**SEMI-ACTIVE CONTROL USING MR DAMPERS FOR RANDOM GROUND MOTIONs**

**DOI 10.37153/2686-7974-2019-16-98-110**

Vishisht BHAIYA[[1]](#footnote-1) Shiv Dayal BHARTI[[2]](#footnote-2), Mahendra Kumar SHRIMALI[[3]](#footnote-3), Tushar Kanti DATTA[[4]](#footnote-4)

**ABSTRACT**

A simulation based semi-active control strategy for partially observed building frames subjected to random ground motions is presented. The control strategy has the following attributes, namely, i) it is suitable for online implementation; ii) it meets the ideal condition for the use of the Kalman filter for the state estimation by converting the input excitation to the Gaussian white noise; and iii) it can accommodate a site-specific random ground motion defined by its power spectral density function (PSDF). In order to meet the requirement of the site-specific input ground motion and to meet the ideal condition for the use of the Kalman filter, the state vector is augmented by the filter variables of the double filter PSDF proposed by Clough and Penzien so that the Gaussian white noise is provided as the input to the system. The structure is also analyzed for the simulated ground motion from the PSDF directly applied as input to the structure without fulfilling the condition that the use of the Kalman filter requires the input excitation or disturbance to be white noise. Two control algorithms are used, namely, i) Linear Quadratic Gaussian (LQG) control with clipped optimal algorithm (LQGCL); and ii) Sliding mode control with clipped optimal control (SMCCl). The results of the study show that i) there is a significant difference in results between the two types of analysis performed; ii) SMCCl provides better control of responses; and iii) the development of the control strategy for site-specific ground motion requires careful consideration of the online implementation.

*Keywords: MR Damper; LQG; Kalman Filter; Semi-active Control; Sliding mode control; Clipped optimal control*

**1. INTRODUCTION**

Natural hazards like earthquakes, cyclones and tsunamis have a tendency to cause large scale damage to structures if they are not properly designed. For the protection of structures against these natural hazards considerable researches have been carried out in the field of structural control in the past. Various control devices like the base-isolator, the tuned mass damper, the friction-damper, the Magneto-rheological (MR) damper etc. have been developed and successfully installed. Out of the different control devices developed, the MR damper is the most widely studied semi active control device because of its low voltage requirement and is fail-safe.

Substantial studies on the development of control schemes for the MR damper and their applications to different structural control problems had been conducted. Some of the popular control schemes which were proposed for the semi-active control using MR damper include the clipped optimal control, the Lyapunov control and the modulated friction control developed by Dyke et al. (1996) and Jansen and Dyke (2000). Xu et al. (2000) put forward two more control schemes for the semi active control of structures fitted with the MR dampers. A quantitative feedback theory for the semi active control using the MR dampers was developed by Zapateiro et al. (2009). [Kori and Jangid (2009)](#_ENREF_7) investigated the effectiveness of input voltage on the MR damper considering various control algorithms under different earthquakes. The control of the pounding effect of a base isolated long span highway bridge using MR dampers was investigated by [Sheikh et al. (2011)](#_ENREF_11). Different control algorithms developed for MR dampers were employed for controlling the responses of piping systems by [Kumar et al. (2012)](#_ENREF_8). A turbo-Lyapunov function-based control scheme for the semi-active control of a nonlinear highway bridge using the MR damper was put forward by Cha and Agarwal (2013). The behaviour of an asymmetric building plan fitted with MR dampers was investigated by [Bharti et al. (2014)](#_ENREF_3). Performances of the clipped-optimal control, decentralized feedback control and passive control were investigated by Cha et al. (2013). The use of MR dampers for coupled buildings for reduction of the response and pounding between the two buildings was investigated by Abdeddaim et al. (2016). A few attempts have also been made to use neural networks for the semi active control with MR dampers. The use of neural network for predicting voltage for the MR damper was presented by [Bahar et al. (2010)](#_ENREF_1). A recurrent neural network model which evaluates the input voltage to be applied across the MR damper was proposed by [Chang and Zhou (2002)](#_ENREF_8). A neuro-controller was used for the reduction of the response of base-isolated structures by Lee et al. (2005). [Das et al. (2012)](#_ENREF_5) presented a semi active scheme combining neural network and fuzzy logic algorithm for the response control of building frames using MR dampers.

