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A feasibility study on smart base isolation systems using magneto-rheological elastomers

Jeong-Hoi Koo

Department of Mechanical and Manufacturing Engineering, Miami University, Oxford, Ohio 45056, USA

Dong-Doo Jang, Muhammad Usman and Hyung-Jo Jung†

Department of Civil and Environmental Engineering, KAIST, Daejeon 305-701, Korea

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Abstract. This study proposes a new smart base isolation system that employs Magneto-Rheological Elastomers (MREs), a class of smart materials whose elastic modulus or stiffness can be varied depending on the magnitude of an applied magnetic field. It also evaluates the dynamic performance of the MRE-based isolation system in reducing vibrations in structures subject to various seismic excitations. As controllable stiffness elements, MREs can increase the dynamic control bandwidth of the isolation system, improving its vibration reduction capability. To study the effectiveness of the MRE-based isolation system, this paper compares its dynamic performance in reducing vibration responses of a base-isolated single-story structure (i.e., 2DOF) with that of a conventional base-isolation system. Moreover, two control algorithms (linear quadratic regulator (LQR)-based control and state-switched control) are considered for regulating the stiffness of MREs. The simulation results show that the MRE-based isolation system outperformed the conventional system in suppressing the maximum base drift, acceleration, and displacement of the structure.

Keywords: magneto-rheological elastomer (MRE); base isolation; linear quadratic regulator (LQR); state-switched control.

1. Introduction

Over the past few decades, various base-isolation systems have been developed and implemented in order to minimize severe damages to large-scale structures, such as high-rise buildings and bridges, as well as their contents in the event of an earthquake. Installed in the base of a structure, conventional base-isolation systems (see Fig. 1(a)) can substantially decouple the structure from the horizontal components of potentially dangerous ground motions, particularly in the frequency range where the structure is mostly affected. Moreover, these systems can offer reduction of inter-story drifts and floor accelerations in a cost-effective manner. As such, base isolation systems have been one of the most widely used seismic protection method for bridges around the world (Skinner *et al.* 1993, Naeim and Kelly 1999).

† Assistant Professor, Corresponding author, E-mail: hjung@kaist.ac.kr

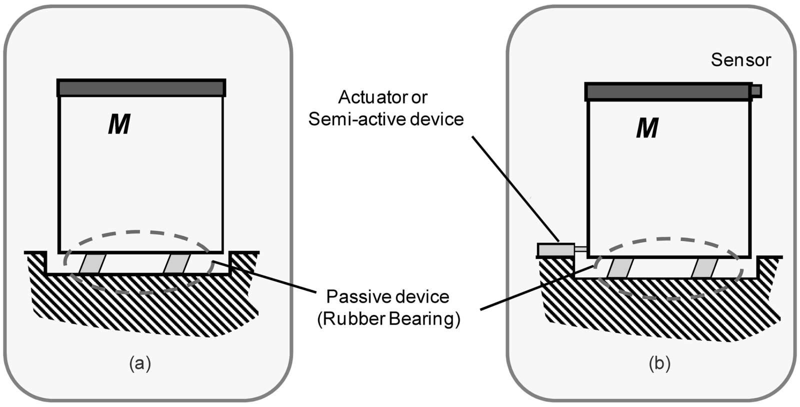


Fig. 1 (a) Passive base-isolation system, (b) Hybrid base-isolation system

Despite the benefits of the conventional base-isolation systems, some researchers have raised concerns regarding the efficiency of the systems (Hall *et al.* 1995, Heaton *et al.* 1995). The conventional base-isolation systems tend to increase the natural period of the structure as well as the base displacement of the structure. This causes a higher cost problem as the isolation systems require considerable seismic gaps between the structure and the ground. Moreover, Spencer and Nagarajaiah (2003) raised concerns regarding the effectiveness of passive-type base-isolation systems in protecting structures, particularly against near-source, high-velocity, long-period pulse earthquakes because the conventional or passive base-isolation systems do not have adaptability with respect to various excitation inputs.

In an effort to improve the performance of passive-type base isolation systems, hybrid-type base-isolation systems (see Fig. 1(b)) have been developed in recent years. Augmented active- or semi-active control devices in passive base-isolation systems, the hybrid systems are intended to provide supplemental damping to enhance the performance of the passive isolation systems, effectively diminishing the excessive base displacement of the structures. In the 1980s and early 1990s, considerable attention was paid to active control device-based hybrid systems (e.g., Kelly *et al*. 1987, Reinhorn *et al*. 1987, Nagarajaiah *et al*. 1993, Schmitendorf *et al*. 1994, Yoshida *et al*. 1994, Yang *et al*. 1996, Reinhorn and Riley 1994). However, these systems were subject to problems of their own (such as instability, reliability, periodic maintenance, cost, and power consumption), and these problems have limited their implementation, particularly for large-scale structures. In the 1990s, many researchers turned their attention to semi-active systems and studied semi-active type hybrid devices for seismic response reduction of base-isolated structures (Feng and Shinozuka 1990, Nagarajaiah 1994, Makris 1997, Johnson *et al*. 1999, Symans and Constantinou 1999, Symans and Kelly 1999, Yoshida *et al*. 1999, Jung *et al.* 2004). This is because semi-active control devices can offer benefits of both active control systems (robustness or adaptability) and passive control systems (stability), while requiring low external power. In their separate studies, Ramallo *et al*. (2002) and Yoshioka *et al*. (2002) proposed a semi-active base isolation system that uses magnetorheological (MR) fluid dampers. They showed the effectiveness of the MR fluid damper-based smart base isolation system with numerical simulations as well as laboratory scale experiments. In addition, Jung and his colleagues have recently carried out a series of numerical studies on the combination of the passive-type base isolators and the semi-actively operated or, sometimes, passively operated MR dampers (Jung *et al.* 2004, 2006, 2007, Choi *et al.* 2008). In the year 2000, the world's first full-scale implementation of such system was carried out at the Keio University School of Science and Technology in Japan (Fujitani *et al*. 2003).

