic field [7]. These dampers are well suited for semi-active control of seismically loaded civil structures because of their low power requirements, high force capacity [8], high dynamic range and mechanical simplicity. Also even when battery power fails, MR dampers will still have some passive damping performance, albeit at a much lower level. Thus it is expected that the hybrid control strategies, consisting of a passive isolation system combined with semi-active control devices could solve the large base drift problem of the passive-type base isolation [9].

Several hybrid type based isolation system employing additional semi-active control devices have been analytically studied with the goal to limit the base drift of the structure ([10, 11]). To systematically compare the effectiveness of control systems for base-isolated buildings, many benchmark studies have been developed. In the benchmark problem, three different kinds of base isolation systems, such as linear elastomeric systems with low damping, frictional systems, and bilinear or nonlinear elastomeric systems, are considered. Some researchers have applied MR damper to develop smart base isolation systems (e.g. Yang et al. 1995 [10]; Symans and Kelly 1999 [12];. Lin et al. 2007 [11]) experimentally showed the effectiveness of semi-active base isolation for a single span bridge model using MR dampers. Several shaking table tests were also conducted with smart dampers in base-isolated building models. However, very few studies have considered equipment isolation with MR damper.

Thus this paper presents the performance evaluation of passive and semi-active control in the equipment isolation system for earthquake protection. Through a 6-story steel frame structure with an equipment located inside, an MR damper together with a friction pendulum isolation system is installed between the equipment and the floor to reduce the vibration of the equipment. The purpose of installing the MR-damper is to limit the drift of the isolator while reducing the acceleration response of the equipment. Control algorithms used for this study, are Clipped-Optimal, Maximum Energy Dissipation, Passive-On and Passive-Off. The equipment system is assumed to be decoupled from the main system. Also the interaction is checked.

2. EQUATION OF MOTION

Consider a general n-DOFs building structure, consisting of m floors and an equipment, located at the ith floor in which: n=m+1. The equipment is modeled as an SDOF system with the mass, stiffness and damping of m_e, k_e and c_e respectively, which is considered as the nth degree of freedom. Therefor the ith and nth degrees of freedom will be related. If the equipment relative displacement with respect to ground is displayed with x_e and floor relative displacement vector with respect to ground is: $[x_1,\dots,x_i,\dots,x_m]^T$; then $\mathbf{x} = [x_1, x_2,\dots, x_n]^T$ is an n-displacement vector representing the floors and equipment displacements with respect to ground that is equal with $\mathbf{x} = \left[x_1, x_2,\dots, x_m, x_e\right]^T$

The matrix equation of motion of the entire building subjected to earthquake ground acceleration $\ddot{x}_g$ is given by Eqn. 2.1.

$$\mathbf{M\ddot{x}} + \mathbf{C\dot{x}} + \mathbf{Kx} = \mathbf{\Gamma} f - \mathbf{M\Lambda}\ddot{x}_g \tag{2.1}$$

In which, $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ and are (n×n) mass, damping and stiffness matrices, respectively. $\mathbf{\Gamma}$ is an (n×1) location vector of the equipment, and $\mathbf{\Lambda}$ is the influence matrix of the earthquake excitation. f is the control force exerted at the equipment and is the summation of MR damper force (f_{MR}) and sliding friction isolation force (f_F) which is expressed with Eqn. 2.2.

$$f_F = m_e g \mu \,\mathrm{sgn}(\dot{x}_n) \tag{2.2}$$

In which μ is the friction coefficient, and $\dot{x}_n$ is the relative velocity of the sliding isolator. The MR damper equation will be discussed in next sections and for calculation purposes the state space representation of Eqn. 2.1. is used [13].