Since real life future excitations are better modelled as a stochastic process and in practice, only a few numbers of measurements are possible, hence, partially observed stochastic control using MR dampers were extensively studied in the past. [Ying et al. (2003)](#_ENREF_14) first presented semi active stochastic control of structures using ER/MR dampers. The control strategy was developed considering the system to be a dissipated Hamiltonian system excited under random loading. For convenience, the control forces developed by ER/MR dampers were divided into two parts namely, passive and active. The controlled responses were obtained using the stochastic averaging technique and solving the Ito equations. Following nearly the same technique, a number of structural systems were controlled by using MR dampers by a few researchers ([Dong et al. 2004](#_ENREF_12), [Zhu et al. 2004](#_ENREF_27), [Cheng et al. 2006](#_ENREF_9), [Hu et al. 2016](#_ENREF_14)).

Although considerable studies on the semi-active control of partially observed systems using MR dampers are reported, there is a lack of rigor in the formulations made. The reason is attributed to the use of the Kalman filter for state estimation which requires that both process and measurement noises should be ideally Gaussian white. While the exact nature of measurement noises is unknown, it may be reasonable to assume it as Gaussian white, since many of the measurement noises are broadband processes, if not white. The same assumption is not valid for the seismic excitation, since except for some ideal situations, the seismic excitations are not white. However, the Kalman filter is used for the state estimation for non-white Gaussian seismic excitation for many partially observed control problems found in the literature. Since the Kalman filter requires only the values of covariance of the excitation and the measurement noise, the state estimation remains the same irrespective of the nature of excitation. However, the formulation of the problem lacks theoretical rigor if the excitation is not white. Herein, an alternative formulation of the problem is presented in which the state variables are augmented by two filter variables. A white noise is passed through the filters to obtain the desired type of the seismic excitation to the structure. The system with augmented variables is analyzed for the control problem in which excitation becomes Gaussian white noise. The results derived from the proposed formulation are compared with those of the conventional formulation in which seismic excitation is directly prescribed as input to the structure. For real time implementation, an artificial neural network (ANN) is trained to transform the measured ground motion to white noise which is considered as the input to the control algorithm in the proposed formulation. An example problem of a 10 storey building frame is presented as an illustration of the proposed control strategy. Two standard semi-active control strategies are employed to obtain the controlled responses using the MR dampers. They include i) Linear Quadratic Gaussian (LQG) control with clipped optimal algorithm (LQGCl); and ii) Sliding mode control with clipped optimal algorithm (SMCCl). Modified Bouc-Wen model is used for the generation of the control force in the MR dampers.

**2. Theory**

Equation of motion of the building frame employed with MR dampers is written as

 (1)

where **Ms** is the mass matrix, **Cs** is the damping matrix and **Ks** is the stiffness matrix, **U**is the vector of MR damper force, **G** denotes the damper location matrix; **z** is the floor displacement vector; **r** is an influence coefficient vector; and is the ground acceleration. The state-space form of Equation 1 is written as:

 (2)

 (3)

where, **Aw** is a 2n x 2n matrix based on the dynamic properties of the structure, **Bw** is a 2n x mcontrol force matrix, **Ew** is a 2n x 1 excitation vector, **Cw** is a p x 2n measurement matrix, **Dw** is a p x m zero matrix, **x** is a 2n x 1 state vector, **y** is a p x 1 vector of measured responses and **v** is a p x 1 measurement noise vector; n, m and p are the numbers of floors, MR dampers and measured outputs, respectively.

The state vector in the above formulation (called VB-1) consists of only the structural displacement and velocity. The ground motion is non-white and assumed as Gaussian. Since excitation is non-white, the full state estimation of the measured state using Kalman filter (described later) lacks theoretical rigor. In order to bring in the theoretical rigor, an alternative formulation (VB-2) is presented by augmenting the state vector of the structure by two filter variables. The VB-1 and VB-2 systems are shown in Figure 1. The filter equations are coupled to the equations of motion of the structure in the state space domain. A white noise is passed through the filters to obtain the desired non-white seismic excitation to the structure. The augmented system is analyzed for the control problem in which white noise forms the input excitation. The following set of filter equations is augmented to the set of Equations 1 and 2.

