University of Wollongong

Research Online

Faculty of Engineering and Information
Sciences - Papers: Part A

Faculty of Engineering and Information
Sciences

1-1-2016

Development of a novel multi-layer MRE isolator for suppression of building vibrations under seismic events

Jian Yang

University of Wollongong, jy937@uowmail.edu.au

Shuaishuai Sun

University of Wollongong, ss886@uowmail.edu.au

Tongfei Tian

University of Wollongong, tongfei@uow.edu.au

Weihua Li

University of Wollongong, weihuali@uow.edu.au

Haiping Du

University of Wollongong, hdu@uow.edu.au

See next page for additional authors

Follow this and additional works at: <https://ro.uow.edu.au/eispapers>

Part of the [Engineering Commons](#), and the [Science and Technology Studies Commons](#)

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

Development of a novel multi-layer MRE isolator for suppression of building vibrations under seismic events

Abstract

Protecting civil engineering structures from uncontrollable events such as earthquakes while maintaining their structural integrity and serviceability is very important; this paper describes the performance of a stiffness softening magnetorheological elastomer (MRE) isolator in a scaled three storey building. In order to construct a closed-loop system, a scaled three storey building was designed and built according to the scaling laws, and then four MRE isolator prototypes were fabricated and utilised to isolate the building from the motion induced by a scaled El Centro earthquake. Fuzzy logic was used to output the current signals to the isolators, based on the real-time responses of the building floors, and then a simulation was used to evaluate the feasibility of this closed loop control system before carrying out an experimental test. The simulation and experimental results showed that the stiffness softening MRE isolator controlled by fuzzy logic could suppress structural vibration well.

Keywords

under, seismic, layer, events, mre, multi, novel, development, isolator, suppression, building, vibrations

Disciplines

Engineering | Science and Technology Studies

Publication Details

Yang, J., Sun, S., Tian, T., Li, W., Du, H., Alici, G. & Nakano, M. (2016). Development of a novel multi-layer MRE isolator for suppression of building vibrations under seismic events. *Mechanical Systems and Signal Processing*, 70-71 811-820.

Authors

Jian Yang, Shuaishuai Sun, Tongfei Tian, Weihua Li, Haiping Du, Gursel Alici, and Masami Nakano

Development of a novel multi-layer MRE isolator for suppression of building vibrations under seismic events

Jian Yang^a, Shuaishuai Sun^a, Tongfei Tian^a, Weihua Li^{*a}, Haiping Du^b, Gursel Alici^a, and Masami Nakano^c

^a*School of Mechanical, Material and Mechatronic Engineering, University of Wollongong, New South Wales, 2522, Australia*

^b*School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, New South Wales, Australia*

^c*Intelligent Fluid Control Systems Laboratory, Institute of Fluid Science, Tohoku University, Katahira 2-1-1, Aoba-ku, Sendai, 980-8577, Japan*

** Corresponding author. Email address: weihuali@uow.edu.au.*

Abstract

Protecting civil engineering structures from uncontrollable events such as earthquakes while maintaining their structural integrity and serviceability is very important; this paper describes the performance of a stiffness softening magnetorheological elastomer (MRE) isolator in a scaled three storey building. In order to construct a closed-loop system, a scaled three storey building was designed and built according to the scaling laws, and then four MRE isolator prototypes were fabricated and utilised to isolate the building from the motion induced by a scaled El Centro earthquake. Fuzzy logic was used to output the current signals to the isolators, based on the real-time responses of the building floors, and then a simulation was used to evaluate the feasibility of this closed loop control system before carrying out an experimental test. The simulation and experimental results showed that the stiffness softening MRE isolator controlled by fuzzy logic proved to suppress any structural vibration.