3. MODELING

3.1. Structure

The supporting structure model used in this study is a 6-story steel frame structure with a light equipment located on the first floor. The height of each story is 3m and we have used the concept of rigid diaphragm. Only one degree of freedom is considered for each story. Fig. 3.1 shows the schematic diagrams of this 6-story model building. The structural damping ratio for all modes is fixed to 2 percent of the critical damping. The equipment is modeled as an SDOF with the mass, stiffness and damping of m_e ,k_e.and c_e respectively, which k_e ,is actually the horizontal stiffness of the friction isolation. This stiffness can be modified to tune the equipment to different frequencies. The equipment damping is assumed to be equal to the structural damping. The mass, stiffness and damping matrices of the structure is depicted with M_s ,K_s ,C_s respectively. The damping matrix is obtained by the Raileigh damping, in which period of 1st and 2nd modes are 0.6868 and 0.2953 sec. The mass, stiffness and damping matrix of the combined structure-equipment model are determined as shown in Eqn. 3.1, Eqn. 3.2. and Eqn. 3.3., respectively.

The equipment-structure interaction for an 1000 kg equipment with the period, tuned to the 1st frequency of the structure is investigated thoroughly and the results are reported in Table 3.1. Two cases of combined structure-equipment model and individual models (in which response of the structure is the input for the equipment) have been considered. As the results show the interaction could be ignored (this estimation makes up to 2% error). So the equipment system is assumed to be decoupled from the main system regarding to its light weight compared to the main system

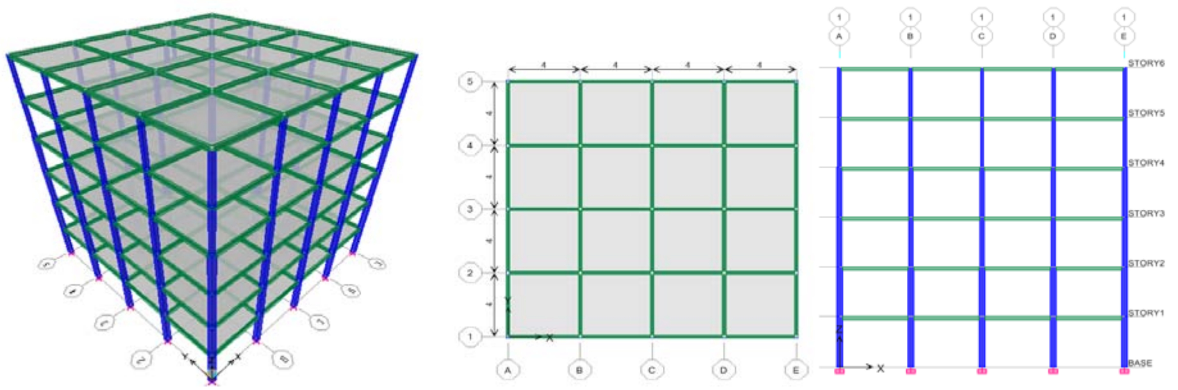

Figure 3.1. 3D, plan and elevation view of the modeled structure

$$[\mathbf{M}]_{n\times n} = \begin{bmatrix} [\mathbf{M}_s]_{m\times m} & \mathbf{0} \\ \mathbf{0} & m_e \end{bmatrix} \tag{3.1}$$

$$[\mathbf{K}]_{n\times n} = \begin{bmatrix} [\mathbf{K}_{11}]_{m\times m} & [\mathbf{K}_{12}]_{m\times 1} \\ [\mathbf{K}_{21}]_{1\times m} & k_e \end{bmatrix};\ [\mathbf{K}_{11}]_{m\times m} = \begin{pmatrix} k_{1s} & \cdots & \\ \vdots & k_{is}+k_e & \vdots \\ & \cdots & k_{ms} \end{pmatrix};$$

$$[\mathbf{K}_{21}]_{1\times m} = [0 \quad \cdots \quad -k_e \quad \cdots \quad 0\ ];\ [\mathbf{K}_{12}]_{m\times 1} = [\mathbf{K}_{21}]^T \tag{3.2}$$

$$[\mathbf{C}]_{n\times n} = \begin{bmatrix} [\mathbf{C}_{11}]_{m\times m} & [\mathbf{C}_{12}]_{m\times 1} \\ [\mathbf{C}_{21}]_{1\times m} & c_e \end{bmatrix};\ [\mathbf{C}_{11}]_{\mathbf{m\times m}} = \begin{pmatrix} c_{1s} & \cdots & \\ \vdots & c_{is}+c_e & \vdots \\ & \cdots & c_{ms} \end{pmatrix};$$

$$[\mathbf{C}_{21}]_{\mathbf{1\times m}} = [0 \quad \cdots \quad -c_e \quad \cdots \quad 0\ ];\ [\mathbf{C}_{12}]_{\mathbf{m\times 1}} = [\mathbf{C}_{21}]^{\mathbf{T}} \tag{3.3}$$

Table 3.1. Comparison of individual and combined models for maximum responses of equipment and structure.

