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SEMI ACTIVE ROBUST VIBRATION CONTROL OF STRUCTURAL SYSTEM WITH MR DAMPER

***Huseyin AGGUMUS**
Yildiz Technical University
Istanbul,Turkey

A. Oguzhan AHAN
Yildiz Technical University
Istanbul,Turkey

Saban CETIN
Yildiz Technical University
Istanbul,Turkey

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* Huseyin AGGUMUS*: phone: 02123832846*
haggumus@yildiz.edu.tr

ABSTRACT

This study investigates the vibration mitigation of the structures under the earthquake excitation using magneto-rheological (MR) damper. In this purpose, an MR damper is installed to the eight floors structure applying different location combination and the system performance is investigated. MR damper is a semi active device which its damping force changes with applied voltage to its magnetic coils. Therefore, a robust controller is designed to determine MR damper voltage. The performance of the proposed method is tested by numerical simulation on an eight floors structural system with MR damper.

INTRODUCTION

The control of structural vibrations equipped with semi-active devices is an important subject that can be studied both experimentally and theoretically. (Atabay and Ozkol (2013); Cetin et al. (2011); Cornejo and Alvarez-Icaza (2011); Paksoy et al. (2014); Cetin et al. (2011)).Three types of the systems have been developed and successfully studied in the literature. These systems can be classified as passive, active and semi-active systems. Active and semi-active systems can be controlled electronically. Passive systems are simple and classical systems that are currently used. Semi active systems have reliability of passive systems and have requirement of lower energy source than active systems.

A number of studies are conducted regarding the control of the MR damper and the arrangement of multiple MR dampers. Dyke et al. (1998) employed MR dampers on the first floor of a three-story structure. Dyke et al. (1996) applied a clipped optimal control algorithm, which was previously tested via simulations (Dyke et al. 1998), by connecting the MR damper to the test model between the ground floor and first floor. Jansen and Dyke (2000) implemented MR dampers in a building model with six DOF; the MR damper was laid out on the first two floors in a parallel configuration. Aldemir (2009) developed a causal sub-optimal control, placing an MR damper on the first floor of the base-isolated structure with 2 DOF. The results were compared with instantaneous optimally controlled and uncontrolled situations, and the presented control algorithm was shown to be effective in reducing the effects of earthquakes on the structure. Bitaraf et al. (2010) used two MR dampers, which were placed on the first and second floors of the structure, and applied two control methods which are direct adaptive control based on a simple adaptation technique and a genetic-based fuzzy control. Cetin et al. (2011) used a six-story steel structural model, and an MR damper was implemented on the first floor. A nonlinear adaptive controller based on the Lyapunov technique, which can balance parametric uncertainties, was used to command the MR damper voltage.

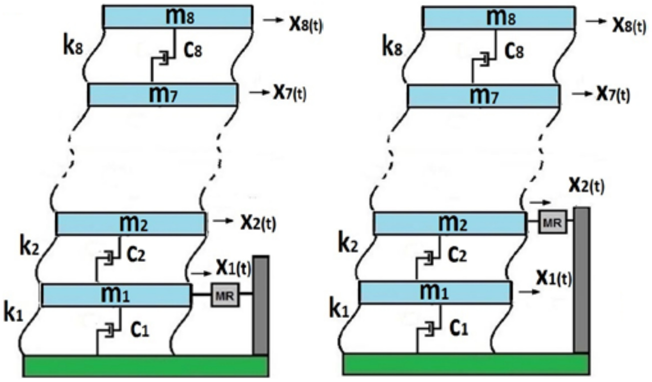
This study reports the control and arrangement of an magneto-rheological (MR) damper that is used to reduce structural vibrations for eigth-story steel structure. H_∞ controller is used for robust control design and application. Two arrangements of MR damper are investigated in this study. One of them is connection of MR damper between first floor and ground and the other one is connection between the second floor and ground. The simulation results show the effectiveness of both arrangements and designed controller.

