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# Velocity Tracking Control Algorithm for Semiactive Control of Building Frames

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**Abstract**

A new control algorithm called velocity tracking control (VTC) is presented for the semi-active control of partially observed building frames using magneto-rheological (MR) dampers. The novelty of the control algorithm relies on the use of special features of the semi active control using MR dampers in which the time history of voltage to be applied to the MR damper can be generated with the help of feedback information from the observed states only; it does not require the estimation of the full state from the measured ones which introduces some errors in the estimated control force generated in the MR damper. The algorithm is developed based on a physical reasoning, which is validated by the Lyapunov stability condition of the first order filter used in the modified Bouc-wen model that models the MR damper. The efficiency of the control algorithm is compared with the passive on control for a number of earthquakes. The response quantities of interest, for which percentage reductions in responses are compared, include the peak top floor displacement, peak inter-story drift and maximum base shear. The results of the study show that the proposed control algorithm provides the maximum percentage reduction in peak inter-story drift in comparison to passive on control. Further, the efficiency of the proposed control algorithm, defined by the percentage reduction of responses per unit control force, is found to be more as compared to the passive on control

*Keywords*: Seismic performance, responses, Semiactive control,MR Damper, Passive on, Modified Bouc wen, Velocity Tracking Control

## 1. Introduction

Safety of buildings from disasters such as earthquake, cyclone, blast, or the tsunami is the key concern in earthquake engineering. There are some restrictions in present structural construction practices, such as imprevisible dynamic loading and incompatible loading conditions. It has led the researchers to develop new structural control methods, which are commonly divided into four types: passive, active, semi-active and hybrid control methods. Semi-active control methods are better than other control methods as the control force generated by semi active control can be of the same order as that generated by active control with rather less power input and at the moment of power failure, it starts behaving as passive device.

Magnetorheological (MR) damper because of its features such as work on battery power, simple to mount and is fail-safe, it is one of the most studied semi-active control devices. In the past, researchers have performed numerous studies on semi-active control using the MR damper. These studies are classified as i) developing control algorithms and assessing their relative efficiency; ii) semi-active control effectiveness using MR dampers in different types of structures[1-6]; and iii) developing hybrid control strategies using MR dampers[7-10]

Some of the earlier works on the development of control algorithms for the MR dampers were carried out by Dyke et al. [11]andJansen and Dyke [12]. They proposed some of the well-established algorithms like Bang-bang control, Clipped optimal control, Lyapunov control and Modulated homogenous friction control algorithms. Xu et al. [13] proposed an optimal displacement control strategy for semi active control using MR dampers. It was shown that with the use of optimum control parameters significant reduction in seismic responses could be achieved. Zapateiro et al. [14] used quantitative feedback theory to reduce the seismic response of a three storey building using real time test hybrid set up. Chang and Zhou [15] using recurrent neural network developed an inverse model that estimate the voltage to be inputted to the damper for generation of desirable control force. Lee et al. [16] proposed a neuro controller whose training algorithm was depended on a cost function and sensitivity evaluation algorithm to calculate the ideal control force. Sarrafan et al. [17]proposed a control system in which a feedback neural network is used to model non-linear system, and fuzzy logic is used to estimate the control force generated by the MR damper. Das et al. [18] developed a fuzzy logic control algorithm by characterizing the MR damper hysteresis loop with the fuzzy logic rules using the fuzzy toolbox of MATLAB. Cha and Agrawal [19] presented a turbo-Lyapunov control algorithm using traditional Lyapunov control algorithm and a turbo function for semi active control using MR damper. The performance of proposed algorithm was investigated and compared with the well-established algorithms. Mohajer Rahbari et al. [20]

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proposed a direct semi-active controller to command the input voltage applied across the MR damper. Hazaveh et al. [21] modified the classical linear quadratic regulator (LQR) and clipped optimal semi active control strategy using the discrete wavelet transform. Cha et al. [22] evaluated the effectiveness of different control algorithms for the semi active control using MR dampers on a three storey steel moment resisting frame. Li and Liang [23] controlled third generation non linear benchmark structure using MR dampers. Fuzzy rules were employed for controlling the voltage to be applied across the MR damper. Bhaiya et al. [24] developed a modified semi active control scheme for site specific earthquakes using MR dampers.