(4)

(5)

where and are the outputs of the first and the second order filters; w is the white noise; ,, and are the filter coefficients. The PSDF of the ground acceleration as obtained from Equations 3 and 4 is given as ([Clough and Penzien,1975](#_ENREF_4)):

**** (6)

where S0 is the ordinate of the PSDF of white noise.

When the Equations 3 and 4 are substituted in Equations 1 and 2, the following state space equations for the structure filter system are obtained.

**** (7)

**** (8)

where ; **A** is a 2(n+2) x 2(n+2) matrix. The elements of **A** matrix are functions of filter coefficients and structure’s characteristics, **B** is a 2(n+2) x mcontrol force coefficient matrix, **E** is a 2(n+2) x 1 excitation coefficient matrix, **C** is a p x 2(n+2) measurement matrix, **D** is a p x m zero matrix, **Ys** is a p x 1 measurement vector and **v** is a p x 1 measurement noise vector. For both the formulations VB-1 and VB-2, the control algorithms are used to obtain the required voltage to be applied to the MR dampers.

a)

*w*

**m1**

**s3**

**s2**

**s1**

**k4**

**m3**

**k1**

**k2**

**k3**

**m2**

**f1**

**k9**

**m4**

**m10**

**k10**

**m9**

**f3**

**f2**

𝜉g, 𝜔g

𝜉s, 𝜔s

xs

**m1**

**s1**

**s2**

**s3**

**k4**

**m3**

**k1**

**k2**

**k3**

**m2**

**f1**

**k9**

**m4**

**m10**

**k10**

**m9**

**f3**

**f2**

b)

Figure **1.** a) VB-1 and b) VB-2 system equipped with three MR dampers and six sensors

***2.1 Linear Quadratic Gaussian Control***

For the partially observed system, at each time step t, using measured output vector **Ys**(t), the controlled full state  is estimated as ([Bhaiya et al. 2016](#_ENREF_2)):

**** (9)

in which **** (10)

For obtaining **P**(t) the following Riccati equation (Equation 10) is solved.

 (11)

where **K**(t) is the Kalman gain, **W** and **V** are the covariance matrices of excitation **w(**t**)** and white gaussian noise **v(**t**)** and T in superscript denotes transpose. The size of **V** and **W** are 2(n + 2) x 2(n + 2) and p x p, respectively.

The LQG is a combination of Linear Quadratic Regulator (LQR) and Kalman filter. The Kalman filter for state estimation is summarized above. Then LQR is used to obtain the desired control force with estimated state vector .The control force **u(t)** is obtained by using the following equation

 (12)

where **L(**t**)** denotes feedback gain matrix and is obtained by solving the following Riccati equation:

**** (13)

 (14)

The sizes of **Q** and **R** matrix are 2(n + 2) x 2(n + 2) and m x m, respectively, and are called constant matrices whose elements are adjusted to provide best results.

***2.2 Sliding mode control***

For the active control of structures, sliding mode control has been extensively used by various researchers ([Yang et al.,1994](#_ENREF_13), [Sarbjeet and Datta,2000](#_ENREF_9), [Sarbjeet and Datta,2003](#_ENREF_10)). The control algorithm consists of two steps: firstly, the sliding surfaces are designed and then the controllers are designed to bring the response trajectory on the sliding surfaces. The external excitation is neglected for the design of sliding surfaces. However, it is considered for the design of controllers. For m numbers of controllers, m numbers of sliding surfaces, S1, S2…Sm are defined as given below

 (15)

where S is a vector consisting of m sliding variables. S is also expressed as a linear combination of estimated state variables as shown in Equation 15.

**** (16)

where **M** is a (m x 2n+2) matrix required to keep the motion on the sliding surface for stability. For the response trajectory to remain on sliding surface, it is required that  ; from Equations 6 and 15, it follows that

**** (17)

Solution of Equation 16 for U gives the equivalent control force **Ueq** on the sliding surface as given below:

**** (18)

The sliding surface can be determined using different methods such as the pole assignment method and the LQR method ([Yang et al.,1994](#_ENREF_13)).

***2.3 Clipped Optimal Control Law***

Clipped optimal law ([Dyke et al. 1996](#_ENREF_6)) is used to obtain the input voltage. If the absolute force in MR damper is greater than the absolute value of desired force, then the voltage is set to minimum. On the other hand, if the force in MR damper is less than the absolute value of the desired force, then the voltage is set to maximum. Mathematically it is given as:

**** (19)

where V is the voltage applied across the MR damper, H is the Heaviside function, Vmax is the maximum value of the voltage, Fd is the desired control force; Fmr is the MR damper force. The desired force Fd is obtained by LQR/sliding mode [Equations 11 and 17] control algorithms.