As a new type of semi-active base-isolation system, this paper proposes to incorporate Magneto-Rheological Elastormers (MREs) in base-isolation systems. MREs are considered to be the solid-state analogue of MR fluids, so their elastic modulus varies based on the applied magnetic fields. Thus, MREs are capable of adjusting the stiffness of the isolations by varying the magnitude of magnetic fields. Consequently, MRE-based isolation systems are versatile and able to adapting to various earthquake excitations. Unlike MR fluids systems, the new MRE systems can simply replace the rubber parts of the conventional rubber bearing systems with controllable MRE elements. For the most part, MREs have been investigated in the field of mechanical engineering (Ginder *et al*. 2001). For civil engineering applications, Hwang *et al*. (2006) carried out a conceptual study on the application of MREs to base isolation systems for building structures. However, feasibility of MREs to base-isolated structures has not been investigated in details yet. As such, the primary objective of this study is to investigate the feasibility of the smart base-isolation system employing MREs by conducting numerical simulations. In numerical simulations, the two degree-of-freedom (2DOF) structural model is considered (Ramallo *et al*. 2002), and three different earthquake excitations (El Centro, Northridge, and Kobe earthquakes) are used as input ground motions. Two control algorithms, LQR (linear quadratic regulator)-based control and state-switched control, are used for controlling the stiffness of MREs. The structural responses of an MRE base-isolated structure are compared with those of a passive base-isolated structure employing rubber bearings to investigate the effectiveness of the MRE-based base isolation system.

2. Smart base-isolation system based on MR elastomers

This section introduces an analytical model for the proposed smart base isolation system based on MREs. After briefly reviewing the characteristics of MREs, the models of the structure and the MRE are explained. Then, the equations of motion of the system employing MREs are derived, which will be used in the numerical simulations in a later section.

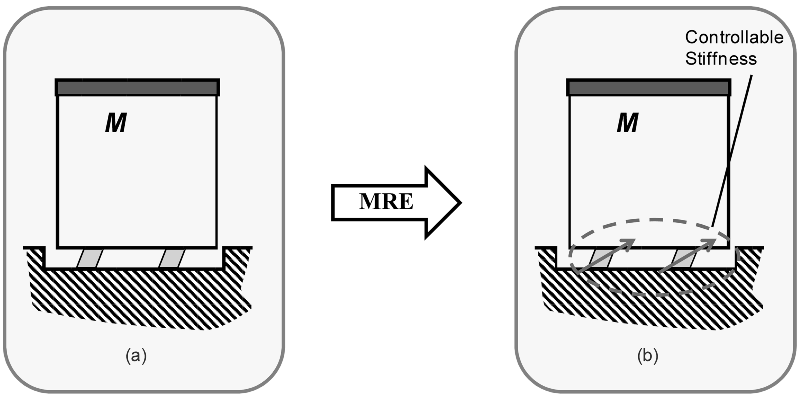


Fig. 2 (a) Passive isolation system, (b) Proposed controllable base-isolation system

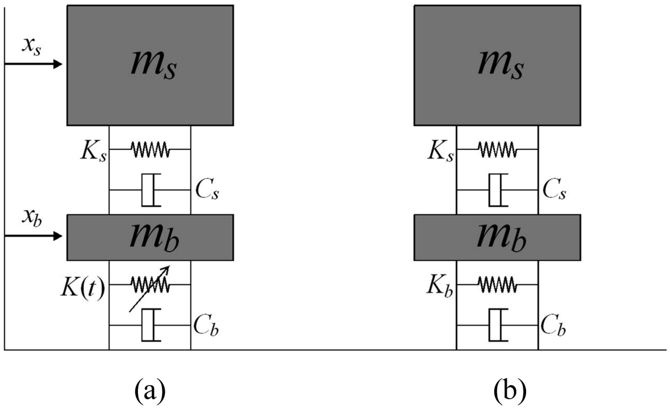


Fig. 3 Two degree-of-freedom (2DOF) models: (a) MRE base-isolation system and (b) Passive base-isolation system

2.1 Proposed base-isolation system

Fig. 2(b) shows the proposed controllable base-isolation system. MREs contain micron-sized magnetizable particles embedded in elastomeric or rubber-like solids (e.g., silicone rubber or natural rubber), whereas MR fluids comprise such particles dispersed in liquids. MREs are a class of smart materials whose elastic modulus or stiffness can be varied depending on the magnitude of an applied magnetic field. They are composed of polarizable particles dispersed in a polymer medium. Applying a magnetic field either by electromagnets or permanent magnets in the elastomers increases the spring rate or stiffness of these components. MRE-based devices or components are anticipated to have some benefits over the MR fluid-based devices in regard to sedimentations, environmental contaminations and sealing problems because particles in MREs are dispersed in a polymer medium. A more detailed explanation on the characteristics of MREs can be found in literature (e.g., Ginder *et al*. 2001, Deng *et al*. 2006).

2.2 Structural system model

This study considered a structure model given by Kelly *et al*. (1987). The structure is modeled as a single degree of freedom (SDOF) system representing the fundamental mode of the five-story building model. When the isolation layer is added to the structural model, the whole structural model can be treated as a 2-DOF system (see Fig. 3). In the figures, m, K and C denote the mass, the stiffness and the damping coefficient, respectively. Moreover, the subscripts s, b represent the structure and base isolator, respectively. The variable stiffness of the MREs is represented as $K(t)$.