Different researchers have used various methods of optimization [25-28] over the last couple of years such as genetic algorithm, particle swarm and cuckoo search to find the optimal positioning of MR dampers and sensors for partially observed building frames Most of the above control strategies require the knowledge of the complete state from the observed ones for developing the semi active control algorithm. Because the estimation of the full state from the measurements is inherently associated with some errors, the estimated full state is not the same as the actual state of the system. Hence, the predicted control force in the feedback control algorithms is always associated with some error.Accordingly, the control of response quantities varies. This source of error can be eliminated if the observed states can be directly used for predicting the control force i.e. eliminating the need of estimation of the full state.

Herein, a recently proposed semi active control algorithm, called the velocity tracking control algorithm (VTC) [29] is developed for partially observed building frames in which only the observed states is used in a closed loop to generate the control force in MR dampers. The control algorithm generates the control force in the MR damper directly without using a desired control force as a reference (like clipped optimal control). The algorithm is based on tracking the velocities of the floors where MR dampers are placed and utilize them to decide the voltage to be applied during a time increment. The algorithm satisfies the Lyapunov condition of stability of the first order filter that relates the voltage to the parameters influencing the properties of the MR damper in the Modified Bouc Wen model. The novelty of the proposed algorithm is that it exploits the special features of the control using the MR dampers in two respects. Firstly, for the MR damper control, only the states (mainly the velocities) of the floors where MR dampers are placed are required in a closed loop to generate the control force in the MR damper. No information about the states of the other floors are required. Secondly, the control algorithm for determining the time history of the maximum-minimum (max-min) voltage to generate MR damper forces is developed by considering the stability of the first order filter equation in the Modified Bouc Wen model which governs the stability of the closed loop control. In order to demonstrate the efficiency of the new control algorithm, the responses of a ten story building frame are controlled under a set of earthquakes, using a limited number of MR dampers and measurement sensors. The results of the developed algorithm are compared with those obtained through Passive-on control in order to show its relative efficiency.

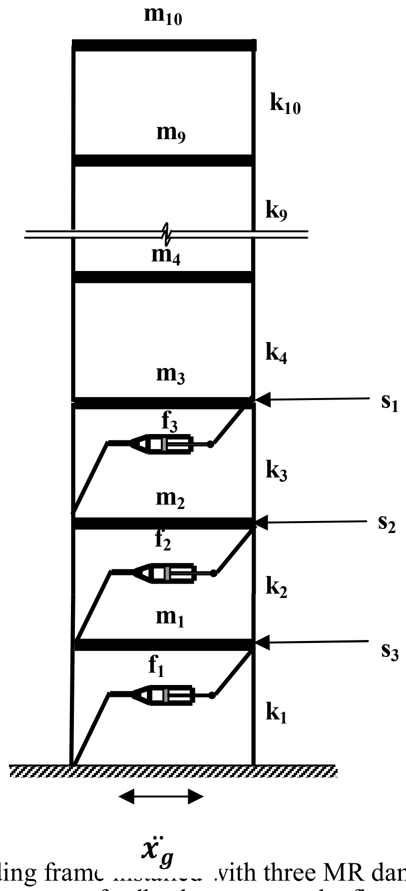


Figure 1-Building frame [illegible] with three MR dampers and three displacement feedback sensors at the first three floors

**2. Integrated MR damper-Structure system**

Consider a multi degree of freedom (MDOF) system as shown in Figure 1. The equations of motion are assembled as:

$$\mathbf{[M][\ddot{x}]+[C][\dot{x}]+[K][x]=[G][u]-[M][r]}[\ddot{u}_g] \quad (1)$$

where,**M**, **K** and **C** are the assembled mass, stiffness, and damping matrices for the multi degree of freedom system.

The governing equation (Eq. 1) is expressed in the state-space form as:

$$\mathbf{[\dot{z}]=[A][z]+[B][u]+[E]}[\ddot{u}_g] \quad (2)$$

$$\mathbf{[y]=[C][z]+[D][u]+[v]} \quad (3)$$

$$\mathbf{A}=\begin{bmatrix}\mathbf{O} & \mathbf{I}\\ \mathbf{-M^{-1}K} & \mathbf{-M^{-1}C}\end{bmatrix};\ \mathbf{B}=\begin{bmatrix}\mathbf{O}\\ \mathbf{-M^{-1}G}\end{bmatrix};\ \mathbf{E}=\begin{bmatrix}\mathbf{O}\\ \mathbf{r}\end{bmatrix};$$

$$\mathbf{z}=\begin{bmatrix}\mathbf{x}\\ \mathbf{\dot{x}}\end{bmatrix}$$

where, **I** and **O** are the identity and null matrices. **y** is the measured outputs, **C** is the measurement matrix which is decided on the basis of sensor location, **D** is the control matrix. The matrix **A**, **B**, **E**, **C** and **D** should be such that the both observability and controllability condition are satisfied.