**3. Neural Network for generating white noise input from the measured ground motion**

For generating white noise input to the filters corresponding to the real ground excitation, a neural network is trained. For the training of neural network, a two layered feed forward neural network is used. The input data and target data for the training of the neural network is the filtered excitation and the corresponding white noise, respectively. The network is trained offline using twenty five sets of both broadband and narrowband filtered excitations and the corresponding white noises. Using gensim command in MATLAB, a neural network function block of the trained neural network is created in SIMULINK of MATLAB. The function block of the neural network is then applied before the state space block in SIMULINK as shown in Figure 2 and real excitation is given as input to the neural network.

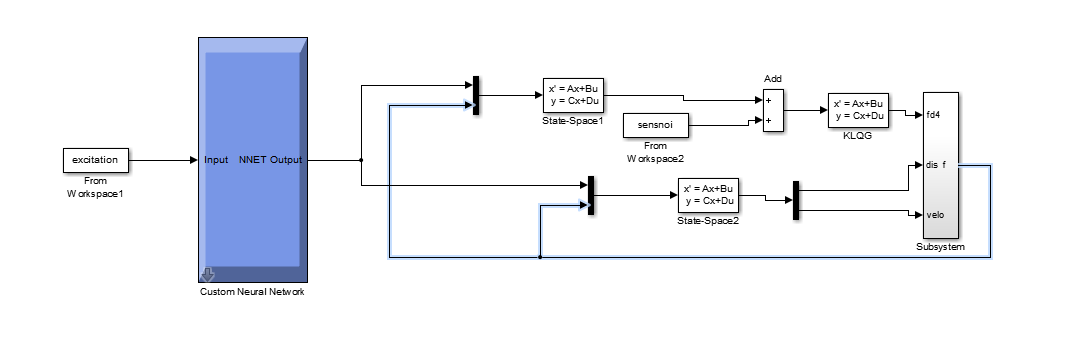


Figure 2**.** Use of ANN for online application of algorithm

**4. Development of MR Damper force**

Force developed by MR damper depends on viscosity of the MR fluid and the piston movement. The viscosity of the MR fluid is varied by changing the input voltage applied across the MR damper and the piston movement is governed by the movement of floors between which the MR damper is placed. In the present study, modified bouc-wen model given by ([Spencer et al.,1997](#_ENREF_12)) is used. As the model is well established, therefore its details are not given here.

**5. Numerical Study**

For the numerical study, a ten story shear building frame is considered. The total mass and stiffness of each floor are taken as 18000 kg and 24965 kN/m. Controlled responses are obtained using VB-1, in which the state vector contains only the structural displacements and velocities, and VB-2, in which the state vector contains filter variables, and the structural displacements and velocities. For the former, the excitation is the simulated ground acceleration from its PSDF, which is shown in Figure 3. For the latter, the excitation is the corresponding white noise, which produces the simulated ground acceleration when passed through the filters. Two types of ground motions are considered, namely, narrow band and broad band excitations. The filter coefficients (Equations 3, 4 and 5) used for generating two types of excitations are shown in Figure 3. The value of S0 in Equation 6 is so adjusted that rms value of the white noise over a frequency band of 30 rad/s is 0.05g. The corresponding PSDFs of both narrow and broad band excitations are shown in Figure 3. Sample time histories of the filtered narrow band and broadband excitations are shown in Figure 4. The corresponding covariance of excitations is 0.2 and 0.58 respectively. Sample time history of the corresponding white noise is shown in Figure 5.

C:\Users\Vishisht Bhaiya\Desktop\doublefiltermodified\Graph1.emf

Figure 3. PSDF plot of broadband (Case 1) and narrowband (Case 2) filtered excitation

C:\Users\Vishisht Bhaiya\Desktop\doublefiltermodified\timehistory.emf

Figure 4. Sample time history of a) broadband and b) narrowband filtered excitation

The control of responses is obtained with three MR dampers placed on the first, second and third floors in a sequence. Since the placement of measurement sensors greatly influences the estimated state of the structure, their locations are decided based on the most accurate estimate of the states of the floors where the MR dampers are placed. As the control forces generated in the MR dampers largely depend on the velocities of the floors where MR dampers are attached, placement of a velocity sensor on each of these floors is the obvious choice. If more than three sensors are used, the extra sensors are placed in locations so as to obtain the best results. In the present example problem, six sensors are used with the three velocity sensors and the three displacement sensors placed at the bottom three floors where the MR dampers are placed.

