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Research Paper

SEISMIC RESPONSE ANALYSIS OF BUILDING USING SEMIACTIVE MR DAMPERS INVOLVING SMART PASSIVE CONTROL

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The issue of seismic hazard mitigation of buildings is being investigated over the years using various strategies to enhance the seismic resistance of buildings. But large scale seismic hazards during recent past earthquakes have underscored the importance of structural control system for mitigation of earthquake hazards. This paper involve a study of reduction in building responses using two proposed controls, namely, semiactive MR control and smart passive MR control are compared with uncontrol building responses. The MR dampers are diagonally connected to each floors and Bouc-Wen phenomenological model has been employed to ascertain dynamic behaviour of semiactive MR damper. The analysis of building responses are studied under four unidirectional earthquakes and simulated by programme coding with the help of SCILAB5.4.0. The results of numerical study reflects that smart passive MR control found more effective than semiactive MR control in reducing seismic responses of uncontrol building.

Keywords: Seismic response, Mitigation, Semi-active MR control, Smart passive MR control, Inclined damper, Uncontrolled building responses

INTRODUCTION

Due to change in the state of fluid from viscous to semisolid state, a considerable change of damping force of MR damper occurs. Hence damping force of MR damper's can be adjusted to desired optimal value by continuous change in the magnitude of applied magnetic field according to a predefined algorithm. Spencer *et al.* has proposed a model to predict the dynamic behavior of MR damper, referred as phenomenological model, that can effectively predicts the response over a wide range of operating conditions (Zhao-Dong Xu *et al*., 2003). This type of response analysis using semiactive MR damper had been studied by the several researches (Housner *et al*., 1997; Michael D Symans *et al*., 1999; Spencer Jr. *et al*., 1997). The

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modified Bouc-Wen phenomenological model is one of those models that closely represent dynamical properties of MR damper (Spencer Jr. *et al.*, 1997). Semiactive MR damper is converted into a smart passive system in which EMI system is attached to the damper which is able to generate the current using kinetic energy of damper connected building. The requirement of variable current for operating MR damper is fulfilled by the EMI system which works on Faraday's law gives better seismic performance as compared to semiactive MR damper under severe earthquakes (Dumne *et al.*, 2010).

The present study investigates the response reduction of individual RC building associated with diagonal MR dampers at each floor using semiactive and smart passive control. The objectives are (1) to study the seismic performance of semiactive MR control and smart passive MR control in reducing the responses of uncontrol building; (2) to compare the peak responses reduction using these proposed controls with uncontrol building response.

STRUCTURAL MODEL

The structural model consists of a 12-storied building and is idealized as linear shear type building as shown in Figure 1.

The governing equations of motion for building with dampers in matrix form is

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}$$

$$=[D_p]\{f_d\}-[M]\{r\}\ddot{u}_g \qquad ...(1)$$

where, [*M*], [*C*] and [*K*] are the mass, damping and stiffness matrices, respectively. The

Figure 1a: Structural Model of Uncontrolled Building

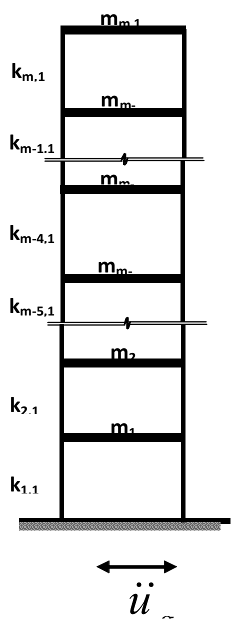
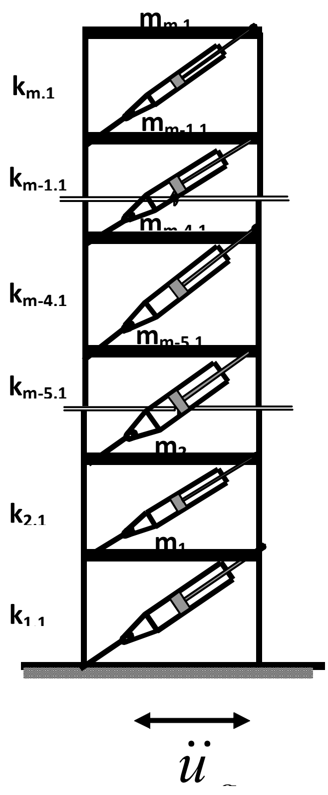