Maximum Acceleration of Floors (m/s^2)						
Story	*1*	*2*	*3*	*4*	*5*	*6*
Individual Models	4.1470	5.8656	8.6902	10.4215	17.1388	19.0856
Combined Model	4.1492	5.8651	8.6467	10.3425	17.1359	19.1169
Error Percent%	0.05%	-0.01%	-0.50%	-0.76%	-0.02%	0.16%

Maximum Responses of Equipment		
Response	*Acceleration (m/s^2)*	*Displacement (m)*
Combined Model	11.4637	0.1369
Individual Models	11.3239	0.1343
Error Percent%	-1.23%	-1.91%

3.2. MR Damper

In this study, a single MR damper (SD-1000) and a friction pendulum-type isolator are modeled. The friction coefficient is 0.02. A mechanical model of the MR damper has been used based on the modified Bouc-Wen model with the maximum force of 3 kN. The simulated force diagrams are shown in Fig. 3.2. which closely agree with the experimental data reported by Dyke et al [14].

3.3. Control Algorithms

3.3.1. Semi-active control algorithms

3.3.1.1. Maximum energy dissipation
For this control algorithm only local measurements (i.e., the velocity and control force) are required to be implemented [15].

3.3.1.2. Clipped-optimal control
Clipped-optimal control approach has been shown to be effective for use with the MR damper [16]. In order to design the optimal controller, H2/LQG methods are used because of their successful application in previous studies. For the control design, an infinite horizon performance index is chosen that weights the acceleration of the equipment and minimize it. The weighting matrix in this study is chosen $[1,0;0,1]$.

3.3.2. Passive control algorithms

Passive-on is the control case for MR damper in which the command voltage is set to be maximum permanently (here 2.25 v) and Passive-off is the control case with the minimum voltage. These cases are employed as references for the discussion on the control effectiveness.

3.4. Excitation

The structure is subjected to one-dimensional ground motions. The earthquake records are: El Centro (1940), Northridge (1994), and Nahanni, Canada (1985) with the PGAs of 0.313g, 0.434g and 0.489g respectively, where the last two records represent near-fault ground motions.

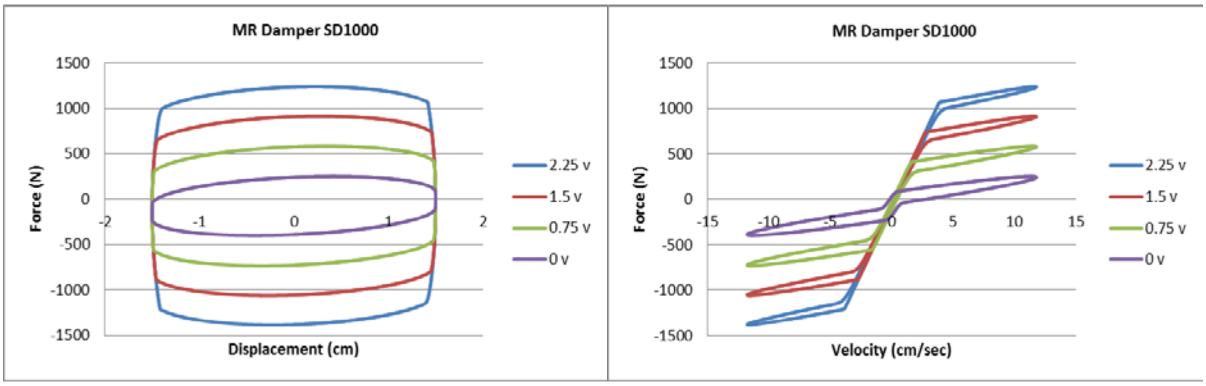

Figure 3.2. Analytically force-displacement and force-velocity diagrams for 2.5 Hz sinusoidal excitation with the amplitude of 1.5 cm.