Keywords: stiffness softening MRE isolator, scaled three storey building, fuzzy logic, vibration isolation

1. Introduction

Base isolation technologies are one of the most adopted and effective means of mitigating unwanted and harmful vibrations in various engineering applications, and to protect buildings, bridges, and other key civil infrastructure from seismic events [1-3]. However, because it is inherently passive, traditional base isolations cannot adapt to changes in the environment or source vibrations, which as a consequence compromises their efficiency and robustness and in some cases, cause adverse effects [4]. Taking seismic applications as an example, a seismic base isolation system decouples structures and their contents from potentially dangerous ground motions and deflects the energy emanated from earthquakes, especially in those frequency ranges where structures are most vulnerable [5]. An effective base isolation system is basically a trade off in design based on the estimated properties of a structure and the magnitude and frequency range of an expected earthquakes [6]. Essentially then, a base isolation system can be effective against designated earthquakes but be ineffective when encountering different types of earthquakes [4, 5]; indeed recent research has revealed that a base isolation system can be vulnerable for near-field [7, 8] or far-field earthquakes [9]. To overcome the shortcomings of traditional passive base isolations, recent and emerging research has been exploring various options such as adding supplementary energy-dissipating members with a magnetorheological damper, or a friction or hydraulic fluid damper, to reduce the seismic response of building structures during near-field earthquakes [4-7, 10-12]. Yoshioka et al. [4] and Ramallo et al. [5] proposed a combination of conventional base isolators and controllable dampers to compensate for a traditional base isolation system in extreme earthquakes. Wongprasert et al. [10] experimentally evaluated a combined spherical sliding bearing and variable fluid damper system for a multi-storey building frame. These methods are classified as hybrid base isolation systems that offer a possible solution for improving the adaptability of traditional base isolation systems under certain types of earthquakes. However, in addition to the inherent limitations in a hybrid solution, simply adding supplementary devices to passive systems may cause additional problems; for example, adding a passive or controllable damper can reduce displacement at the top of the isolators but also increase the floor accelerations of the isolated structure as higher vibration modes are passed to the superstructure. Moreover, hybrid base isolation systems increase the complexity of a design and implementing a base isolation system is not only costly, it also potentially compromises the reliability of these systems [13]. Thus far, hybrid systems cannot deal with far-field earthquakes [9] because the base isolators are still passive devices whose natural frequencies cannot be changed by supplementary devices to decouple the incoming earthquake excitations.

In an attempt to address the challenges faced by the current base isolation design/practice, Behrooz et al. incorporated a magnetorheological elastomer (MRE) into a base isolator and then succeeded in protecting a scaled three storied building from seismic motions using a Lyapunov algorithm [14, 15]. MRE is a class of smart materials that can increase its elastic modulus or stiffness monotonically as the magnetic field increases [16, 17], and then immediately revert to its initial status when the magnetic field is removed. The unique property of MRE is an opportunity to develop adaptive base isolators with real-time controllability that could overcome the shortcomings inherent in traditional base isolation systems. Inspired by the commercialised traditional base isolator utilising natural rubber, Li et al. developed a large capacity adaptive base isolator [18, 19] that is the first adaptive base isolator utilising stiffness hardening MRE. This MRE adaptive base isolator consists of a classical laminated structure of steel and MRE layers from traditional rubber bearings [20, 21]. The results obtained from testing the characteristics of this MRE adaptive base isolator showed it can increase lateral stiffness by up to 18 times [19]. Despite the success and breakthrough on the development and proof-of-concept of the adaptive base isolator with stiffness hardening MRE, one critical challenge emerged as a result of the pilot research: an adaptive base isolator with stiffness hardening MRE may not be suitable for the practical implementation of seismic protection of civil infrastructures. This conclusion was based on the fact that the principle underlying the adaptability of a stiffness hardening MRE base isolator is its ability to increase lateral stiffness (i.e. the isolating frequency) away from damaging earthquake frequencies by magnetising MRE, but the effectiveness of base isolation relies on decoupling a structure from its source of vibration, i.e., decreasing the lateral stiffness of (softening) the isolators. Although increasing the isolation frequency makes it possible to shift the entire structural frequencies away from the resonant frequencies of the sources of vibration and therefore suppress vibration in the structure, this is not as effective as decoupling the structure from the source of vibration. In order to provide a softening lateral stiffness when an earthquake begins, stiffness hardening MRE isolators must be powered up for most of their operational time, which means these systems are not sustainable or reliable in practice. Fortunately, the authors have found a solution to this problem; they developed a stiffness softening MRE base isolator by adopting two permanent magnets [22-24] that can energise the MRE continuously without consuming power, while the solenoids produces an electromagnetic field (EMF) that is opposed to the permanent magnetic field (PMF), so the lateral stiffness of the MRE isolator can be lowered. Now, the new stiffness softening base isolator can operate in a passive mode under normal operating conditions without any requiring power, and it only needs to be activated to a semi-active mode when certain pre-set events trigger the system.

