MR DAMPER-BASED SEMI-ACTIVE CONTROL SYSTEMS FOR A BASE ISOLATED STRUCTURE

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Abstract

In this paper, the effectiveness of the MR damper-based semi-active control systems for seismic protection of base isolated building structures employing some semi-active control algorithms, such as the modified clipped-optimal control, the modulated homogeneous friction, and the neural network-based control algorithms, has been investigated by examining the smart base isolated benchmark building problem. The semi-active control systems were applied to a benchmark building installed linear elastomeric isolation system. The numerical simulation results showed that most of the control systems considered herein could be beneficial in reducing seismic responses, especially the base displacement or the isolator deformation, of the base isolated building.

INTRODUCTION

Base isolation systems, such as elastomeric, friction and lead-rubber bearing systems, have been accepted as an effective means for seismic protection of building structures, and also widely applied in numerous full-scale structures (Skinner et al., 1993; Soong and Constantinou, 1994). Those systems can reduce the responses of super-structure, especially inter-story drifts and floor accelerations. On the other hand, the base displacements in those systems under near-fault ground motions may be increased, resulting in expensive loss of space for the seismic gap. To mitigate these problems, base isolation systems have been augmented with supplemental control devices. Because semi-active control devices such as MR (magnetorheological) dampers have the potential to achieve the majority of the performance of fully active systems as well as offer the adaptability of active devices without requiring the associated large power sources, it is expected that the hybrid-type base isolation system employing additional semi-active control devices could solve the large base drift problem of the passive-type base isolation.

In this study, the benchmark base isolation problem developed by Narasimhan et al. (2006) is examined to systematically compare the effectiveness of control systems for a base isolated building. The effectiveness of the MR damper-based control systems for seismic protection of base isolated building structures is verified when some semi-active control algorithms, such as the modified clipped-optimal control, the modulated homogeneous fiction, and the neural network-based control algorithms, are used to mitigate the base displacements of the building structure. A linear elastomeric system with low damping is considered as a base isolation system.

MR DAMPER-BASED CONTROL SYSTEM

In this paper, an MR damper is considered as a supplemental control device, which is the same as the sample semi-active controller for linear isolation system (Nagarajaiah and Narasimhan, 2006). The capacity, total number and configuration of MR dampers are also the same as those of the sample semi-active control system (i.e., 2,200kN, 16, 8 in the X- and 8 in the Y-direction at the isolation level, respectively). The difference between the sample controller and the controllers considered in this study is only the control algorithm used for calculating the desired command signal. While the original clipped-optimal control strategy is adopted as the control algorithm in the sample controller, several different control strategies are considered to find the appropriate control algorithm for a base isolated building structure in this study. The block diagram for the MR damper-based control system of base isolated building is shown in Figure 1.

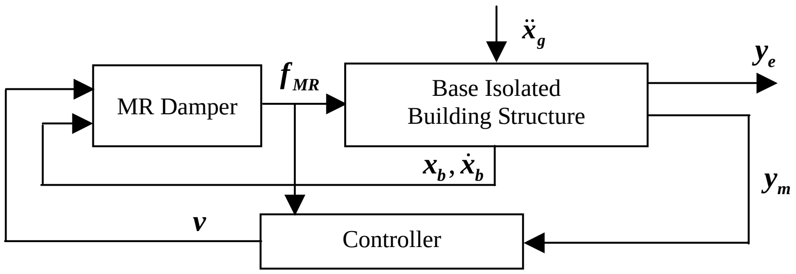

Figure 1. Block diagram for MR damper-based control system.

In the diagram, $\ddot{x}_g$ is the ground acceleration, y_e is the regulated output, y_m is the measured output, x_b is the base displacement, f_{MR} is the control force from MR dampers, and v is the command signal for MR dampers. In the block diagram, the dependence of the MR damper forces on the structural responses is indicated by the link feeding back the vectors x_b and $\dot{x}_b$ which contain the displacements of the devices and velocities at the attachment points of the MR damper.

CONTROL ALGORITHMS

A variety of semi-active control algorithms have been proposed for control of MR dampers (Jansen and Dyke, 2000). In this paper, three different control algorithms are considered. Two of them are model-based control algorithms such as the modified clipped-optimal control algorithm and the modulated homogeneous friction algorithm, and one of them is the nonmodel-based control (i.e., intelligent control) algorithm such as the neuro-control algorithm. In this chapter, each algorithm is briefly explained, and further details can be found in Jansen and Dyke (2000), Jung et al. (2006), and Lee et al. (2006).