For VB-1, the covariance matrix of the excitation (**W**) is of size 20 x 20. In the last 10 diagonal terms, the covariance of excitation is inserted. Similarly, the covariance matrix of measurement noise **(V)** is of size 6 x 6 having diagonal terms equal to the covariance of measurement noise. For VB-2, **W** is the covariance matrix of white noise having size of 24 x 24. The last 12 diagonal terms contain the covariance of white noise. **V** matrix remains the same as that of VB-1. The values of matrices are selected based on a separate sensitivity analysis.

C:\Users\Vishisht Bhaiya\Desktop\doublefiltermodified\broadwhi.emf

Figure 5. Sample time history of white noise

**Q** and **R** matrices for the LQR algorithm are of size 20 x 20 and 3 x 3 respectively, for the VB-1 system, and of size 24 x 24 and 3 x 3 respectively, for the VB-2 system. **Q** and **R** matrices are adjusted for each earthquake to obtain the best results. Similarly, the **QS** matrix in the sliding mode control is adjusted for each earthquake to get the best results.

An ensemble of twenty five time histories is used to find the response reductions and associated control force. The results of the analysis are shown in the form of the following control measures:

Percentage reduction**** (20)

Percentage reduction  (21)

(i = 1, 2, 3; 1- top floor displacement; 2- maximum inter story drift; 3- base shear)

in which ] are the expected rms value of the uncontrolled and controlled responses; are the expected uncontrolled and controlled absolute peak responses. Expectations are taken over 25 samples of the ensemble. Note that in Figures 6 and 7, Dd, Dr, and Bs represent the peak top floor displacement, the maximum inter story drift and the peak base shear.

***5.1 Comparison between the percentages of control of responses obtained by VB-1 and VB-2***

Figures 6 and 7 show the comparison between the percentage reductions in expected peak and rms values of the response quantities of interest obtained by VB-1 and VB-2 for broadband and narrowband excitations. It is seen from the figures that the response reductions in general are different for the two schemes and the difference varies with the response quantities of interest. Further, the difference is more pronounced for the narrowband excitation; VB-2 provides more reduction in responses.



Figure 6. Comparison between percentage reductions in expected peak values of different response quantities obtained by VB-1 and VB-2 (broadband excitation) for a) top floor displacement b) maximum inter-story drift and c) base shear



Figure **7.** Comparison between percentage reductions in expected rms values of different response quantities obtained by VB-1 and VB-2 (broadband excitation) for a) top floor displacement b) maximum inter-story drift and c) base shear

Incertain cases, VB-2 gives a much higher response reduction compared to VB-1. Comparison between the response reductions obtained for different response quantities of interest shows that the LQGCl control generally provides more reductions in responses as compared to the SMCCl. The maximum percentage reductions in the drift and the top floor displacements are about 60% and 50%, respectively. The percentage reduction in the peak base shear is always less as compared to the other two response quantities; maximum reduction is of the order of 30%.

The peak control forces developed in the MR damper located in the first floor are compared for the two control schemes in Table 1. It is seen from the table that there is not much difference between the peak control forces required for the two control schemes. The reason for this may be attributed to the limitation of the maximum voltage that can be applied to the MR dampers. Since the maximum voltage remains the same for the two schemes, it limits the control forces generated in the MR damper resulting in nearly the same peak control forces for the two.

Table 1. Peak control forces developed in the MR damper for different control strategies

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Control Algorithm** | **Broadband Excitation**  **(kN)** | | **Narrowband Excitation**  **(kN)** | |
| **VB-1** | **VB-2** | **VB-1** | **VB-2** |
| LQGCl | 107 | 95 | 91 | 93 |
| SMCCl | 104 | 97 | 92 | 92 |

Force-displacement and force-velocity plots of the first story MR damper are shown for some typical cases in Figures 8, 9, 10 and 11. It is seen from the figures that the nature of the plots is different for the two control schemes, VB-1 and VB-2. Further, they are different for different control algorithms.