2.3 Control of the MRE system

In this study, the MRE element is assumed to be a linearly variable stiffness element. Although the linear approximation does not represent the actual behavior of MREs, it represents overall dynamics of the MREs in a small deformation range and enables us to investigate the *controllable* base-isolation system. Therefore, the stiffness of the MRE is denoted as $K(t)$, which is the sum of a nominal stiffness and time varying stiffness that depends on the external input current (magnetic field). The MRE stiffness can be expressed as

$$K(t) = K_0 + K_1(u(t)) \tag{1}$$

where K_0 means the baseline stiffness of MREs and $K_1(u(t))$ represents the variation in stiffness due to the command input $u(t)$. The maximum and minimum physically achievable values of the stiffness are $K_0 - K_1$ and $K_0 + K_1$, respectively. Although the stiffness of MREs increases as an applied magnetic field increases, the stiffness can be set to a nominal value and varied below and above its nominal value by designing an external magnetic actuation system. An example of such system can be found in Wang *et al.* (2005). According to experimental tests (Koo *et al.* 2008), the elastic modulus or stiffness can vary more than 50% from its nominal stiffness value. In this study, the maximum value of K_1 is modeled as 0.5 K_0 (i.e., $K_1 = 0.5K_0$). Therefore, the range of the variation in the stiffness of MREs is

$$0.5K_0 \le K(t) \le 1.5K_0 \tag{2}$$

The additional force due to the variable stiffness K_1 from Eq. (1) can be expressed as

$$f(t) = -K_1(u(t))x(t) \tag{3}$$

and its range is

$$-0.5K_0x(t) \le f(t) \le 0.5K_0x(t) \tag{4}$$

where $x(t)$ is the deformation of MREs or the base displacement. The additional force $f(t)$ can be varied with the command input $u(t)$ that is calculated from the semi-active control algorithm. In this study, two control algorithms such as the LQR (linear quadratic regulator)-based control and the state-switched control are used.

Linear quadratic regulator (LQR) control algorithm is an optimal control algorithm. The basic concept behind this control algorithm is to minimize the following cost function

$$J = \int_0^t [z^T(t)Qz(t) + u^T(t)Ru(t)]dt \tag{5}$$

with respect to the control input $u(t)$ and subject to the following constraining equation

$$\dot{z}(t) = Az(t) + Bu(t) + Hf(t) \quad z(0) = z_0 \tag{6}$$

In regulator type algorithm problems, the system is assumed to be in equilibrium, and the purpose of the LQR control algorithm is to maintain the equilibrium despite the fact that the system is subjected to disturbances or to minimize the response of the system from the disturbances of any nature.

The state-switched control algorithm can be considered as an "on-off" control that switches the state of MREs between the two discrete stiffness values (i.e., maximum and minimum stiffness of MREs). Kenneth *et al.* (2000) proposed a switching criterion for the state-switched control algorithm based on the product of the velocity of the base and the relative velocity. For the current study, a SDOF structure with very high stiffness, as compared to the stiffness of MRE, is considered, so the relative velocity between the structure and the base may not be a good choice for switching criterion. Therefore, a switching criterion based on the motion of the base (i.e., the product of the displacement and the velocity of the base) was developed for the MRE-based isolation system. The switching criterion is summarized in the following equation.

$$K_{MRE} = \begin{Bmatrix} K_{s1} & \text{if} & -x_b\dot{x}_b > 0 \\ K_{s2} & \text{if} & -x_b\dot{x}_b < 0 \\ K_0 & \text{if} & -x_b\dot{x}_b = 0 \end{Bmatrix} \tag{7}$$

where K_{s1} and K_{s2} correspond to the two extreme values of the control force range in the Eq. (4), and K_0 is the mean value of the range (i.e., base line stiffness of the MRE without any magnetic field applied). This criterion may need to be revised for multi degree of freedom systems where the relative velocities may come into play.

2.4 Equations of motion and numerical model

Assuming the structural motion is sufficiently small such that nonlinear effects may be neglected, and denoting the base and structure displacements relative to the ground by $x = [x_b \;\; x_s]^T$, the equations of motion of the base-isolated system may be expressed as

$$M\ddot{x} + C\dot{x} + K(t) = -M\Gamma\ddot{x}_g \tag{8}$$

or

$$M\ddot{x} + C\dot{x} + K_0 x = \Lambda f - M\Gamma\ddot{x}_g \tag{9}$$

where x ($x = [x_b \;\; x_s]^T$) is displacement vector of the structure and base isolator; M, C and K are the mass, damping, and stiffness matrices, respectively; f is the supplemental force exerted by the MREs, Λ ($\Lambda = [1 \;\; 0]^T$) vector represents the position of the supplemental damper force; Γ vector are unity vector; $\ddot{x}_g$ is the ground acceleration. The system matrices can be expressed as

$$M = \begin{bmatrix} m_b & 0 \\ 0 & m_s \end{bmatrix}, \quad C = \begin{bmatrix} c_b + c_s & -c_s \\ -c_s & c_s \end{bmatrix} \quad K_0 = \begin{bmatrix} k_b + k_s & -k_s \\ -k_s & k_s \end{bmatrix} \tag{10}$$

Defining the state vectors as $z = [x \;\; \dot{x}]^T$ and the output vector to be regulated as $y = z = [x \;\; \dot{x} \;\; \ddot{x}]^T$, the state-space form of the equations of motion can be given by

$$\dot{z} = Az + Bf + E\ddot{x}_g \tag{11}$$

$$y = C_y z + D_y f + F_y \ddot{x}_g \tag{12}$$

where $$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ M^{-1}\Lambda \end{bmatrix}, \quad E = \begin{bmatrix} 0 \\ -\Gamma \end{bmatrix}$$

$$C_y = \begin{bmatrix} I & 0 \\ 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad D_y = \begin{bmatrix} 0 \\ 0 \\ M^{-1}\Lambda \end{bmatrix} \quad \text{and} \quad F_y = \begin{bmatrix} 0 \\ 0 \\ -\Gamma \end{bmatrix}$$

The state-state equations are modeled in the MATLB/SIMULINK environment, and Fig. 4 shows the simulation model. The system and simulation parameters are provided in the next section along with the inputs to the model.