4. NUMERICAL RESULTS

4.1. Parameter Studies Related to equipment location

Considering the SDOF equipment, the control performance of the equipment isolation system for four control algorithms and 3 mentioned earthquakes has been examined. For the study, a 500 kg equipment with the period of 0.5 sec and 2% damping, is considered and its location has been changed among the floors in order to investigate the effect of equipment location on the MR damper performance. Table 4.1 shows results for the comparison of the equipment maximum acceleration and displacement for the 3rd record and the values of the maximum MR damper force in each cases are reported in Table 4.2. Results of record 3 are shown in Fig. 4.1 and Fig. 4.2 as illustrations.

As the equipment is located in the upper stories, the uncontrolled responses will increase almost linearly due to the increase in the input acceleration while the equipment characteristics are unchanged. Regarding this fact the placement of equipment in lower stories is preferable, as it results in lower uncontrolled responses. However if the equipment has to be placed in higher stories of the structure (Due to some limitation), this study states that MR damper easily controls the responses in all the structure stories and all the methods ‘including Passive-Off’ with substantial reduction in responses.

The overall trend of responses for different control methods is the linear increase with the story number in which the equipment is located. The highest responses are produced in Passive-Off method in which as the story number goes up the response would be worse than other methods and performance of the method will reduce significantly. On the other hand, the lowest response is provided by the Passive-On method and the semi-active responses have more similarity with it.

Comparing the two semi-active methods shows that MED method functions better in controlling the acceleration response; it also shows better performance in controlling displacement response in lower stories, while Clipped-Optimal method usually exhibits higher performance in upper stories.
Passive-On and MED methods have very low sensitivity to the location of MR damper; while Clipped-Optimal method usually exhibits higher performance in upper stories and Passive-Off is more successful in lower stories.
Comparison of MR damper forces shows that Passive-off algorithm produces the lowest force in all cases. Also MED algorithm has the highest forces in most cases. In lower stories Clipped-Optimal and Passive-Off forces are close as the input acceleration is low, however with the increase in the story number the responses will rise so that they approach the maximum values in some cases.

Table 4.1. Comparison of maximum equipment responses for different stories, in different control method, record 3

Nahanni Earthquake									
Acceleration (cm/sec^2)									
story	MED	Reduction Percent	Clipped Optimal	Reduction Percent	Passive-On	Reduction Percent	Passive-Off	Reduction Percent	Uncontrolled
1	80.7	79%	85.9	78%	79.9	79%	86.5	77%	383.1
2	84.8	86%	128.7	78%	86.6	85%	134.9	77%	595.6
3	127.0	86%	182.4	79%	128.0	85%	248.5	72%	882.7
4	161.7	86%	217.5	81%	159.6	86%	344.2	69%	1122.1
5	224.3	86%	265.8	84%	239.3	85%	554.7	66%	1642.9
6	293.6	85%	332.3	83%	297.7	84%	669.5	65%	1919.6
Displacement (cm)									
1	0.214	91%	0.392	84%	0.088	96%	0.395	84%	2.424
2	0.271	93%	0.138	96%	0.110	97%	0.663	82%	3.769
3	0.357	94%	0.196	96%	0.147	97%	1.302	77%	5.585
4	0.491	93%	0.251	96%	0.185	97%	1.841	74%	7.100
5	0.773	93%	0.409	96%	0.291	97%	3.031	71%	10.395
6	1.020	92%	0.716	94%	0.524	96%	3.676	70%	12.146

Table 4.2. Comparison of maximum MR damper force for different stories, in different control method, record 3

Nahanni Earthquake				
MR Damper Force (N)				
story	MED	Clipped Optimal	Passive-On	Passive-Off
1	507.3	185.7	422.1	186.4
2	546.4	607.3	435.2	261.2
3	766.6	909.6	636.7	432.9
4	983.4	1074.8	783.6	577.3
5	1201.8	1144.2	1098.6	893.3
6	1340.0	1256.5	1198.1	1069.5

4.2. Parameter Studies Related to Equipment Period

Considering the SDOF equipment, the control performance of the equipment isolation system for four control algorithms and 3 mentioned earthquakes has been examined. For the study, a 500 kg equipment and 2% damping, is considered and its period will be varied for the range of 0.1-4 sec in order to investigate the effect of equipment period on the MR damper performance. Table 4.3 shows results for the comparison of the equipment maximum acceleration and displacement for the 1st record. Also the values of the maximum MR damper force in each cases are reported in Table 4.4. Results of record 1 are shown in Fig. 4.3. and Fig. 4.4. as illustrations.