C:\Users\Vishisht Bhaiya\Desktop\thesis first draft\chapter4graphs\forcedisplcementsclipped\babrfdisp.emf

Figure 8. Force-displacement and force-velocity plots of the MR damper located on the first floor for the LQGCl under broadband white noise (VB-2 system)

C:\Users\Vishisht Bhaiya\Desktop\thesis first draft\chapter4graphs\VB1system\lqg+clipped\babrfdisp.emf

Figure 9. Force-displacement and force-velocity plots of the MR damper located on the first floor for the LQGCl under broadband filtered excitation (VB-1 system)

C:\Users\Vishisht Bhaiya\Desktop\thesis first draft\chapter4graphs\forcedisplcementsliding\babrfdisp.emf

Figure 10. Force-displacement and force-velocity plots of the MR damper located on the first floor for the SMCCl under broadband white noise (VB-2 system)

C:\Users\Vishisht Bhaiya\Desktop\thesis first draft\chapter4graphs\VB1system\sliding\babrfdisp.emf

Figure 11. Force-displacement and force-velocity plots of the MR damper located on the first floor for the SMCCl under broadband filtered excitation (VB-1 system)

**6. Conclusions**

A modified semi active control of partially observed building frames under seismic excitation is presented. The new formulation incorporates more theoretical rigor in the analysis by making the input excitation to be Gaussian white with the help of a double filter incorporated in the structural system. The results of the alternative formulation are compared with the conventional analysis. A ten story building frame is taken as an example problem. Two control algorithms are used for obtaining the time histories of the voltage to be applied to MR dampers. The control of responses for a ten story building frame is realized with the help of three MR dampers placed at the bottom three stories and the states of the system are observed with the help of six sensors. Numerical study leads to the following conclusions:

(1) Response reductions obtained by the proposed alternative formulation (VB-2) differ from those of the conventional formulation (VB-1) showing the need for improving the state estimation with more theoretical rigor; in general, the response reductions are found to be more for the VB-2 as compared toVB-1.

(2) Out of the two control algorithms employed, the SMCCl generally provides better control of responses as compared to the LQGCl; however, the maximum control forces developed in the MR dampers remain nearly the same for all cases.

(3) The force-displacement and the force-velocity plots derived from measurements are of different for different cases even though the peak control force and the peak responses remain nearly the same.

**7. References**

Abdeddaim, M., A. Ounis, N. Djedoui and M. Shrimali (2016). "Pounding hazard mitigation between adjacent planar buildings using coupling strategy." *Journal of Civil Structural Health Monitoring*: 1-15.

Bahar, A., F. Pozo, L. Acho, J. Rodellar and A. Barbat (2010). "Hierarchical semi-active control of base-isolated structures using a new inverse model of magnetorheological dampers." *Computers & Structures* 88(7): 483-496.

Bhaiya, V., S. Bharti, M. Shrimali and T. Datta (2016). "Effect of noises on the active optimal control of partially observed structures for white random ground motion." *Noise Control Engineering Journal* 64(6): 789-799.

Bharti, S., S. Dumne and M. Shrimali (2014). "Earthquake response of asymmetric building with MR damper." *Earthquake Engineering and Engineering Vibration* 13(2): 305-316.

Cha, Y.-J., J. Zhang, A. K. Agrawal, B. Dong, A. Friedman, S. J. Dyke and J. Ricles (2013). "Comparative studies of semiactive control strategies for MR dampers: pure simulation and real-time hybrid tests." *Journal of Structural Engineering* 139(7): 1237-1248.

Cha, Y. J. and A. K. Agrawal (2013). "Velocity based semi‐active turbo‐Lyapunov control algorithms for seismically excited nonlinear smart structures." *Structural Control and Health Monitoring* 20(6): 1043-1056.

Chang, C.-C. and L. Zhou (2002). "Neural network emulation of inverse dynamics for a magnetorheological damper." *Journal of Structural Engineering* 128(2): 231-239.

Cheng, H., W. Zhu and Z. Ying (2006). "Stochastic optimal semi-active control of hysteretic systems by using a magneto-rheological damper." *Smart Materials and Structures* 15(3): 711.