To evaluate its ability to protect structures from seismic motions, this new MRE isolator was used to isolate a scaled three storey building from the earthquakes simulated in this study. Fuzzy logic was used to control the magnitude of the electromagnetic field based on the real-time responses of the building floors. A detailed experimental setup is introduced in Section 2. Model establishment, control algorithm development, and control system evaluation by simulation were completed in Section 3. Section 4 evaluated the closed-loop three story building system and discussed the experimental results, and Section 5 summarises all the work through this article.

2. Experimental setup

2.1 Dynamic performance of the stiffness softening MRE isolator.

This stiffness softening MRE isolator used a laminated structure of traditional isolators with 10 layers of MRE sheets bonded onto 11 layers of steel sheets. A permanent magnet was placed at each end of this laminated structure, which was placed along the central axis of the solenoid with an appropriate gap between them. The solenoid was enclosed in a steel cylinder with a top plate and bottom plate in order to generate a closed loop magnetic field. There was also an appropriate gap between the top plate and steel cylinder for any possible relative movement. The overall magnetic field working on MRE was the superposition of the PMF and EMF. The direction and the magnitude of the EMF were controlled by the direction and amount of applied direct current. To soften the lateral stiffness, an EMF that was opposed to the PMF was chosen so that the lateral stiffness of the isolator would decrease when the applied current increased, because part of the PMF was offset.

To demonstrate the stiffness softening capability of the MRE isolator, transmissibility under different levels of current were obtained by running the isolator with a sinusoidal swept frequency. As Fig.1 shows, two accelerometers measured the acceleration of the top and bottom plates, respectively. The transmissibility of the top and bottom accelerations versus the sweeping frequency is shown in Fig.2, and indicates that increasing the applied current decreases the natural frequency and the lateral stiffness of the isolator. The natural frequency decreased from 16.8Hz to 5Hz with a change percent of 70% when the current was changed from 0A to 3A.

Fig.1. Prototype photograph of MRE isolator.

Fig.2. Transmissibility of the MRE isolator due to different current.

2.2 Design of the scaled three story building.

A model three storey building was designed and built with a length scale factor of 1:9. The height of the first two stories was 0.75m, which corresponds to a real three storey building approximately 10m high. All the variables and dimensions were scaled down according to the scaling laws [24], with some examples shown in Table 1.

Table 1. Scaling factors of the variables.

Variables	Length	Displacement	Acceleration	Time
Scaling factor	1:9	1:9	1	1:3

Fig.3 shows a schematic view of the scaled building model with four MRE isolators. The three storey building with adjustable masses was fixed to the top plates of the four isolators, and the

isolators were fixed to the shaking table via two linear shearings. The building with four isolators was forced to vibrate horizontally by a shaker (VTS, VC 100-8) driven by a signal source from the computer through a power amplifier (YE5871). DC power was ready at hand to supply current signals to the isolators when needed.

Fig.3. Schematic view of the scaled building model.

2.3 Closed loop control system.

The interface used to link the software and hardware was a HILINK board (ZELTOM) that offers a seamless interface between physical plants and Matlab/Simulink to implement hardware-in-the-loop real-time control systems. It was fully integrated into Matlab/Simulink and has a broad range of inputs and outputs. Fig.4 shows a schematic diagram of the closed control system. The real-time responses of the building were transmitted to the computer through the HILINK input channels, after being processed and calculated by the controller in the computer, a current signal was sent to the isolators through the HILINK output channel.