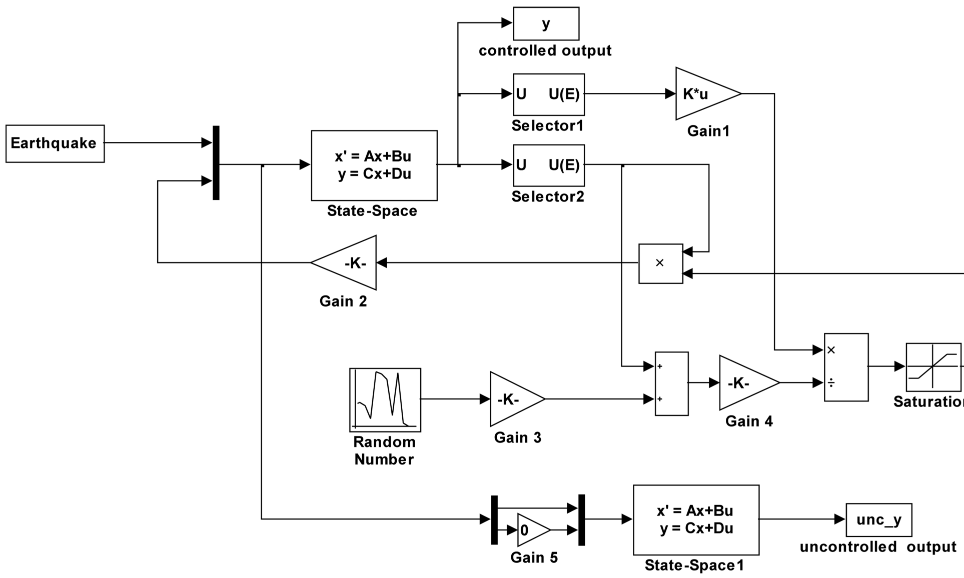


Fig. 4 MATLAB/SIMULINK block diagram

3. Numerical simulation results and discussion

3.1 System parameters

To evaluate the feasibility of the MRE-based smart base isolation system, numerical simulations are carried out using the system models developed in the previous section. The numerical simulation results of the MRE-based system are compared to those of a passive-type base isolation system based on rubber bearings (RB). The structural parameters of the 2-DOF base-isolated structure model are given in Table 1.

As inputs to the system, three different historical earthquakes were used. The earthquake input excitations considered herein are

- El Centro earthquake (PGA 0.350 g), which is the N-S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of May 18, 1940;
- Hachinohe earthquake (PGA 0.229 g), which is the N-S component recorded at Hachinohe City, Japan during the Tokachi-oki earthquake of May 16, 1968;
- Northridge earthquake (PGA 0.843 g), which is the N-S component recorded at Sylmar County Hospital parking lot in Sylmar, California, during the Northridge, California earthquake of January 17, 1994.

Table 1 Structural model parameters

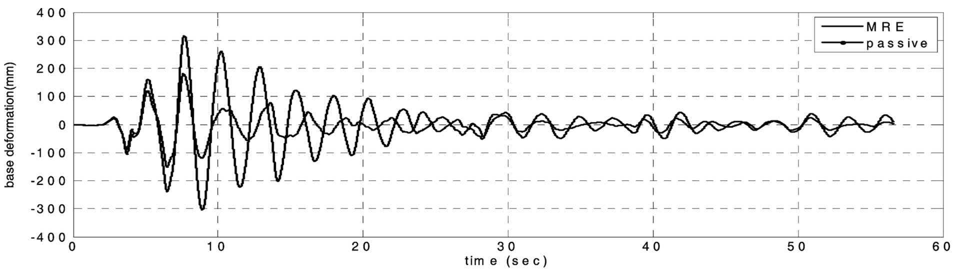
Mass (kg)	Stiffness (kN/m)	Damping (kN·s/m)
$m_b = 6800$	$K_b = 232$	$C_b = 3.74$
$m_s = 29485$	$K_s = 11912$	$C_s = 23.71$

3.2 Numerical analysis

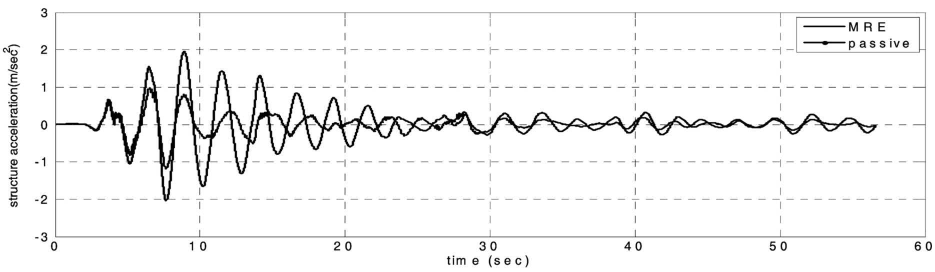
The numerical simulations were carried out for both LQR-based control and the state-switched control using the above mentioned the structural parameters and input excitations. The structural responses with both control algorithms and without control (i.e., the passive system) are compared in this section.

3.2.1 LQR-based control

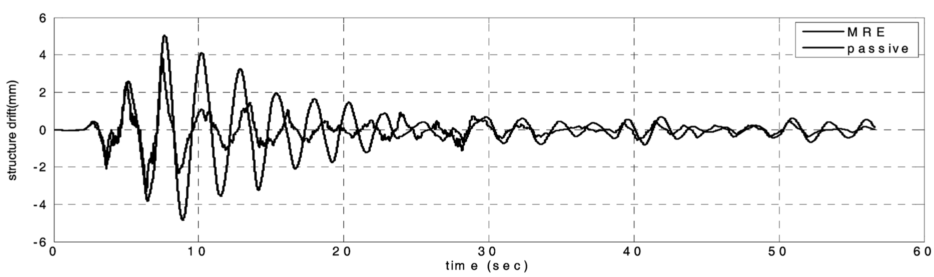
Figs. 5-7 show the time history responses of the base drift and the acceleration and relative displacement of the structure under three historical earthquake records (El Centro, Hachinohe and Northridge earthquakes). As shown in the figures, the MRE-based smart base isolation systems employing the LQR-based control algorithm significantly reduce all the responses compared with the passive-type base isolation system.