## 3. VTC algorithm

Bhaiya et. al. [29]proposed a new control algorithm called velocity tracking control algorithm. The control algorithm initially was developed for fully observed building frames and applied for semi active tuned mass damper. Here, the performance of the control algorithm is evaluated for the partially observed building frames. The control algorithm makes use of the fact that the force generated in MR damper depends upon the movement of piston and viscosity of MR fluid which is governed by the voltage applied across the MR damper. Voltage is decided based on a control algorithm and the movement of the piston is governed by the structure's response to earthquake shaking. In the proposed control algorithm, the required voltage in the MR damper and hence, the force generated in it is decided based on the observed states of the floors where MR dampers are placed. Therefore, observations are made only at the floors where MR dampers are situated. For predicting the control force developed by the MR damper, the Modified Bouc Wen model [30] is used. Details of the model are omitted as it is well established in the literature.

The control algorithm takes the advantage of special feature of MR damper i.e., for control force estimation, information of displacements and velocities of floors where MR dampers are placed is only required. Hence, both velocity and displacement sensors are needed to be placed at only those floors where MR dampers are placed. In the control algorithm, input voltage for the MR damper located at $q^{th}$ floor for the next time step i.e., $j+1^{th}$ time step is decided on the basis of feedback information available at $j^{th}$ time step. It is known that as the input voltage across MR damper is increased, magnitude of MR damper force increases but the direction of force remains the same. Keeping in view, the logic of the control algorithm is developed. When the direction of damper force and velocity of $q^{th}$ floor i.e., $\dot{x}^q$ is same, a minimum voltage is applied and when their direction is opposite maximum voltage is applied. These voltages act over the time interval $\Delta t$ i.e. between $t_{j+1}$ and $t_j$. The above stated conditions are expressed mathematically as

$$\dot{x}_j^q u_j^q < 0,\ V_{j+1} = V_{max}(t_j < t \le t_{j+1}) \tag{4}$$

$$\dot{x}_j^q u_j^q > 0,\ V_{j+1} = V_{min}(t_j < t \le t_{j+1}) \tag{5}$$

It can be proved that the conditions represented by Eqs. (4-5), is synonymous to the Lyapunov stability conditions of the first order filter equation of the Modified Bouc Wen model which relates the voltage to the parameter $U_0$ influencing the properties of MR fluid. The filter equation is given as [30]:

$$\dot{U}_0 = \eta(U_0 - V) \tag{6}$$

where $U_0$ is the output of the first order filter; $\eta$ is the shape parameter and V is the voltage applied to the MR damper.

For the proof, it is necessary to show that for positive values of V, $U_0$ is always positive. This can be shown by solving Eq. 6.

$$\frac{dU_0}{dt} - \eta U_0 = -\eta V \tag{7}$$

Integration of Eq. 7 gives,

$$U_0(t) = e^{\eta(t-t_0)}U_0(t_0) + e^{\eta t}\int_{t_o}^{t}(-\eta V)(e^{-\eta\tau})d\tau \tag{8}$$

Integration of the second part of the above equation provides

$$e^{\eta t}\int_{t_o}^{t}(-\eta V)(e^{-\eta\tau})d\tau = e^{\eta t}\frac{-\eta V}{-\eta}\left\{e^{-\eta\tau}\right\}_{t_0}^{t} = e^{\eta t}Ve^{-\eta(t-t_0)}$$

Using Eq. 9, incremental form of the Eq. 7 can be written as

$$U_0(t) = e^{\eta\Delta t}U_0(t_0) + e^{\eta t}Ve^{-\eta(t-t_0)} = e^{\eta\Delta t}U_0(t_0) + Ve^{\eta t_0}$$

in which $\Delta t$ is the time increment between the previous time $t_0$ and the current time t. For positive values of $\eta$, Eq. 10 shows that $U_0(t)$ will be always positive, if V and the initial value of $U_0(t=0)$ are positive. Thus, $U_0$ is always positive since the applied voltage is always positive (battery only provides DC current) and $U_0(t=0)$ can always be set greater than zero as specified initial condition.

For $U_0 > 0$, the Lyapunov function for the first order filter (Eq. 7) is formulated as

$$L = \frac{1}{2}U_O^2 \tag{11}$$

and derivative of the Lyapunov function is given as:

$$\dot{L} = U_0\dot{U}_0 \tag{12}$$

Substituting $\dot{U}_0$ from Eq. 7 in Eq. 12 and establishing the Lyapunov condition of stability as $\dot{L}$ to be negative,

$$U_0(U_0 - V) < 0 \tag{13}$$

Since, both $U_0$ and V are positive, the Lyapunov condition is satisfied for $U_0<V$.