Clough, R. W. and J. Penzien (1975). Dynamics of structures, New York: McGrowHill Inc

Das, D., T. Datta and A. Madan (2012). "Semiactive fuzzy control of the seismic response of building frames with MR dampers." *Earthquake Engineering & Structural Dynamics* 41(1): 99-118.

Dong, L., Z. Ying and W. Zhu (2004). "Stochastic Optimal Semi-Active Control of Nonlinear Systems by Using MR Dampers." *Advances in Structural Engineering* 7(6): 485-494.

Dyke, S., B. Spencer Jr, M. Sain and J. Carlson (1996). "Modeling and control of magnetorheological dampers for seismic response reduction." *Smart Materials and Structures* 5(5): 565.

Hu, R., H. Xiong, W. Jin and W. Zhu (2016). "Stochastic minimax semi-active control for MDOF nonlinear uncertain systems under combined harmonic and wide-band noise excitations using MR dampers." *International Journal of Non-Linear Mechanics* 83: 26-38.

Jansen, L. M. and S. J. Dyke (2000). "Semiactive control strategies for MR dampers: comparative study." *Journal of Engineering Mechanics* 126(8): 795-803.

Kori, J. G. and R. Jangid (2009). "Semi-active MR dampers for seismic control of structures." *Bulletin of the New Zealand Society for Earthquake Engineering* 42(3): 157.

Kumar, P., R. Jangid and G. Reddy (2012). "Response of piping system with semi-active magnetorheological damper under tri-directional seismic excitation." *International Journal of Applied Science and Engineering* 10 (2): 99-111.

Lee, H. J., Yang, G., Jung, H. J., Spencer, B. F., & Lee, I. W. (2006). Semi‐active neurocontrol of a base‐isolated benchmark structure. *Structural Control and Health Monitoring: The Official Journal of the International Association for Structural Control and Monitoring and of the European Association for the Control of Structures*, *13*(2‐3), 682-692.

Sarbjeet, S. and T. Datta (2000). "Nonlinear sliding mode control of seismic response of building frames." *Journal of Engineering Mechanics* 126(4): 340-347.

Sarbjeet, S. and T. Datta (2003). "Sliding mode control of building frames under random ground motion." *Journal of Earthquake Engineering* 7(01): 73-95.

Sheikh, M. N., J. Xiong and W. Li (2011). "MR damper in reducing pounding effect of base-isolated rc highway bridge."

Spencer, B., S. Dyke, M. Sain and J. Carlson (1997). "Phenomenological model for magnetorheological dampers." *Journal of Engineering Mechanics* 123(3): 230-238.

Xu, Y., W. Qu and J. Ko (2000). "Seismic response control of frame structures using magnetorheological/electrorheological dampers." *Earthquake Engineering & Structural Dynamics* 29(5): 557-575.

Yang, J. N., J. Wu, A. Agrawal and Z. Li (1994). Sliding mode control for seismic-excited linear and nonlinear civil engineering structures. Technical Report NCEER, *US National Center for Earthquake Engineering Research.* 94.

Ying, Z., W. Zhu and T. Soong (2003). "A stochastic optimal semi-active control strategy for ER/MR dampers." *Journal of Sound and Vibration* 259(1): 45-62.

Zapateiro, M., H. R. Karimi, N. Luo and B. F. Spencer Jr (2009). "Frequency domain control based on quantitative feedback theory for vibration suppression in structures equipped with magnetorheological dampers." *Smart Materials and Structures* 18(9): 095041.

Zhu, W., M. Luo and L. Dong (2004). "Semi-active control of wind excited building structures using MR/ER dampers." *Probabilistic Engineering Mechanics* 19(3): 279-285

1. Research Associate, National Centre for Disaster Mitigation and Management (NCDMM), Malaviya National Institute of Technology (MNIT) Jaipur, India, Email: vishishtbhaiya@gmail.com [↑](#footnote-ref-1)
2. Professor, NCDMM, MNIT, Jaipur, India, Email: sdbharti@mnit.ac.in [↑](#footnote-ref-2)
3. Professor, NCDMM, MNIT, Jaipur, India Email: shrimlaimk@gmail.com [↑](#footnote-ref-3)
4. Formerly Emeritus Professor, IIT Delhi, Now, Adjunct Faculty, NCDMM, MNIT, Jaipur, India, Email: tushar\_k\_datta@yahoo.com [↑](#footnote-ref-4)