The Problem Formulation of the Building Model

In this study, two different layouts of MR damper in an eight-story steel structure are investigated, as shown in Figure 1(a-b). The mathematical representation of the building model depicted in Figure 1 can be given as follows,

$$M_s\ddot{x}(t)+C_s\dot{x}(t)+K_s x(t)=-Hf(t)-M_sL\ddot{x}_g(t) \tag{1}$$

where *f(t)* is the damping force of the MR damper and M_s, C_s, and K_s $\in \Re^{8x8}$ are the mass, damping and stiffness matrices, respectively. $\ddot{x}(t),\ \dot{x}(t)\ and\ x(t)$ $\in \Re^{8x1}$ are the acceleration, velocity and displacement vectors, respectively.



a) b)

Figure 1. a) The MR damper is located between the first floor and the ground (MR1). **b)** The MR damper is located between the second floor and the ground (MR2).

Unidirectional horizontal movement is considered in this model. The relative displacement vector for the model is $x=\begin{bmatrix}x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8\end{bmatrix}^T$.The H vector indicates the placement of the control units. If the MR damper is placed between the first floor and the ground, H vector is defined $H_{MR1}=\begin{bmatrix}1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}^T$.H vector will be $H_{MR2}=\begin{bmatrix}0 & 1 & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}^T$ when the MR damper is placed between the second floors and the ground. The seismic input vector is $L=\begin{bmatrix}1 & 1 & 1 & 1 & 1 & 1 & 1 & 1\end{bmatrix}^T$. $\ddot{x}_g(t)$ is the earthquake ground acceleration.

Robust Controller Design

Considering the structural system modeled in the previous section, the full-order model of the system in physical coordinates can be written in the state space model as follows:

$$\dot{x}_f=A_fx_f+B_fu,\ \ y_r=C_fx_f \tag{2}$$

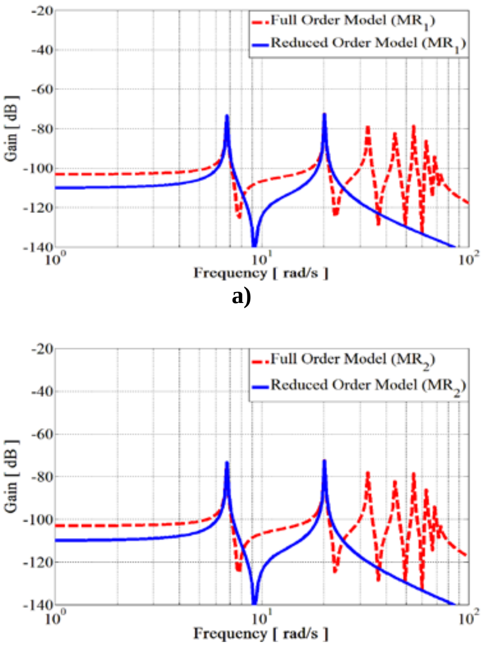
where A_f, B_f, C_f and D_f, are the linear system matrices and given respectively, by

$$A_f=\begin{bmatrix}0 & I\\ -M_f^{-1}K_f & -M_f^{-1}C_f\end{bmatrix},\ \ B_f=\begin{bmatrix}0\\ M_f^{-1}F_f\end{bmatrix},\ \ C_f=[C_y \quad 0],$$
$$P_f(s)=\begin{bmatrix}A_f & B_f\\ C_f & 0\end{bmatrix} \tag{3}$$

For the model order reduction, the system must be transformed from the physical space to the modal space. The equation in modal coordinates can be written for full order and reduced order models as

$$\ddot{\eta}+C_f\dot{\eta}+K_f\eta=H_f\,f\ ,\ \ \ddot{\eta}_r+C_r\dot{\eta}_r+K_r\eta_r=H_r\,f\ . \tag{4}$$

The reduced order models and full order models are illustrated in Figure 2 (a and b).



a)

b)