Fig.4. Schematic diagram of the closed-loop control system.

Fig.5 shows the whole isolation system where the scaled El Centro seismic motion was used to excite the shake platform and the fuzzy logic controller designed in the Simulation (Section 3.2) was used to change the stiffness of the isolation system in real-time. Two laser displacement sensors (MICRO-EPSILON Company) were used to measure the relative displacements of the third floor to the first floor, and the first floor to the ground motions, respectively. Another laser sensor (DT20-X224Bx, SICK) recorded the displacement data of the ‘ground motion’, and three accelerometers recorded the accelerations of three floors, respectively. Three cases were considered in this experiment: ‘fixed base’ means the building was fixed to the shake table directly without isolators between them; ‘passive’ means no control logic was applied to but isolators were included in this system; ‘controlled’ means the isolation system was controlled by fuzzy logic.

Fig.5. Photograph of the practical experimental setup.

3. Simulation

3.1 Modelling the isolated building.

By considering a three degrees-of-freedom (DOF) linear building structure controlled by four isolators and subject to a horizontal earthquake excitation (1940 El Centro), as shown in Fig.6, the motion equations can be written as:

Fig.6. Mathematical model of the scaled building.

$$\begin{aligned}
 m_1 \ddot{x}_1 + c_2(\dot{x}_1 - \dot{x}_2) + k_2(x_1 - x_2) + c_1 \dot{x}_1 + k_t(I)x_1 &= -m_1 \ddot{x}_g \\
 m_2 \ddot{x}_2 - c_2(\dot{x}_1 - \dot{x}_2) - k_2(x_1 - x_2) + c_3(\dot{x}_2 - \dot{x}_3) + k_3(x_2 - x_3) &= -m_2 \ddot{x}_g
 \end{aligned} \tag{1}$$

$$m_3 \ddot{x}_3 - c_3(\dot{x}_2 - \dot{x}_3) - k_3(x_2 - x_3) = -m_3 \ddot{x}_g$$

$$M\ddot{X} + C\dot{X} + KX = -M\ddot{x}_g$$

where

$$X = [x_1 \quad x_2 \quad x_3]^T, M = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix}, C = \begin{bmatrix} c_2 & -c_2 & 0 \\ -c_2 & c_2 + c_3 & -c_3 \\ 0 & -c_3 & c_3 \end{bmatrix}$$

$$, K = \begin{bmatrix} k_2 & -k_2 & 0 \\ -k_2 & k_2 + k_3 & -k_3 \\ 0 & -k_3 & k_3 \end{bmatrix}, m_i \text{ (} i=1, 2, 3 \text{) is the mass of the } i\text{th floor; } x_i \text{ (} i=1, 2, 3 \text{) is the relative}$$

displacement of the i th floor with respect to the ground; c_i ($i=2, 3$) and k_i ($i=2, 3$) is the damping and stiffness coefficients of inter floors, respectively; $c_t(I)$ and $k_t(I)$ are the current-dependent damping and stiffness coefficients of the isolators, respectively. The masses of the building model are identical for each storey unit and given as $m_i=25\text{Kg}$, for $i=1, 2, 3$.

3.2 Fuzzy logic controller.

Fuzzy logic control can offer a simple and robust framework for specifying nonlinear control laws that can accommodate uncertainty and imprecision [26, 27]. Alternatively, a fuzzy controller does not rely on the analysis and synthesis of the mathematical model of the process, so the uncertainties of input data from external loads and structural response sensors were treated in a much easier way by the fuzzy controller than with classical control theory. Fuzzy logic uses IF-THEN rules as an interface to connect the inputs and outputs, which means that continuous inputs are transformed into linguistic variables which are then converted into numerical values through defuzzication. In semiactive control, the numerical values provide control commands that vary the mechanical properties of a semiactive control device. In this study the relative displacement between the first and third floors, the first floor displacement, and the scaled earthquake velocity data were used as inputs to obtain the lateral stiffness of the MRE isolators controlled by the controller output.