Thus, V can be set to $V_{max}$ for the period for which the above condition (i.e. stability condition) remains valid, thereby maximizing the control force. Since V is set to $V_{max}$ in Eq. 4, the condition given by Eq. 4 is synonymous to the stability condition of the first order filter arising out of Eq. 13. When the Lyapunov stability condition is not satisfied, i.e., $U_o>V$, V is set to zero providing the minimum control force in order to avoid the instability of the controlled system. This condition is synonymous to Eq. 5.

## 4. Numerical Study

In the numerical study, the problem adopted by Bhaiya et. al. [25]is taken. Three MR dampers are positioned at the bottommost three stories. Since the requirement of VTC algorithm is that the velocity and displacement sensors should be placed at location of MR dampers, therefore, three displacement and velocity sensors are positioned at the first, second and third floor. For full observation, it is assumed that displacements and velocities of all floors are measured and used for the estimation of control force. Two near field and two far field earthquakes, namely, El Centro (3.1276 m/s$^2$), Victoria (0.6611 m/s$^2$), Kobe (4.9320 m/s$^2$), and Spitak (1.9521 m/s$^2$), respectively are used for the numerical study. Note that in the brackets peak ground acceleration (PGA) is given for different earthquakes. Note that in figures and tables, $D_D$, $D_r$ and $B_s$ represents the top floor displacement, maximum inter-story drift and maximum base shear, respectively.

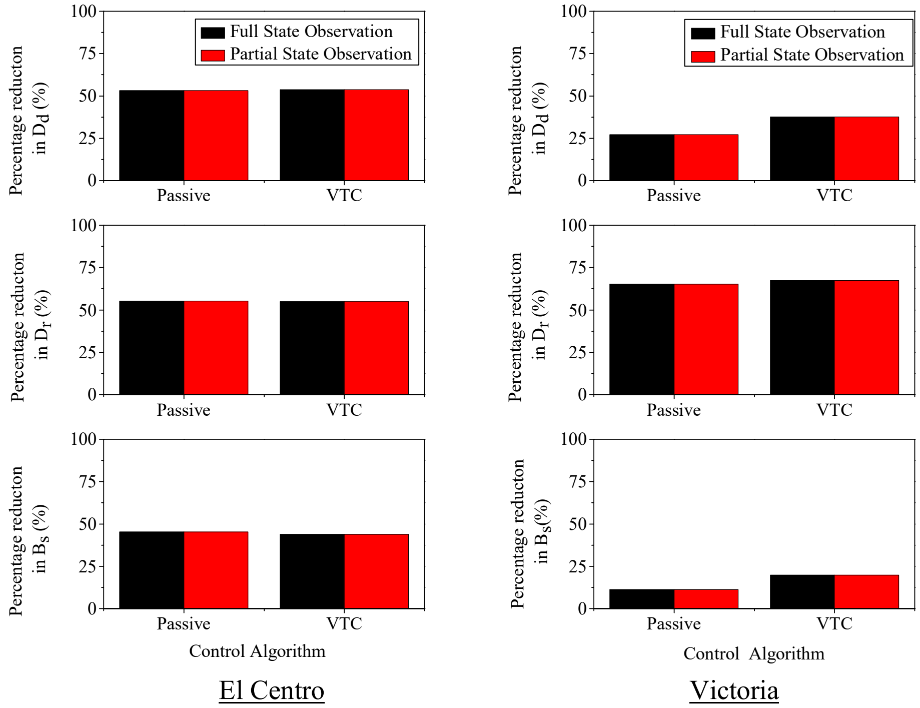


Figure 2-Comparison of percentage reduction in different response quantities for full state and partial state observations for El Centro (1940) and Victoria (1980) earthquake