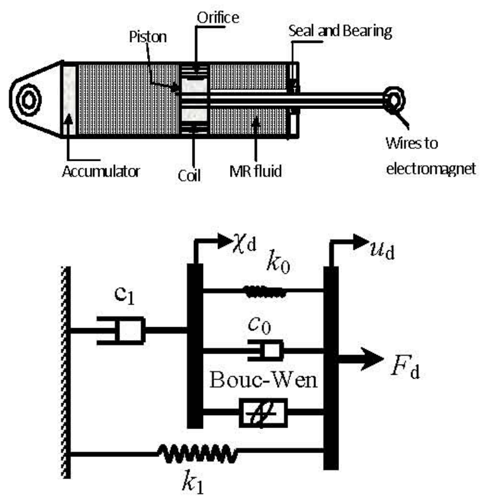
Figure 1b: Structural Model of Building with MR Dampers



displacement vector with respect to the ground is expressed as $\{u\} = \{u_1, u_2, u_3, u_n\}$, in which u_i is the displacement of i^{th} floor from base. Similarly, $\{\dot{u}\}$ and $\{\ddot{u}\}$ are velocity and acceleration vector, respectively. Further, $\{r\}$ is the vector of influence coefficient consisting all elements equal to one, $\ddot{u}_g$ is the ground acceleration due to earthquake, $[D_p]$ is the matrix for the positions of damper, $\{f_d\}$ is the damper force vector.

Further, equation (Eq. 1) is expressed in state-space form as

Figure 2: Cross Section and Modified Bouc-Wen Model of MR Damper



$$\{\dot{z}(t)\} = [A]\{z(t)\} + [B_d]\{f_d(t)\} + [E]\ddot{u}_g(t) \quad \text{...(2)}$$

The force generated by MR damper is expressed as

$$f_d = c_1\dot{x} + k_1(u_d - x_0) \quad \text{...(3)}$$

$$\dot{z} = -\gamma|\dot{u}_d - \dot{x}|(z)|z|^{(n-1)} - \beta(\dot{u}_d - \dot{x})|z|^n + A_d(\dot{u}_d - \dot{x}) \quad \text{...(4)}$$

$$\dot{x} = \left\{\frac{1}{(c_0 + c_1)}\right\}\{\alpha_0 z + c_0\dot{u}_d + k_0(u_d - x) \quad \text{...(5)}$$

where, u_d is the damper displacement, x is the internal pseudo-displacement of damper; z is the hysteretic displacement of damper; k_1 is the accumulator stiffness; c_0 is parameter to control the viscous damping of damper at large velocities, c_1 is the viscous damping; x_0 is the initial displacement of linear spring k_1. The model parameters $(c_0, c_1\ and\ \alpha_0)$ depends on command voltage (U) and are expressed as

$$c_0 = c_{0a} + c_{0b}U\ ,\ c_1 = c_{1a} + c_{1b}U$$

and $\alpha_0 = \alpha_{oa} + \alpha_{ob}U$

where, U is the output of first order filter which is given as

$$\dot{U} = -\eta(U - V) \quad \text{...(6)}$$

The Equation (6) is necessary to model the dynamics in reaching rheological equilibrium in MR damper. The first-order filter equation between the maximum command voltage applied (V_{max}) and output of first-order filter *(U)* using time constant ($1/\eta$) is necessary to accommodate time lag.

Control Algorithm for Semiactive MR Damper Involving Smart Passive

In this study, Lyapunov direct theory is used as a control algorithm for the stability analysis and design of semi-active controller. It states, "If the total energy of a system is continuously dissipated, then the system must eventually settle down to equilibrium". This approach requires the use of Lyapunov function, denoted by $L(\{Z\})$, which must be a positive definite function of state of the system $\{Z\}$. According to Lyapunov stability theory, if the rate of change of Lyapunov function $\dot{L}(\{Z\})$ is negative semi-definite function, the origin is stable. Thus, in determining the control law, goal is to choose a control input, which will result in making $\dot{L}$ as negative as possible. Leitmann (1994) applied Lyapunov stability theory for the design of semi-active controller.