The designing process of a fuzzy controller begins with choosing inputs and output, and defining the membership functions (MFs). As mentioned before, the inputs chosen were x_3-x_1 , x_1 , $\dot{x}_g$, where x_3-x_1 is the control target which is supposed to be small as much as possible; x_1 , is the relative displacement to the ground of the first floor, together with $\dot{x}_g$ which predicts the direction the earthquake will move and also determines the relative position of the isolators to the ground. Each input has two member functions which were abbreviated to: P-Positive, N-Negative. The output is the current signal and the membership functions were defined as: L-Large, S-Small. Table 2 gives the inference rule based on the three inputs. It should be noted that the softening lateral stiffness of the isolator corresponds to the largest value of the current.

Table 2. The inference rule of the fuzzy logic.

Variable	MF							
x_3-x_1	N	N	N	N	P	P	P	P
x_1	N	P	N	P	N	P	N	P
$\dot{x}_g$	P	P	N	N	P	P	N	N
Isolator stiffness	Soft	Hard	Soft	Hard	Hard	Soft	Hard	Soft
Current	L	S	L	S	S	L	S	L

3.3 Simulation results.

The 1940 El Centro record was chosen as the input to the simulation and experiment since it covers a wide frequency range. A Simulink model that incorporated the isolated building and fuzzy logic

algorithm was built. The responses of the inter-story displacement and relative acceleration were good demonstrations for the effectiveness of the control logic. Fig.7 shows the maximum inter-storey displacements of x_3-x_1 and x_2-x_1 . Here the performances of the controlled case and passive case were much better than the fixed case. The maximum value under fuzzy logic was 28.6% and 36.4%, which was smaller than under the passive operation for x_3-x_1 and x_2-x_1 , respectively. Fig.8 shows the simulation results in terms of relative acceleration under three cases. From an overall aspect, the controlled situation performed best and the fixed situation performed the worst. A closer analysis of the simulated data reveals that the peak accelerations $\ddot{x}_3$, $\ddot{x}_2$, and $\ddot{x}_1$, were reduced by 16.7%, 26.8%, and 15%, respectively, under fuzzy logic control, rather than under a passive operation. The simulation results verified that the isolated building performed better under fuzzy logic.

Fig.7. Maximum values of the inter-story displacement.

Fig.8. Maximum values of the relative accelerations for three floors.

4. Experimental results and discussion

The transmissibility of the earthquake motion to the building was measured first by subjecting the isolation system to a sinusoidal sweeping signal, as shown in Fig.9. Obviously, the transmissibility decreased dramatically for the semi-active case, unlike the passive case, which was up to 38.7%. Fig.10 shows the first floor displacement to the ‘ground motion’ such that the magnitude under control was larger than in a passive operation. This was reasonable because the softened isolators under fuzzy logic gave the building more freedom to move, relative to the ‘ground’. This did not alter the effectiveness of isolation because the objective was to minimise the inter-storey displacement to protect the building from fracture or collapse. Fig.11 clearly shows the relative displacement between the first floor and the third floor in three cases, where obviously, the ‘fixed base’ had the worst performance and the controlled case had the minimum magnitude over the

whole period. This minimisation of inter drift would really help the building survive seismic events. Now look at the accelerations of the second floor and the third floor individually, as shown in Fig.12 and Fig.13, respectively. The isolated building definitely performed better than the fixed one, as the difference between the passive case and fixed case show, but it is also clear that the maximum magnitude in the passive case decreased dramatically in the controlled case. Moreover, the reduction in vibration continued until the scaled earthquake ended.

Fig.9. The transmissibility of earthquake motion to the building for passive and semi-active cases.

Fig.10. The relative displacement of the first floor to the ground.

Fig.11. The relative displacement of the third floor to the first floor.

Fig.12. The acceleration response of the third floor.

Fig.13. The acceleration of the second floor.

Table 3. Peak responses of structures due to the El Centro earthquake.