(a) Base drift

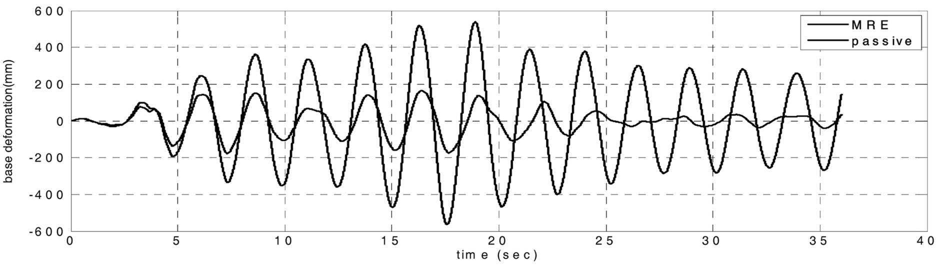


(b) Structure acceleration

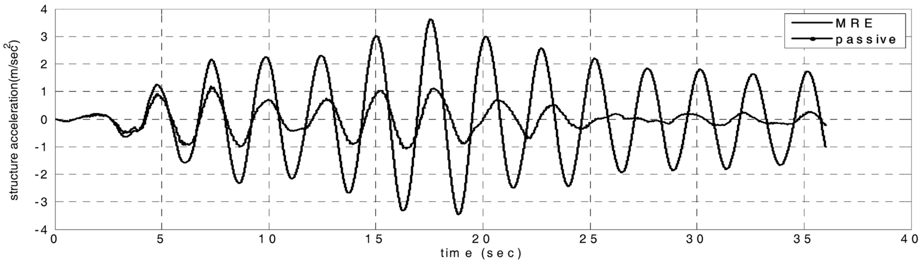


(c) Structure drift

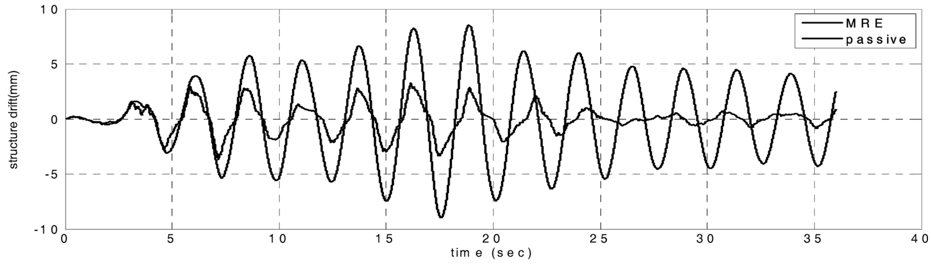
Fig. 5 Time history responses under El Centro earthquake



(a) Base drift



(b) Structure acceleration

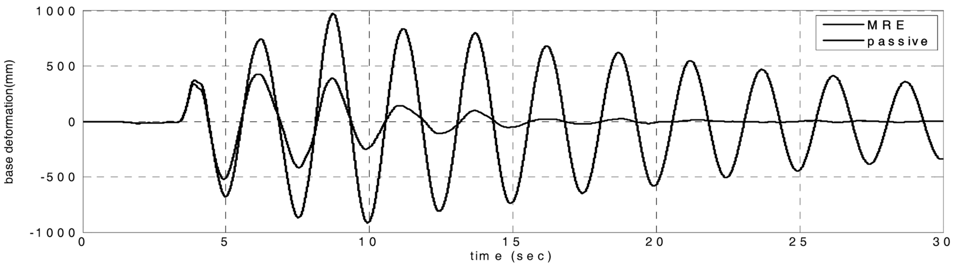


(c) Structure drift

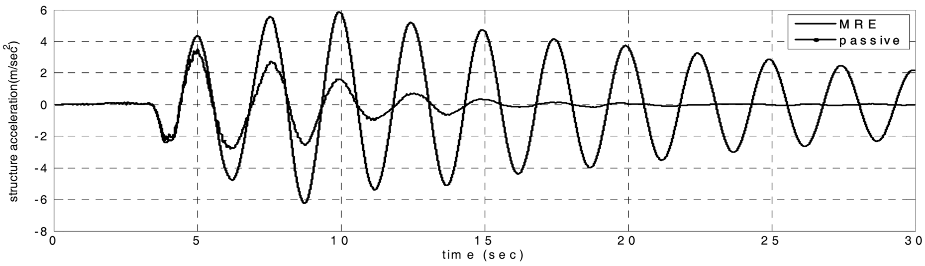
Fig. 6 Time history responses under Hachinohe earthquake

To quantitatively compare the performance, Table 2 summarizes the peak responses of the structure. As seen in Table 2, the peak drift of MRE system significantly decreased compared with the passive base isolation system. The maximum structural peak accelerations of the passive and smart base isolation systems are 6.24 m/s^2 and 3.50 m/s^2, respectively, in the case of Northridge earthquake. The improvement of the maximum structural acceleration is about 44% compared to the passive system. And the peak structural drifts are 10.10 mm (MRE-based smart system) and 15.45 mm (passive system) in the same excitation case. Consequently, the improvements of peak structural drifts are about 35%. These results show that the MRE-based smart passive isolation system can significantly reduce the peak base drifts, peak structural accelerations and peak structural drifts compared to passive system.