Figure 2. Full order model and reduced order model: **a)** MR1, **b)** MR2

When structural control is considered, controlling the first two modes provide good results for the earthquake hazard mitigation of structural systems and reduce the amplitudes. Differences between real systems and dynamic models are modeled as $\Delta_t(s)=P_f(s)-P_r(s)$. The two primary transfer functions in this control system are *S(s)* is defined as the sensitivity transfer function, and *T(s)* is the complementary sensitivity transfer function. When *T(s)* and $\Delta_t(s)$ are considered stable, using a W_T filter and provided that the upper limit of $\Delta_t(s)$ satisfies

$$\left|\Delta_t(j\omega)\right|\le\left|W_T(j\omega)\right| \tag{5}$$

a norm W_T condition from ω to z_2, the feedback system can be stable

$$\|W_T T(s)\|_\infty < 1 \tag{6}$$

The second aim of the H∞ controller is to improve the performance of the feedback control system. The H∞ norm condition can be written as

$$\|S(s)\|_\infty = \sup \bar{\sigma}[S(s)] \tag{7}$$

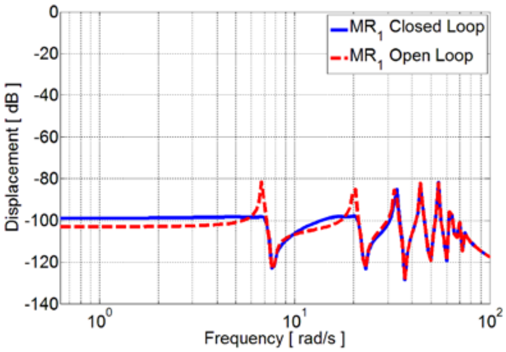
where W_S is the filter for the system output. Thus, specifying the $W_T(\mathrm{s})$ and $W_S(\mathrm{s})$ filters in the control system satisfies both robust stability and response performance. This type of H∞ controller is called a mixed sensitivity problem and is defined as

$$\left\| \begin{bmatrix} W_S S \\ W_T T \end{bmatrix} \right\|_\infty < \gamma \tag{8}$$

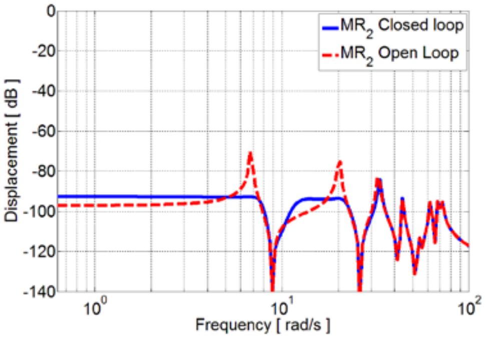
where γ is a design parameter that is positive. An important step in H∞ control is to determine the frequency shape filters. Additive uncertainty is used to select W_T. A filter should cover the uncertainty to provide robust stability. In this manner, frequency shape filters take the following form:

$$W_T = k_w \left(\frac{s^2 + 2\xi_{nm}\omega_{nm}s + \omega_{nm}{}^2}{s^2 + 2\xi_{dm}\omega_{dm}s + \omega_{dm}{}^2} \right) \tag{9}$$

where ω_{nm} is the frequency of the last controlled mode and ω_{dm} is the frequency of the first uncontrolled mode. For MR$_1$ and MR$_2$ The open- and closed-loop responses of the full order models are shown in Figure 3 (a-b)



a)



b)

Figure 3. Open- and closed-loop responses of system. **a)** MR$_1$ **b)** MR$_2$

Controller Application in Semi-Active System

The voltage of the MR damper is selected as follows (El-Kafafy and El-Demerdash, 2012; Lam and Lio, 2002):

$$\begin{gathered} \text{If} \quad G(f_c - f_d)\operatorname{sgn}(f_d) > V_{\max},\ v = V_{\max} \quad \text{or} \\ G(f_c - f_d)\operatorname{sgn}(f_d) < V_{\min},\ v = V_{\min} \quad \text{otherwise,} \\ v = G(f_c - f_d)\operatorname{sgn}(f_d) \end{gathered} \tag{10}$$