In this approach, a Lyapunov function is chosen of the form as below

$$L(\{Z\}) = \frac{1}{2}\left\|\{Z\}\right\|_p^{\,2}$$

The term $\left\|\{Z\}\right\|_p$ is the P-norm of state defined by $\left\|\{Z\}\right\|_p = \left[\{Z^T\}[P_L]\{Z\}\right]^{1/2}$

where, $[P_L]$ is real, symmetric, positive definite matrix and in case of a linear system, to ensure $\dot{L}$ as negative definite then $[P_L]$ is found out from the Lyapunov equation as below

$$\left[A^T\right][P_L] + [P_L][A] = -[Q_P]$$

For a positive definite matrix, $[Q_p]$ is considered as a unit matrix. The derivative of Lyapunov function for the solution of state-space equation is

$$\dot{L} = -\frac{1}{2}\{Z^T\}[Q_P]\{Z\} + \{Z^T\}[P_L][B_d]\{f_d\}$$

$$+\{Z^T\}[P_L][E]\ddot{u}_g$$

In developing the control law, command voltage (v) supplied to the MR driver is restricted to either zeros or maximum, that is, $V \in [0, V_{max}]$ corresponding to a fixed set of states. Then control law that will minimize is

$$V = V_{max} H\left(\{-Z^T\}[P_L][B_d]\{f_d\}\right) \qquad ...(7)$$

where, $H(\times)$ is Heavy side step function. When the function H (×) is greater than zero, command voltage supplied V to the MR driver is maximum ($V = V_{max}$) otherwise, the command voltage set to zero ($V = 0$).

The smart passive damper consists of an MR damper and an Electromagnetic Induction (EMI) system that uses a permanent magnet and a coil. The EMI system attached to the MR damper produces the electric energy as per Faraday law of induction. This energy is applied to the MR damper to vary the damping characteristics of damper. The amount of maximum induced emf of the EMI system can be regulated by the turns of coil or intensity of the permanent magnet.

Faraday's law of induction is

$$\varepsilon = \left(-N d\Phi_B / dt\right) \qquad ...(8)$$

where ε is induced electromotive force (emf), N is number of coil turns, $d\Phi_B$ is rate of change of magnetic flux and d_t is the incremental time interval. Negative sign in above equation is the direction of induced current. Magnet flux can be defined as

$$d\Phi_B = BdAcos(\varphi) \qquad ...(9)$$

where B is magnetic field, A is area of cross section, and ϕ is the angle between B and dA.

Hence Faraday's law can be rewritten as

$$\varepsilon = -NA\, dB/dt \qquad ...(10)$$

Faraday's law of induction states that the induced emf in a closed loop equals the negative of the time rate of change of magnetic flux through the loop. Rate of change of magnetic flux is proportional to the velocity. Hence the voltage developed is given by

$$V=(v_i/v_{max})V_{max}H\left(\left\{-Z^T\right\}\left[P_L\right]\left[B_d\right]\left\{f_d\right\}\right) \quad ...(11)$$

where v_i is the velocity of i[th] floor. V_{max} is the designed velocity and will depend on EMI system.

NUMERICAL STUDY

A lumped mass structural model of realistic twelve-storey RC building of shear type having mass of each floor as 199 tons, Stiffness per floor as 3.08 x 10^5 kN/m and damping as 5% considered which render its fundamental period of 1.27 s. The proposed MR dampers of capacity 1000 kN at each storey are diagonally connected to control the building from seismic hazards. The building is subjected to unidirectional excitation for which four earthquake ground motions considered as shown in Table 1. The parameters of MR damper as shown in Table 2 to suit the damper deformation behavior whereas maximum voltage supplied to the current driver of MR damper is 6 V. The response parameters of interest are: peak floor displacement, acceleration and base shear are taken into