Control strategy	Fixed base	Passive	Controlled
$x_1-x_g (m)$	None	1.49×10^{-3}	2.14×10^{-3}
$x_3-x_1(m)$	1.92×10^{-3}	9.91×10^{-4}	7.75×10^{-4}
$\ddot{x}_3(m/s^2)$	5.02	1.65	0.67
$\ddot{x}_2(m/s^2)$	6.33	0.78	0.58

The peak responses of the structures for each control strategy are provided in Table 3; obviously the fixed base did not perform as well as the passive case and controlled case. Moreover the data indicates that fuzzy logic control effectively reduced the peak responses due to the El Centro earthquake, particularly the inter-storey drift and the accelerations. The maximum inter-storey displacement (x_3-x_1) of 21.8% decreased more under fuzzy logic control than in a passive operation. It was remarkable that the peak third floor acceleration ($\ddot{x}_3$) was 59.4% smaller with fuzzy logic than with the passive control, while peak acceleration of the second floor ($\ddot{x}_2$) decreased by up to 25.6%. These results are quite persuasive and indicate that fuzzy logic was a better choice than semi-active control.

5. Conclusions

A model three storey building with a scaling factor of 1:9 was designed and built for experimental tests. Four MRE isolators that can remain stiff under normal operating conditions and without any power needed and soften its lateral stiffness to isolate the building from seismic hazards were

mounted between the shake table and the model. A scaled El Centro earthquake motion was used as input to excite the isolation system, and fuzzy logic was used to output the current signal sent to change the mechanical property of the isolators in real-time. Both of these simulations and the experimental results showed that fuzzy logic reduced the inter-storey drift and acceleration over the full time range. The reductions in acceleration of the third floor and second floor were by approximately sixty per cent and one quarter, respectively, and relative displacement between the third floor and first floor decreased by more than 20 per cent. These results verified that the stiffness softening MRE isolators isolated vibrations and also proved that fuzzy logic was a better choice for semi-active control.

Acknowledgements

This research is supported by ARC Discovery Grants (Nos. 140100303, 150102636), an ARC Linkage Grant (LP150100040) the National Natural Science Foundation of China (Nos. 51205100, & 51328502), and the University of Wollongong and China Scholarship Council joint scholarships (No. 201206450060).

References

- [1] F. Naeim, Design of seismic isolated structures: from theory to practice: John Wiley & Sons, 1999.
- [2] E. M. Lui, Seismic Isolation for Earthquake Resistant Structures, Journal of Structural Engineering, vol. 127, pp. 1117-1118, 2001.
- [3] P. Pan, D. Zamfirescu, M. Nakashima, N. Nakayasu, and H. Kashiwa, Base-isolation design practice in Japan: introduction to the post-Kobe approach, Journal of Earthquake Engineering, vol. 9, pp. 147-171, 2005.
- [4] H. Yoshioka, J. Ramallo, and B. Spencer Jr, "Smart" base isolation strategies employing magnetorheological dampers, Journal of engineering mechanics, vol. 128, pp. 540-551, 2002.
- [5] J. Ramallo, E. Johnson, and B. Spencer Jr, "'Smart" base isolation systems," Journal of Engineering Mechanics, vol. 128, pp. 1088-1099, 2002.
- [6] T. A. Morgan, The use of innovative base isolation systems to achieve complex seismic performance objectives: ProQuest, 2007.
- [7] J. N. Yang and A. K. Agrawal, Semi-active hybrid control systems for nonlinear buildings against near-field earthquakes, Engineering Structures, vol. 24, pp. 271-280, 2002.
- [8] F. Mazza and A. Vulcano, Effects of near-fault ground motions on the nonlinear dynamic response of base-isolated rc framed buildings, Earthquake Engineering & Structural Dynamics, vol. 41, pp. 211-232, 2012.
- [9] J. Abdalla, J. Petrovski, and Y. Mohamedzein, Vibration characteristics of a far-field earthquake and its shaking effects on Dubai emerging skyscrapers, in 14th World Conference on Earthquake Engineering, Beijing, China, October, 2008, pp. 12-17.
- [10] N. Wongprasert and M. Symans, Experimental evaluation of adaptive elastomeric base-isolated structures using variable-orifice fluid dampers, Journal of Structural Engineering, vol. 131, pp. 867-877, 2005.