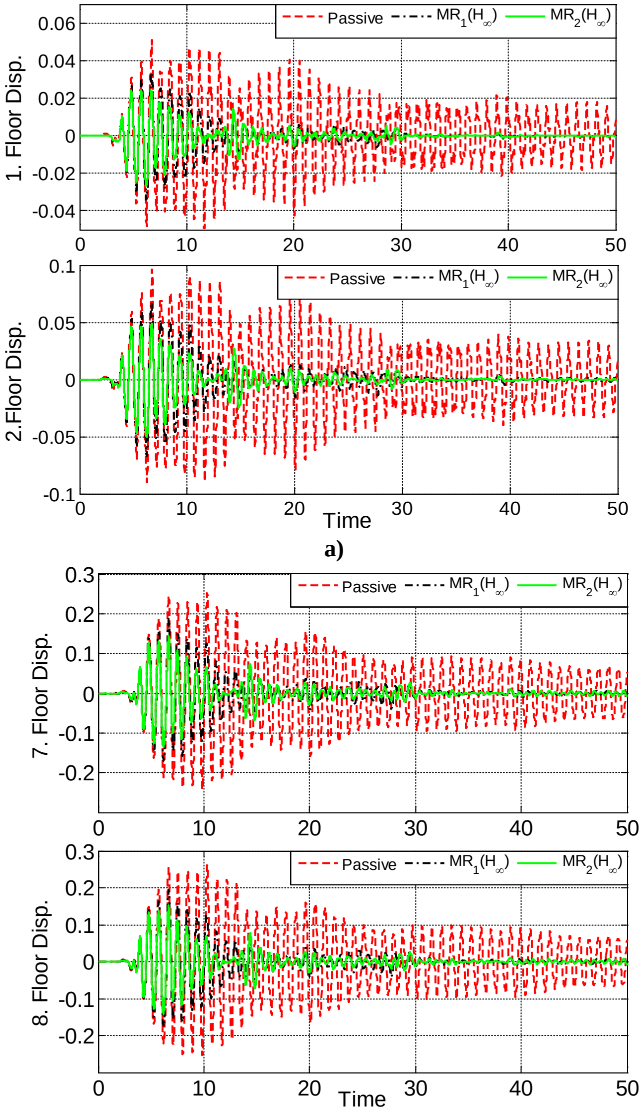
where $V_{\max}$ is the maximum voltage in the MR damper, $V_{\min}$ is the minimum voltage in the MR damper, f_c is the force necessary for the system and is determined by the controller, and f_d is the force formed by the MR damper and is measured by the system. Finally, G is the MR damper control gain.

RESULTS AND DISCUSSION

The mass value of system for each floor is 107.5, and the mass matrix is $M_f = diag[107.5]_{8x8}$. Considering the connection with 8 bars made of spring steel, the stiffness of the system for each floor is evaluated as $k_{1\text{-}8} = 8*12EI/l^3 = 145152N/m$ (Cetin *et al.*, 2011). According to the Rayleigh damping principle, if $\alpha_0 = 0.0265$ and $\beta_0 = 0.00011431$, $[C_s] = \alpha_0[M_s] + \beta_0[K_s]$, the damping coefficient is $C_{1,2,3,4,5,6,7,8} = 16.59N.s/m$, and the controller gain G = 0.04. The maximum voltage $V_{\max}$ is 2 V, and the minimum voltage $V_{\min}$ is 0 V.

The time responses for the situation of the MR damper's layouts MR$_1$ and MR$_2$ are shown in Figure 4 and Figure 5. The passive case, the case in which the MR damper is on the first floor (MR$_1$) and on the second floors (MR$_2$) are examined. Also, the passive (MR damper disconnected) and H∞ controlled situations of MR$_1$ and MR$_2$ are compared to determine the performance of the controller. The displacement responses of

(1-2) floors and (7-8) floors are shown in Figure 4. The connection of the MR damper for MR_1 and MR_2 reduces the vibration of each floor. The amplitudes of the displacement in situation corresponding to the MR with the controller are lower than the displacement amplitude in the situation corresponding to the passive system (without the MR damper). In addition, the MR damper connected between the second floor and the ground is more effective than the damper connected between the first floor and the ground.