Generally the acceleration and displacement of equipment control by MR damper undergo less fluctuations in comparison with uncontrolled condition. As the time period increases the damper force and the equipment responses gradually approach a saturation limit.

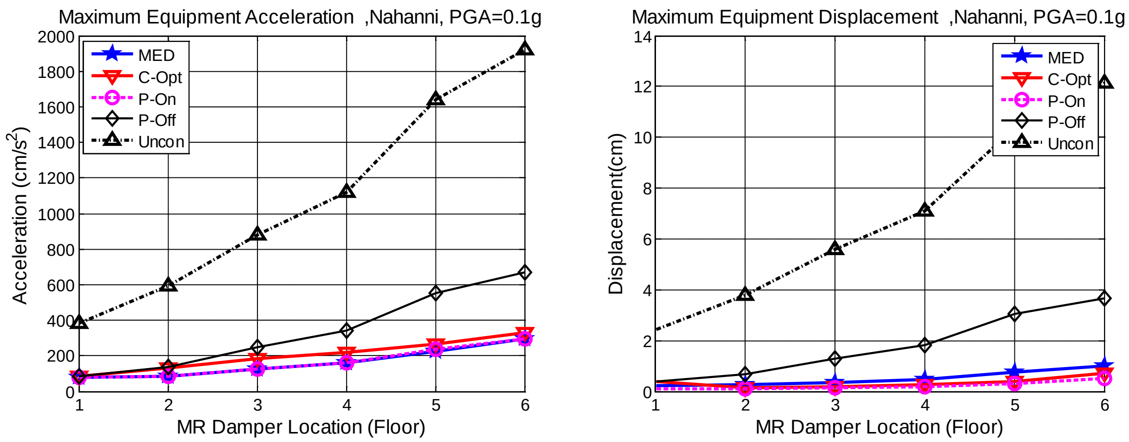

Figure 4.1. Equipment maximum responses vs Equipment floor, in different control methods and uncontrolled case, record 3

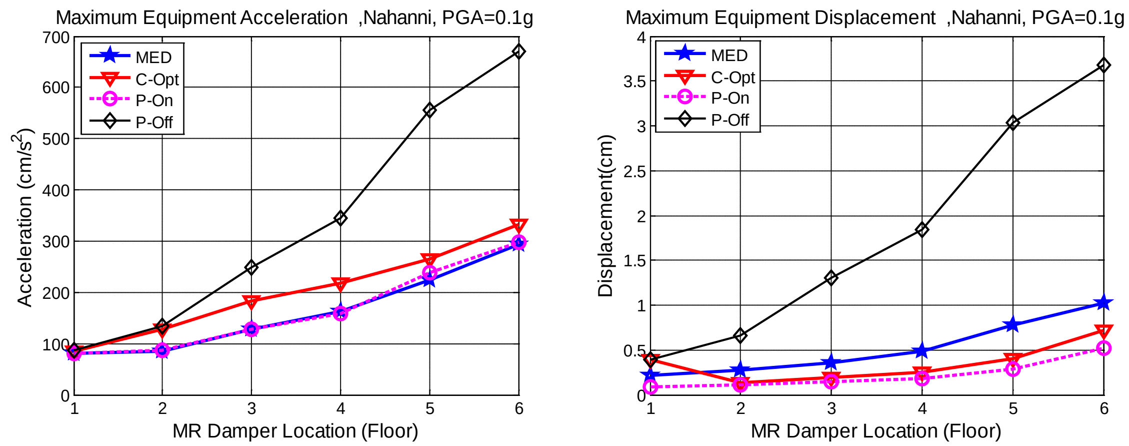

Figure 4.2. Equipment maximum acceleration and displacement vs. Equipment floor, in different control methods, record 3