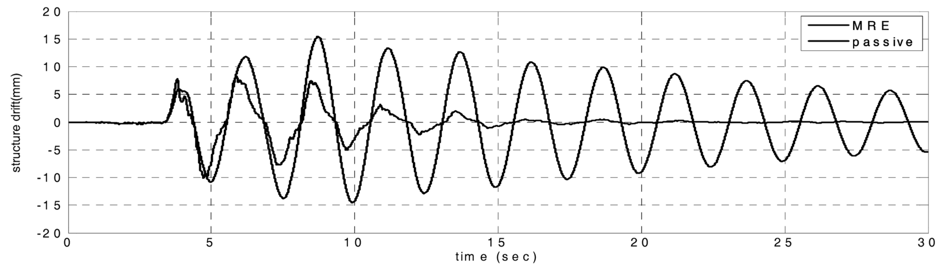
To further visualize the results, Fig. 9 shows the percent response improvement of the proposed smart system over the passive base isolation system. The numbers in the figure are all positive for all earthquake excitations, indicating that the responses of the proposed MRE system are smaller than those of the passive system. Overall, the maximum response reduction was achieved for the



(a) Base drift



(b) Structure acceleration



(c) Structure drift

Fig. 7 Time history responses under Northridge earthquake

Table 2 Peak responses under three historical earthquakes

Earthquake	El Centro		Hachinohe		Northridge	
Control system	Passive	MRE	Passive	MRE	Passive	MRE
Maximum base drift (mm)	316.51	181.96	564.03	177.45	971.58	521.79
Maximum structure accelerations (m/s^2)	2.03	1.18	3.62	1.18	6.24	3.50
Maximum structure drift (mm)	5.03	3.82	8.96	3.66	15.45	10.10

Hachinohe case among the earthquake excitation considered in this study. For Hachinohe input, the maximum base drift is reduced nearly 70% by the MRE-system. For other cases, the responses are also reduced, ranging 25% to 55%. The numerical simulation results show that the smart base isolation system based on MREs outperform the passive base-isolation system in reducing the maximum responses.

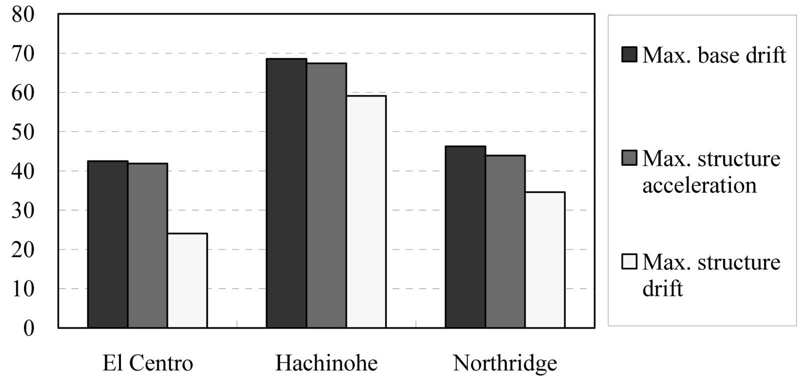


Fig. 8 Percent response improvement of the smart system compared to the passive system

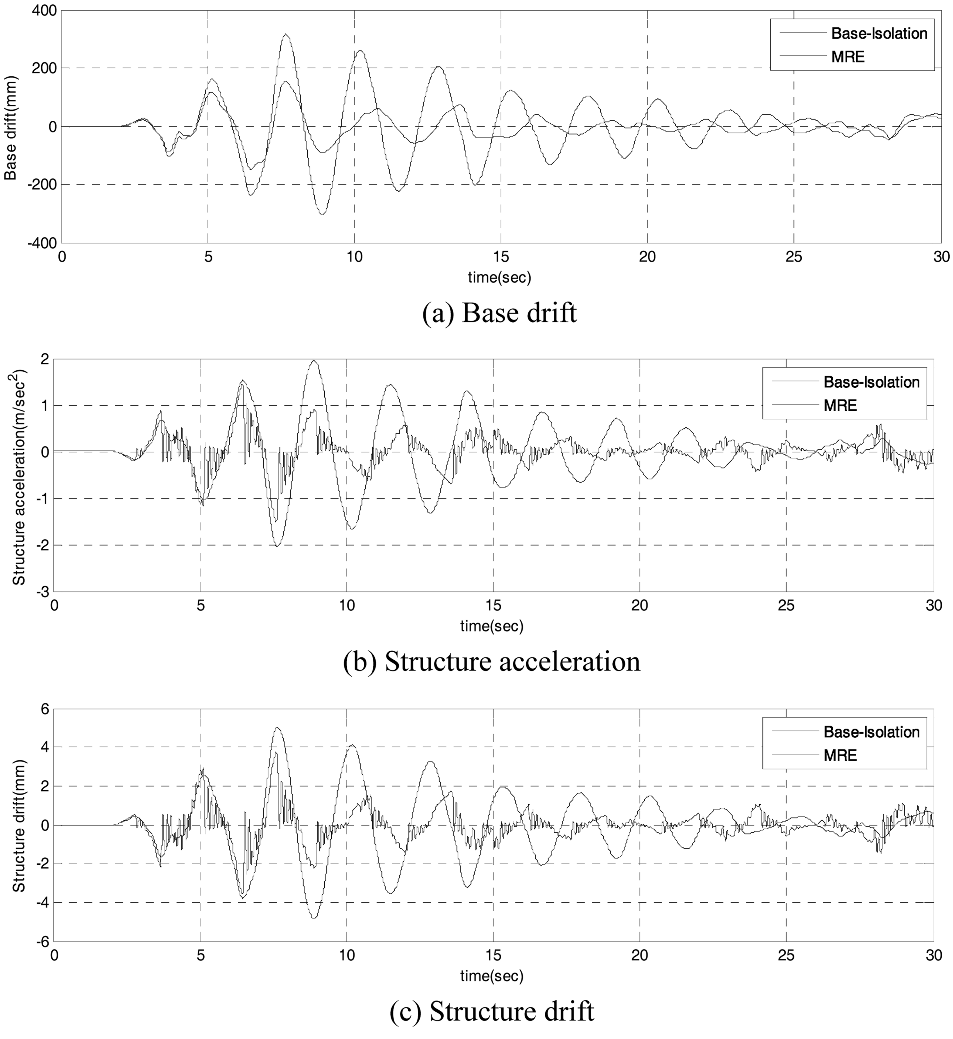
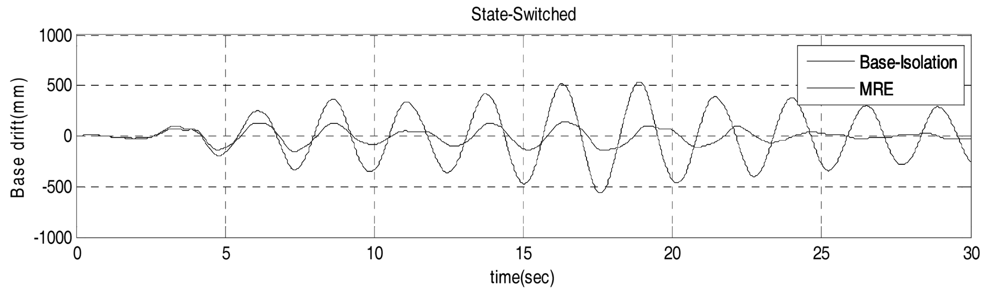
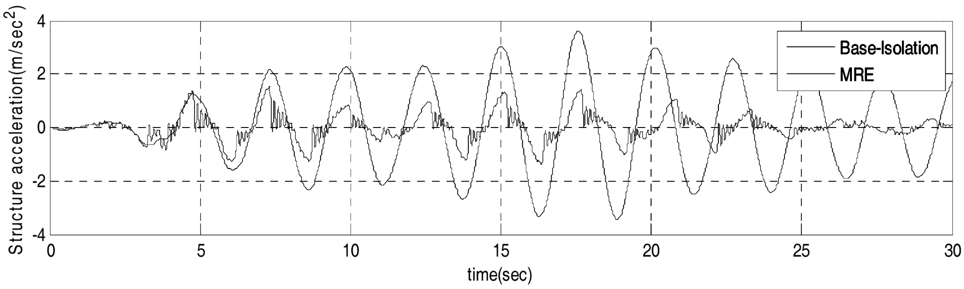