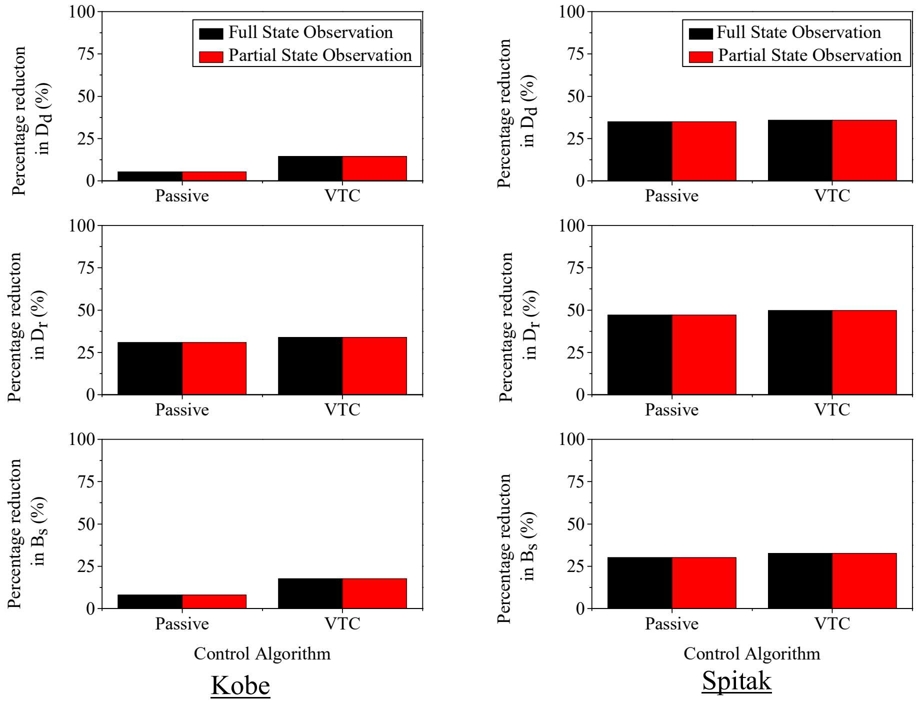


Figure 3-Comparison of percentage reduction in different response quantities for full state and partial state observations for Kobe (1988) and Spitak (1995) earthquake

Table 1- Values of R for different response quantities

| | | El Centro | Victoria | Kobe | Spitak |
|---|---|---|---|---|---|
| Passive | $D_d$ | 7.42 | 6.79 | 0.72 | 4.77 |
| | $D_r$ | 7.71 | 16.33 | 4.08 | 6.42 |
| | $B_s$ | 6.13 | 2.80 | 1.22 | 4.11 |
| VTC | $D_d$ | 8.54 | 10.60 | 1.65 | 6.20 |
| | $D_r$ | 8.73 | 18.94 | 5.08 | 8.61 |
| | $B_s$ | 6.98 | 5.55 | 2.55 | 5.66 |

### 4.1 Comparison of control of responses obtained by the full and partial observed states

Figure 2 shows a comparison of maximum percentage reduction obtained in top floor displacement, maximum inter-story drift and base shear using El Centro (1940) and Victoria(1980) earthquake for the two observation strategies considered in the study. Similarly, Figure 4 shows a comparison for Kobe (1988) and Spitak (1995) earthquakeFor the passive-on and the VTC control algorithms, the response reductions remain the same for the full state and the partial state observations, since these algorithms generate the control force in MR damper using the measured states of the floors, where MR dampers are positioned.

### 4.2 Evaluation of the efficiency of the VTC algorithm

The percentage control of the response quantities of interest per unit control force denoted by the factor R is obtainedis defined as

$$R = \frac{P_r}{F_n} \tag{14}$$

where $P_r$ is the percentage reduction in response quantity and $F_n$is the normalized peak control force expressed as a percentage of the total weight of the frame.

The greater the value of R more is the efficiency of the control algorithm. Table 1 shows the values of R for different response quantities obtained by different algorithms for different earthquakes. It is seen from the table that values of R are consistently higher for all response quantities of interest for the VTC algorithm for all earthquakes considered in the study.

## 5. Conclusions

The performance of semi-active control strategy (VTC) for partially observed building frames using MR dampers subjected to real earthquake records is evaluated. The algorithm differs from other conventional semi active control algorithms used for controlling structures with MR dampers in two aspects, namely, (i) it does not require the estimation of the complete state from the observed states and (ii) no reference control force is required to clip the voltage for applying across MR dampers. The controlled responses are compared with those obtained using Passive on control.. Three response quantities of interest are considered in the study, namely, top floor displacement, maximum drift and base shear. Interpretations of the analysis of the simulations performed lead to the following conclusions:

1. In VTC algorithm, there is no need to assess the complete state for the prediction of control voltage and hence, it is a direct algorithm as no reference control force is required to predict the control voltage.
2. For the VTC control algorithms, prediction of the controlled responses is more reliable as the errors involved in the state estimation are less as compare to the other standard algorithms.
3. Response reduction per unit control force denoted by the factor R is consistently higher for VTC algorithm for all earthquakes; from this consideration, the VTC algorithm is anefficient algorithmas compared to Passive on control.

## Disclosures

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