Modified Clipped-Optimal Control Algorithms

Dyke et al. (1996) proposed a clipped-optimal control strategy based on acceleration feedback for controlling an MR damper. Because the force generated in the MR damper is dependent on the local responses of the structural system, the desired optimal control force, $\boldsymbol{f_c}$, cannot always be produced by the device. Only the control voltage, $\boldsymbol{v}$, can be directly controlled to increase or decrease the force produced by the device. The algorithm for selecting the command signal for the MR damper can be stated as

$$\boldsymbol{v} = \boldsymbol{V}_{\max} \boldsymbol{H}\left(\{\boldsymbol{f_c} - \boldsymbol{f_{MR}}\}\boldsymbol{f_{MR}}\right) \tag{1}$$

where $\boldsymbol{V}_{\max}$ is the maximum voltage, and $\boldsymbol{H}(\cdot)$ is the Heaviside step function.

In some situations when the dominant frequencies of the system under control are row, large changes in the forces applied to the structure may result in high local acceleration values in the original clipped optimal control algorithm. Jung et al. (2006) proposed the modified clipped optimal control algorithm to solve the problem of the original algorithm as follows:

$$\boldsymbol{v} = \boldsymbol{V_c} \boldsymbol{H}\left(\{\boldsymbol{f_c} - \boldsymbol{f_{MR}}\}\boldsymbol{f_{MR}}\right), \tag{2}$$

in which $\boldsymbol{V_c} = \begin{cases} \mu\, \boldsymbol{f_c} & \textbf{\textit{for}}\ \ |\boldsymbol{f_{MR}}| \le |\boldsymbol{f_c}| < \alpha|\boldsymbol{f_{MR}}| \\ \boldsymbol{V}_{\max} & \textbf{\textit{for}}\ \ |\boldsymbol{f_c}| \ge \alpha|\boldsymbol{f_{MR}}| \end{cases}$ (3)

where $\alpha > 1$ is the coefficient to be properly selected.

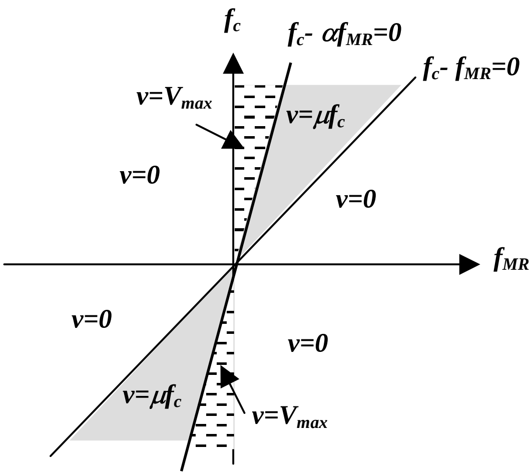

Figure 2. Graphical representation of the modified clipped-optimal control algorithm

As shown in the equation and the figure, the command voltage input to the MR damper should be the maximum value (i.e., $\boldsymbol{V}_{\max}$) inside the region where the difference between the desired control force ($\boldsymbol{f_c}$) and the actual control force ($\boldsymbol{f_{MR}}$) is quite large. Otherwise, the command signal should be calculated according to the modified algorithm.

Modulated Homogeneous Friction Algorithm

The modulated homogeneous friction algorithm was originally proposed for the controller using a variable fiction damper (Inaudi 1997), but there are strong similarities between the behavior of a variable friction device and the MR damper. This algorithm commends more slip force with damper deformation larger by increasing the damping coefficient through feedback of the damper deformation to improve the energy dissipation process of semi-active dampers (Inaudi 1997). This algorithm was modified for MR dampers by Jansen and Dyke (2000). The control law is

$$\boldsymbol{v} = \boldsymbol{V}_{\max}\boldsymbol{H}\left(\boldsymbol{f_n} - \left|\boldsymbol{f_{MR}}\right|\right) \qquad \text{where} \quad \boldsymbol{f_n} = \boldsymbol{g_n}\left|\Delta(\boldsymbol{t}-\boldsymbol{s})\right| \tag{4}$$

defining $\Delta(\boldsymbol{t}-\boldsymbol{s})$, in which $\boldsymbol{s} = \{\min \boldsymbol{x} \ge 0 : \Delta(\boldsymbol{t}-\boldsymbol{x}) = 0\}$, as the most recent local extrema in the deformation of the MR damper. The proportionality constant $\boldsymbol{g_n}$ has units of stiffness (kN/m), and its optimal value is dependent on the amplitude of the ground excitation.

Semi-active Neurocontrol Algorithm

In this study, the semi-active neurocontrol algorithm developed by Jung et al. (2004) is applied to the base isolated benchmark structure. The neurocontrol system adopts a training algorithm based on a cost function and sensitivity algorithm to calculate the desired control force. A clipped algorithm is then employed to induce the MR damper to generate approximately the desired control force by selecting appropriate command voltage.