Table 1: Detail of Earthquake Ground Motions

Earthquake	Recording station	Component	PGA(g)
Imperial Valley,1940(EQ1)	El-Centro	N00E	0.348
Kobe, 1995 (EQ2)	Japan Meteorological Agency	N00E	0.834
Loma Prieta, 1989 (EQ3)	Los Gatos Presentation Centre	N00E	0.570
Northridge, 1994 (EQ4)	Sylmer Converter Station	N00E	0.843

Table 2: Bouc-Wen Phenomenological Model Parameters for Damper (Farahmand Azar *et al.*)

Parameter	Value	Parameter	Value
H	100 s^{-1}	g	164 m^{-2}
c_{1a}	8359.2 kN-s/m	$\hat{a}$	164 m^{-2}
c_{1b}	7482.9 kN-s/m/V	A_d	1107.2
c_{0a}	110 kN-s/m	n_s	2
c_{0b}	114.3 kN-s/m/V	k_0	0.002 kN/m
a_{0a}	46.2 kN/m	x_0	0 m
a_{0b}	41.2 kN/m/V	k_1	0.0097 kN/m

consideration and base shear has been normalized by the total weight of building. The seismic response of building has been simulated with the help of SCILAB5.4.0

Figure 3: Time Varying Top Floor Acceleration Response Under Smart Passive MR Control

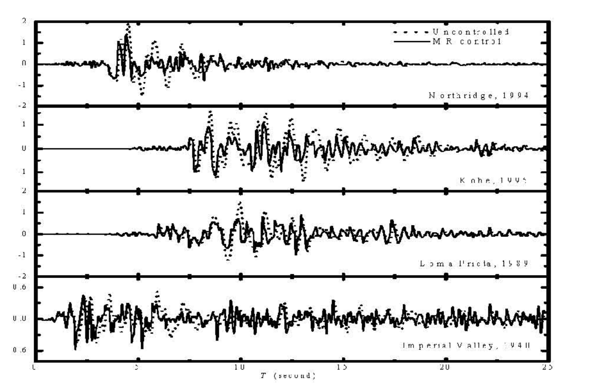


Figure 4: Time Varying Top Floor Displacement Response Under Smart Passive MR Control

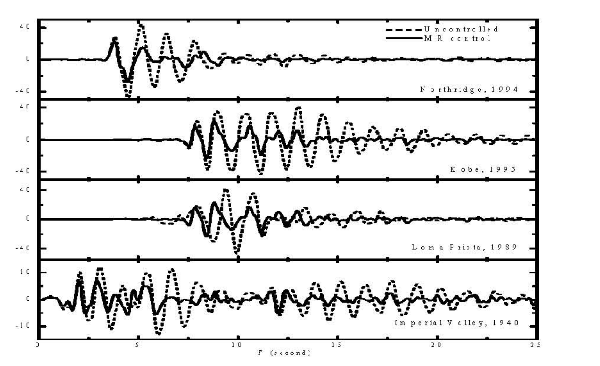


Figure 5: Time Varying Top Floor Acceleration Response Under Semi Active MR Control

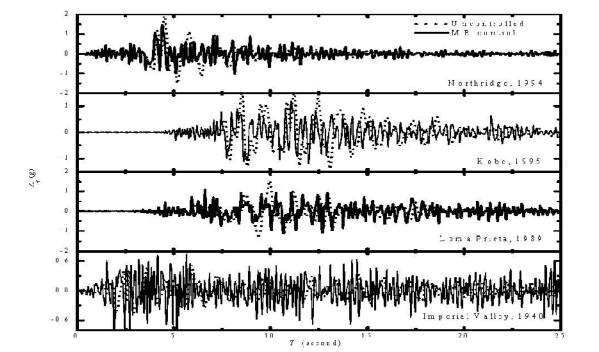


Figure 6: Time Varying Top Floor Displacement Response Under Semi Active MR Control