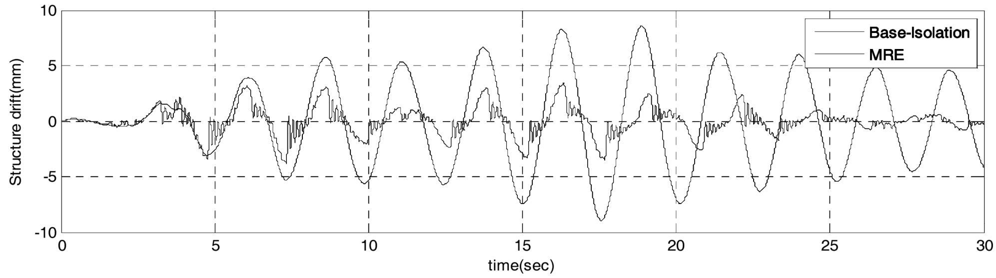
Fig. 9 Time history responses under El Centro earthquake



(a) Base drift



(b) Structure acceleration



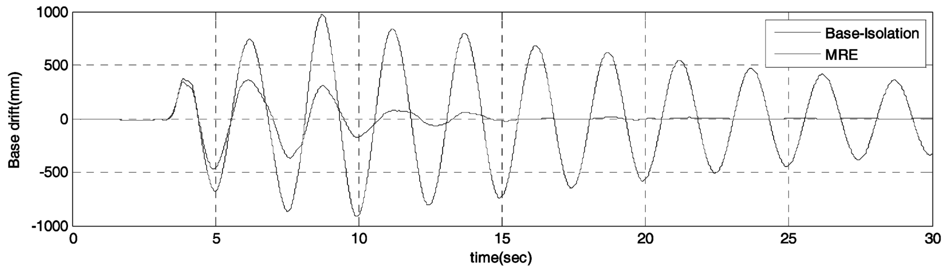
(c) Structure drift

Fig. 10 Time history responses under Hachinohe earthquake

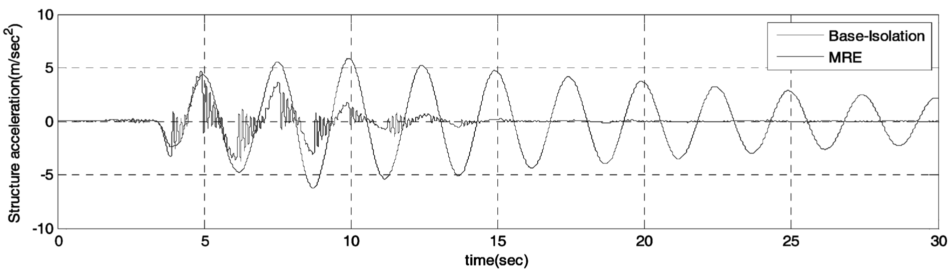
3.2.2 State-switched control

Figs. 9-11 show the time history responses of the base drift and the acceleration and relative displacement of the structure for the sate-switched control case. Overall, the MRE-based smart base isolation systems with the state-switch control algorithm significantly reduce all the responses compared with the passive system.