Table 4.3. Comparison of maximum equipment responses for different equipment periods, in different control methods, record 1

Imperial Valley Earthquake									
Acceleration (cm/sec^2)									
Period (sec)	MED	R.P.	C-Opt	R.P.	P-On	R.P.	P-Off	R.P.	Uncon.
0.1	484.4	63%	483.7	75%	483.5	63%	821.9	38%	1928.5
1.0	271.9	42%	309.1	55%	309.1	34%	309.5	34%	687.5
2.0	250.2	-79%	210.2	8%	294.6	-111%	207.2	-49%	229.5
3.0	251.7	-230%	191.4	-37%	291.6	-282%	192.2	-152%	139.4
4.0	252.3	-347%	187.1	-331%	290.5	-414%	187.2	-231%	43.4
Displacement (cm)									
0.1	0.111	66%	0.100	79%	0.100	69%	0.195	40%	0.488
1.0	2.655	76%	0.968	94%	0.914	92%	3.812	66%	17.392
2.0	3.545	68%	3.791	84%	0.945	92%	3.958	64%	23.227
3.0	3.662	66%	3.843	88%	1.015	90%	3.913	63%	31.759
4.0	3.692	66%	3.931	78%	1.015	90%	3.831	65%	17.476

Table 4.4. Comparison of maximum MR damper force for different equipment periods, in different control methods, record 1

Imperial Valley Earthquake				
MR Damper Force (N)				
Equipment Period(sec)	MED	Clipped Optimal	Passive-On	Passive-Off
0.1	1550.5	1834.8	1408.0	878.1
1.0	1928.2	2593.8	1778.2	1395.3
2.0	1869.1	2186.1	1829.9	1171.9
3.0	1863.1	2049.4	1833.2	928.5
4.0	1790.3	2016.7	1825.5	1000.6

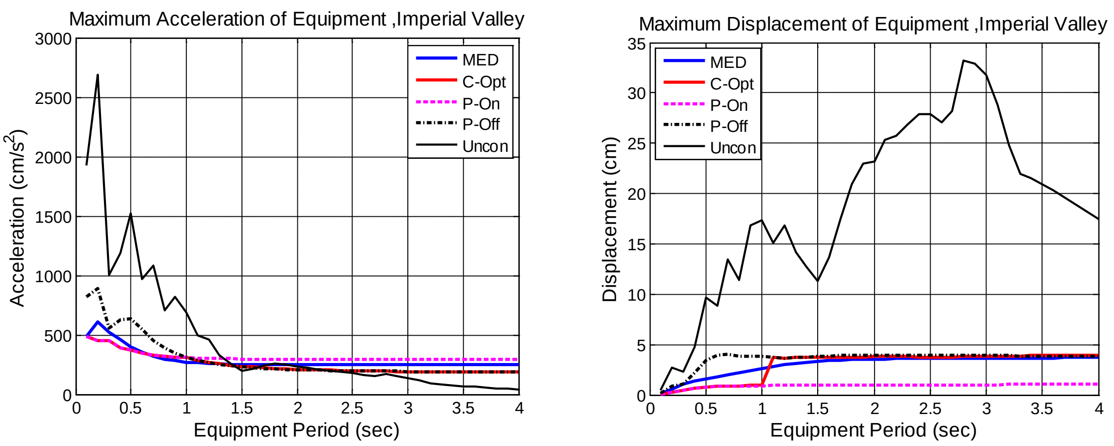

Figure 4.3. Equipment maximum responses vs Equipment period, in different control methods and uncontrolled case, record 1