NUMERICAL SIMULATION RESULTS

The benchmark structure considered is an eight-story base isolated building similar to existing buildings in Los Angeles, California. The base isolation system includes both linear elastomeric bearings with low damping. The super-structure is considered to be a linear elastic system with lateral-torsional behavior. The linear elastomeric isolation system consists of 92 low damping elastomeric bearings, and the fundamental period and the damping ratio of the system are T_b=3 sec and 3%, respectively. A total of 16 semi-active control devices (i.e., MR dampers), 8 in the X- and 8 in the Y-direction, are placed at the isolation level. More detailed information on the model can be found in Narasimhan et al. (2006) and Nagarajaiah and Narasimhan (2006).

In numerical simulation, the three control algorithms are considered for the MR damper-based system. The first controller is designed by using the modified clipped-optimal control algorithm with α=2 proposed in Jung et al. (MCO). The second controller is designed by using the modulated homogeneous friction algorithm with $\boldsymbol{g_n}$=200 kN/m (MHF). The final controller is designed by using the semi-active neural network-based control algorithm (Neuro).

A total of seven historical earthquake records are considered (Nagarajaiah and Narasimhan, 2006): Newhall, Sylmar, El Centro, Rinaldi, Kobe, Jiji and Erzinkan records. To systematically evaluate the control performance of each controller, the five evaluation criteria related to peak responses defined in the benchmark problem statement as follows (Narasimhan et al., 2006): normalized peak base shear (J_1), normalized peak structure shear (J_2), normalized peak base displacement or isolator deformation (J_3), normalized peak inter-story drift (J_4), and normalized peak absolute floor acceleration (J_5).

The results of evaluation criteria for the three different control designs are presented in Tables 1 to 2. Table 1 shows the performance of all the control algorithms. MCO considerably improve the peak floor acceleration (J_5) except the Erzinkan record as seen from the table. Thus, if it is required to reduce the base displacement without increasing the floor acceleration, MCO is more appropriate to the control algorithm for the base isolated building. In addition, MHF and Neuro show the reliable overall performance for the all the seven earthquakes. The control performance of Neuro is better than that of other two algorithms except the peak floor acceleration (J_5). Table 2 represents the maximum evaluation criteria of each algorithm for all the seven earthquakes considered herein. As seen from the table, all the control algorithms such as MCO, MHF and Neuro are appropriate under various ground motions.

Table 1. Evaluation criteria for various control algorithms

Earthquakes		J_1	J_2	J_3	J_4	J_5
Newhall	MCO	0.91	0.91	0.73	0.94	0.97
	MHF	0.92	0.91	0.79	0.92	0.94
	Neuro	0.97	0.91	0.72	0.86	1.14
Sylmar	MCO	0.93	0.94	0.88	0.90	0.95
	MHF	0.93	0.94	0.92	0.94	0.97
	Neuro	0.83	0.85	0.76	0.75	0.87
El Centro	MCO	0.94	0.93	0.64	0.84	0.87
	MHF	0.95	0.93	0.67	0.82	0.86
	Neuro	0.74	0.74	0.36	0.66	1.55
Rinaldi	MCO	1.00	0.99	0.86	0.97	0.99
	MHF	1.00	1.00	0.92	0.98	1.01
	Neuro	0.93	0.93	0.65	0.92	1.41
Kobe	MCO	0.82	0.81	0.69	0.80	0.97
	MHF	0.83	0.82	0.76	0.83	0.97
	Neuro	0.70	0.72	0.46	0.72	1.58
Jiji	MCO	0.92	0.91	0.83	0.91	0.93
	MHF	0.93	0.93	0.90	0.93	0.94
	Neuro	0.90	0.90	0.80	0.92	0.95
Erzinkan	MCO	0.99	1.02	0.65	0.88	1.05
	MHF	0.96	0.98	0.83	0.88	0.97
	Neuro	0.84	0.85	0.56	0.72	0.88

Table 2. Maximum evaluation criteria for seven earthquakes

	MCO	MHF	Neuro
J_1	1.00	1.00	0.97
J_2	**1.02**	1.00	0.93
J_3	0.88	0.92	0.80
J_4	0.97	0.98	0.92
J_5	**1.05**	**1.01**	**1.58**

CONCLUSIONS

Some semi-active control algorithms, such as the modified clipped-optimal control, the modulated homogeneous friction and the neural network-based control algorithms, are considered to verify the effectiveness of the MR damper-based control systems for seismic protection of the base isolation system by investigating the benchmark base isolated building problem. The numerical simulation results demonstrate that most of the control systems considered could be beneficial in reducing seismic responses of base isolated building structures. In the case that it should be required to reduce the base displacement without increasing the floor acceleration, the modified clipped-optimal control and the modulated homogeneous friction algorithms could be considered as one promising candidate for the linear benchmark base isolated system.

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