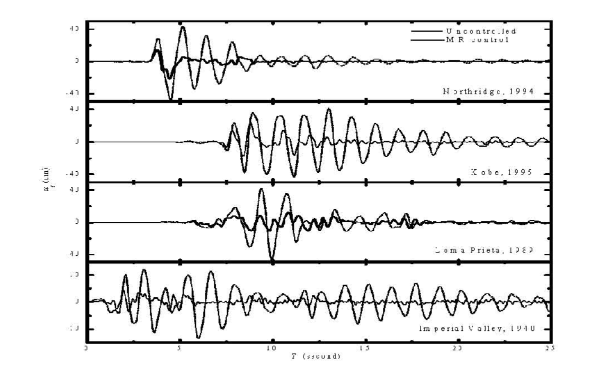


Table 3: Values of Peak Floor Displacements (Normalised by The Respective Uncontrolled Response) Control-I: Semiactive MR Control and Control-II: Smart Passive MR Control

	Floor No.→	1	2	3	4	5	6	7	8	9	10	11	12
EQ1	I	1.13	1.06	1.19	1.62	1.71	1.51	1.91	1.69	1.97	1.37	1.47	1.82
	II	1.08	0.87	0.86	1.09	1.02	0.87	0.81	0.94	1.05	0.90	0.88	1.13
EQ2	I	0.87	0.86	0.81	0.75	0.67	0.58	0.72	0.98	0.97	0.83	0.72	0.76
	II	0.92	0.86	0.73	0.57	0.59	0.57	0.59	0.62	0.81	0.78	0.71	0.71
EQ3	I	0.91	0.79	0.81	0.83	0.85	0.92	0.78	0.71	0.65	0.57	0.61	0.72
	II	0.89	0.83	0.81	0.84	0.79	0.83	0.71	0.65	0.57	0.51	0.48	0.63
EQ4	I	1.02	0.99	0.92	0.77	0.71	0.72	0.79	0.95	0.80	0.71	0.65	0.78
	II	0.94	0.83	0.75	0.76	0.72	0.71	0.74	0.77	0.74	0.66	0.69	0.70

Table 4: Values of Peak Floor Accelerations (Normalised By The Respective Uncontrolled Resp[Onses) Control-1: Semiactive Mr Control and Control-2: Smart Passive Mr Control

	Floor No.→	1	2	3	4	5	6	7	8	9	10	11	12
EQ1	I	1.13	1.06	1.19	1.62	1.71	1.51	1.91	1.69	1.97	1.37	1.47	1.82
	II	1.08	0.87	0.86	1.09	1.02	0.87	0.81	0.94	1.05	0.90	0.88	1.13
EQ2	I	0.87	0.86	0.81	0.75	0.67	0.58	0.72	0.98	0.97	0.83	0.72	0.76
	II	0.92	0.86	0.73	0.57	0.59	0.57	0.59	0.62	0.81	0.78	0.71	0.71
EQ3	I	0.91	0.79	0.81	0.83	0.85	0.92	0.78	0.71	0.65	0.57	0.61	0.72
	II	0.89	0.83	0.81	0.84	0.79	0.83	0.71	0.65	0.57	0.51	0.48	0.63
EQ4	I	1.02	0.99	0.92	0.77	0.71	0.72	0.79	0.95	0.80	0.71	0.65	0.78
	II	0.94	0.83	0.75	0.76	0.72	0.71	0.74	0.77	0.74	0.66	0.69	0.70

platform. From numerical result obtained from the time varying response shown in Figures 3 to 6, it is observed that smart passive MR control work effectively in reducing the uncontrolled building responses than the Semiactive MR control. Further, normalized values of maximum floor displacement, acceleration and base shear (Normalized these responses by the respective uncontrolled responses) are shown in Tables 3 and 4, respectively. The values imply that both proposed controls perform well during earthquakes but MR control based on smart passive yields better required result than MR control based on semiactive.

CONCLUSION

This paper proposed two controls, that is, semiactive MR control and smart passive MR control in order to mitigate the building responses during excitation due to earthquake. These controls are employed to the 12-storied RC building in which each story is connected by diagonal MR damper. From the numerical observations, one can outline the following concluding remarks.

1. The results demonstrate that proposed both control schemes perform effectively during excitation due to earthquake. Further, control based on smart passive MR works more significant than semiactive MR control to reduce the earthquake responses of uncontrolled building.
2. The normalized peak responses, that is, displacement, accelerations and base shear illustrate that smart passive MR control gives consistent performance in reducing seismic responses as compared to the semi active MR control.

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