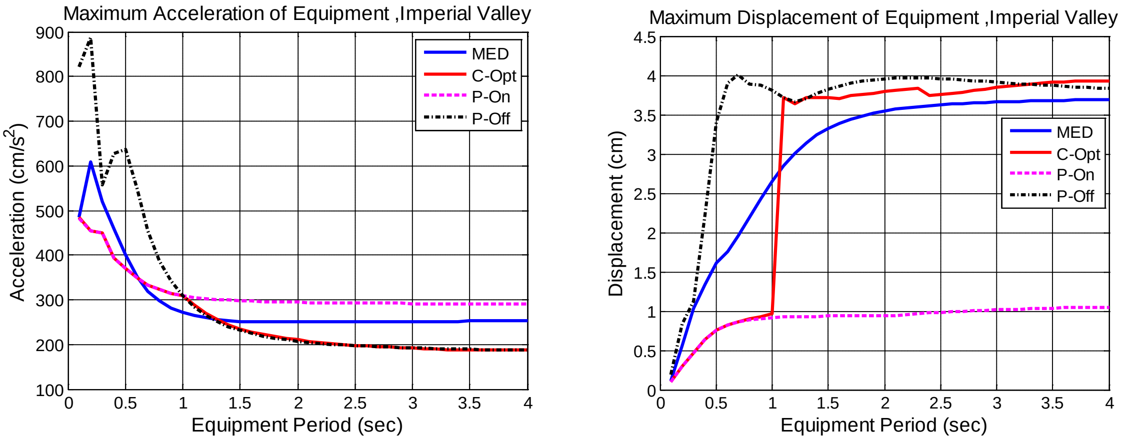

Figure 4.4. Equipment maximum acceleration and displacement vs. equipment period, in different control methods, record 1

Responses obtained from Clipped-optimal method for low time periods are almost the same as those obtained from Passive-On methods. Also MED method responses for most values of time period fall between the two passive algorithms.

Comparing performance of four algorithms, implies that Passive-On algorithm provides the highest reduction as the voltage holds the maximum value, furthermore any of semi-active methods could have the best performance, which is suggestive of high performance of these methods while consuming the least amount of energy. However, Passive-on method acceleration responses are worse than other methods when the time period surpass a specific value. The reason for this is fact attributed to the lock-up phenomenon. As the voltage is maximum in this method, the damper yield force will have high values; Thus, for a similar input earthquake force, the occurence of the lock phenomenon would be more probable which imposes extra stiffness to the system. Comparing the responses of semi-active method shows that Clipped-Optimal acceleration responses are lower than MED method in the most intervals of time period. The reverse is true for displacement response. However both semi-active methods produce appropriate responses. MED method produces the highest force values. (in medival time period, Clipped-Optimal method and at the higher time period, Passive-On method results in the highest force values), while passive-Off method provides the lowest forces.

Totally MR damper is capable of controlling the displacement of the system and in many cases the percentage of reduction will reach about 90%. Meanwhile, there are some points noteworthy about the negative performance of damper for acceleration in some period intervals:

1. The observed negative performance in acceleration, is viewed in comparison with the isolation usage lonely. In case the responses are compared to fixed connection conditions–which has very high frequency- positive performance of damper would be resulted.
2. Application of isolation solely not only imposes high acceleration to the system in high frequency intervals, but also produces large displacement in low frequency regions which brings about several difficulties in application of equipment on ordinary occasions.

5. CONCLUSION*S*

This paper presented the performance evaluation of passive and semi-active control in the equipment isolation system for earthquake protection. Through a 6-story steel frame an MR-damper together with a friction pendulum isolation system was installed between sensitive equipment and the floor to reduce the vibration of the equipment. Four control algorithms were used for this semi-active control studies, including Clipped-Optimal, Maximum Energy Dissipation, Passive-On and Passive-Off.

Investigating the effect of equipment location on the MR damper performance, MR damper could easily control the equipment responses in all the structure stories and all the methods 'including Passive-Off' produce substantial reduction in responses. Comparing the two semi-active method showed that MED method functions better in controlling the acceleration response; and also displacement response in lower stories, while Clipped-Optimal method usually exhibits higher performance in upper stories.

To investigate the effect of equipment period on the MR damper performance, results implies that any of semi-active methods could have the best performance, which is suggestive of high performance of these methods while consuming the least amount of energy. Results show, the occurrences of the lock phenomenon would be more probable with the increase of period, which imposes extra stiffness to the system. Comparing the responses of semi-active methods shows that Clipped-Optimal acceleration responses are lower than MED method in the most intervals of time period.

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