- [11] P.-Y. Lin, P. Roschke, and C. Loh, Hybrid base-isolation with magnetorheological damper and fuzzy control, *Structural control and Health monitoring*, vol. 14, pp. 384-405, 2007.
- [12] L.-Y. Lu and G.-L. Lin, Fuzzy friction controllers for semi-active seismic isolation systems, *Journal of Intelligent Material Systems and Structures*, vol. 20, pp. 1747-1770, 2009.
- [13] J. M. Kelly, The role of damping in seismic isolation, *Earthquake engineering & structural dynamics*, vol. 28, pp. 3-20, 1999.
- [14] M. Behrooz, X. Wang, and F. Gordaninejad, Performance of a new magnetorheological elastomer isolation system, *Smart Materials and Structures*, vol. 23, art. no. 045014, 2014.
- [15] M. Behrooz, X. Wang, and F. Gordaninejad, Modeling of a new semi-active/passive magnetorheological elastomer isolator, *Smart Materials and Structures*, vol. 23, art. no. 045013, 2014.
- [16] W.H. Li, Y. Zhou, and T.F. Tian, Viscoelastic properties of MR elastomers under harmonic loading, *Rheologica Acta*, vol. 49, pp. 737-740, 2010.
- [17] K.M. Popp, M. Kroger, W. Li, X.Z. Zhang, and P.B. Kosasih, MRE properties under shear and squeeze modes and applications, *Journal of Intelligent Material Systems and Structures*, vol. 21, pp. 1471-1477, 2010.
- [18] Y. Li, J. Li, W. Li, and B. Samali, Development and characterization of a magnetorheological elastomer based adaptive seismic isolator, *Smart Materials and Structures*, vol. 22, art. no. 035005, 2013.
- [19] Y. Li, J. Li, T. Tian, and W. Li, A highly adjustable magnetorheological elastomer base isolator for applications of real-time adaptive control, *Smart Materials and Structures*, vol. 22, art. no. 095020, 2013.
- [20] W. Robinson, Lead-rubber hysteretic bearings suitable for protecting structures during earthquakes, *Earthquake Engineering & Structural Dynamics*, vol. 10, pp. 593-604, 1982.
- [21] K. Fuller, J. Gough, T. Pond, and H. Ahmadi, High damping natural rubber seismic isolators, *Journal of Structural Control*, vol. 4, pp. 19-40, 1997.
- [22] S. Sun, H. Deng, J. Yang, W. Li, H. Du, G. Alici, and M. Nakano, An adaptive tuned vibration absorber based on multilayered MR elastomers, *Smart Materials and Structures*, vol. 24, art. no. 045045, 2015.
- [23] J. Yang, S. Sun, H. Du, W. Li, G. Alici, and H. Deng, A novel magnetorheological elastomer isolator with negative changing stiffness for vibration reduction, *Smart Materials and Structures*, vol. 23, art. no. 105023, 2014.
- [24] J. Yang, H. Du, W. Li, Y. Li, J. Li, S. Sun, *et al.*, Experimental study and modeling of a novel magnetorheological elastomer isolator, *Smart Materials and Structures*, vol. 22, art. no. 117001, 2013.
- [25] R. S. Mills, Model Tests on Earthquake Simulators: Development and implementation of experimental procedures, 1979.
- [26] R. S. Subramaniam, A. M. Reinhorn, M. A. Riley, and S. Nagarajaiah, "Hybrid control of structures using fuzzy logic," *Computer-Aided Civil and Infrastructure Engineering*, vol. 11, pp. 1-17, 1996.
- [27] L. Zhou, C.-C. Chang, and B. Spencer, Intelligent technology-based control of motion and vibration using MR dampers, *Earthquake Engineering and Engineering Vibration*, vol. 1, pp. 100-110, 2002.