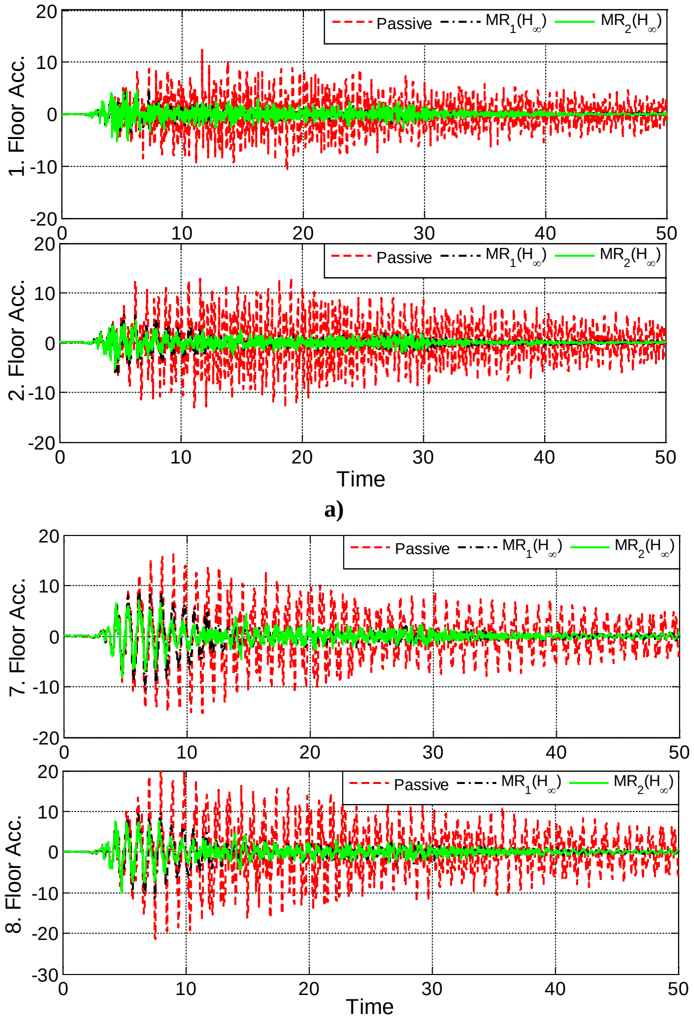


a)

b)

Figure 4. Displacements responses of floors for the combinations of the MR damper layout: MR_2 and MR_1. **a)**1.floor and 2.floor, **b)**7. floor and 8.floor.

The acceleration responses of each floor for the MR damper layout is shown in Figure 5. The connection of the MR damper and the application of the robust controller improve the acceleration responses of each floor. In the same way, the MR damper connected between the second floor and the ground is more effective than the damper connected between the first floor and the ground.



a)

b)

Figure 5. Accelerations responses of floors for the combination of the MR damper layout: MR_2 and MR_1. **a)**1.floor and 2.floor, **b)** 7. floor and 8.floor.

CONCLUSION

In this study, an H_∞ robust controller is designed to command MR damper voltage, by placing an MR damper on first floor and on second floor to reduce building vibrations during earthquakes. The designed controller is tested in an eight-story structural model. By simulation studies the performances of the controller and MR damper are investigated. Comparison is made among case when the MR damper is not connected and controlled with H_∞. The evaluations are based on the displacement and acceleration responses. The arrangement of the MR damper connected between the first floor and the ground with between second floor and ground are effective in reducing the vibration amplitudes. In addition, the MR damper connected between the second floor and the ground is more effective than the damper connected between the first floor and the ground .Furthermore, the designed controller improves the system performance.

NOMENCLATURE

M_s	Mass matrix of the structural system
C_s	Damping matrix of the structural system
K_s	Stiffness matrix of the structural system
L	The seismic input vector
H	The placement of the control units
$\ddot{x}(t)$	Acceleration vector
$\dot{x}(t)$	Velocity vector
x(t)	Displacement vector
f(t)	Damping force of the MR damper
$\ddot{x}_g(t)$	The earthquake ground acceleration
ℓ	The length of the column
I	Cross-sectional moment of inertia
E	Young's modulus
α_0, β_0	Rayleigh damping coefficients
ω_{nm}	The frequency of the last controlled mode
ω_{dm}	The frequency of the firs uncontrolled mode
V_{min}	The minimum voltage in the MR damper
V_{max}	The maximum voltage in the MR damper
f_d	The force necessary for the system
f_c	The force is measured by the system
W_T, W_M	Filters
S(s)	The sensitivity transfer function
T(s)	The complementary sensitivity transfer function
$\Delta_t(s)$	The uncertainty.
$\bar{\sigma}$	The maximum singular value of S(s)
G	The MR damper controller gain

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