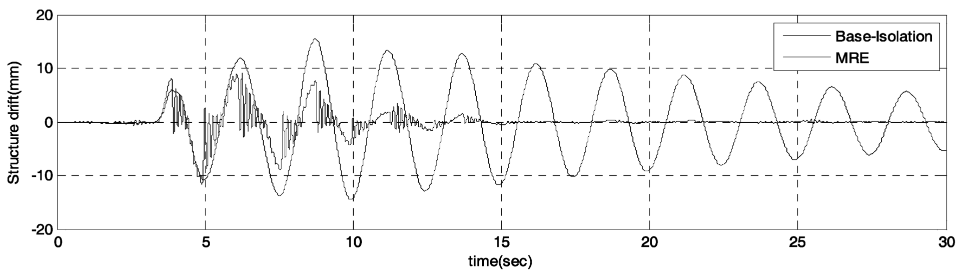
Table 3 shows the peak responses under three historical earthquakes in the case of state-switched control algorithm. It shows that the peak base drift was decreased more than 70% by the MRE system for the Northridge case. The maximum structural accelerations of the passive and smart base isolation systems are 6.24 m/s^2 and 4.69 m/s^2, respectively, which means that the MRE system reduced the response about 25% as compared with the passive system. Moreover, the peak structural drifts are 9.13 mm (MRE-based smart system) and 15.45 mm (passive system), the reduction of about 40% by the MRE system. These results show that the MRE-based smart passive



(a) Base drift



(b) Structure acceleration



(c) Structure drift

Fig. 11 Time history responses under Northridge Earthquake

Table 3 Peak responses under three historical earthquakes

Earthquake	El Centro		Hachinohe		Northridge	
Control system	Passive	MRE	Passive	MRE	Passive	MRE
Maximum base drift (mm)	316.51	154.30	564.03	138.16	971.58	363.23
Maximum structure accelerations (m/s^2)	2.03	1.44	3.62	1.53	6.24	4.69
Maximum structure drift (mm)	5.03	3.74	8.96	3.40	15.45	9.13

isolation system can significantly reduce the peak base drifts, peak structural accelerations, and peak structural drifts compared with the passive system.

The percent response reduction analysis of the state-switched case is shown in Fig. 12. As seen from the figure, all the responses of the proposed system are much smaller than those of the passive

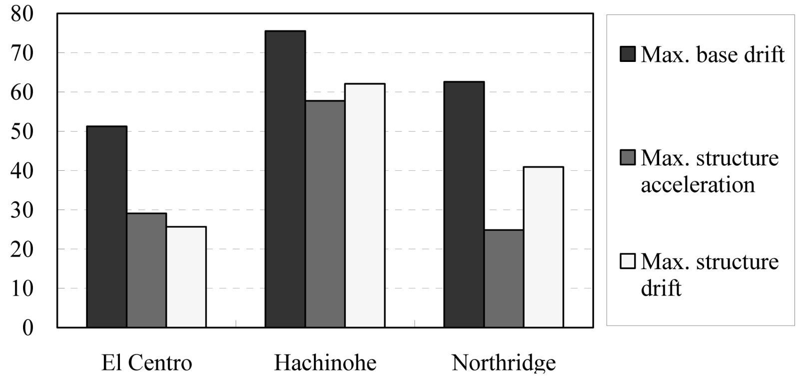


Fig. 12 Percent response improvement of the smart system compared to the passive system

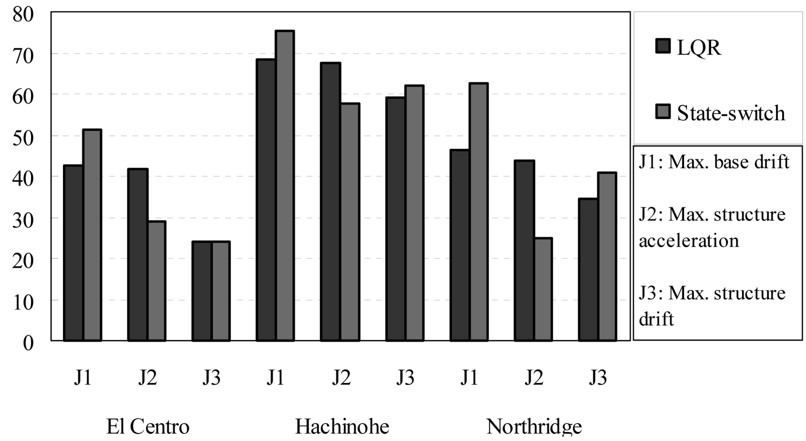


Fig. 13 Percent response reduction of the MRE system with two control algorithms (LQR and State-Switch Control) over the passive system

system. The response reduction of the MRE system over the passive system ranges from 25% to 75%. The numerical simulation results indicate that the MRE system with the state-switched control also outperforms the passive system.

3.3 Comparison between LQR-based control and state-switched control

This section evaluates the performance of the two control algorithms (LQR and State-switched control) used for the MRE-based smart base isolation system. Fig. 13 shows the percent reduction of the structural responses of the MRE system using the two algorithms over the passive system. As shown in the figure, overall performance of two algorithms is very similar. The state-switched control reduces the maximum base and structure drifts more than the LQR-based control. On the other hand, the LQR-based control outperforms the state-switched control in reducing the maximum structure acceleration. Based on the controller performance analysis, it is quite difficult to select a better control algorithm. However, from the prospect of implementing the control algorithm, the state-switched control may be easier because it is essentially an on-off controller.

4. Conclusions

This paper proposed a new smart base-isolation system that uses MREs. It also investigated the feasibility of the proposed isolation system by evaluating the dynamic performance of the system. In this study, MREs are idealized as linearly controllable stiffness elements. To study the control performance of the MRE-based smart system, numerical simulations were conducted by using a 2-DOF system with the El Centro, Hachinohe and Northridge earthquakes as the input. Moreover, two control algorithms (LQR-based control and state-switched control algorithms) were considered for changing the stiffness of MREs. The performance of the MRE-based system is compared to that of the passive base isolation system, which uses rubber bearings. According to the numerical simulation results, all the responses (base drift, structural acceleration and inter-story drift) of the smart system based on MREs were smaller than those of the passive system, indicating that the MRE system outperformed its passive counterpart. Therefore, the smart base-isolation system using MREs should be considered a good strategy for improving the seismic protection capability of base-isolated structures. This study demonstrated the feasibility of a MRE-based isolation system as a new smart base isolation system using a 2DOF structure model. However, more studies (both numerical and experimental) should be performed before applying MREs in large engineering structures, such as high-rise buildings and long-span bridges.

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