Investigation of Adaptive Base Isolation System Utilising Magnetorheological Elastomer

By: **Xiaoyu Gu**

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University of Technology, Sydney

Faculty of Engineering & IT

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To my dearest parents

CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Date

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LIST OF PUBLICATIONS RELATED TO THIS THESIS

Refereed Journal Articles

1. **Gu, X.**, Li, Y. & Li, J., 2016. Investigations on response time of magnetorheological elastomer isolator for real-time control implementation. *Smart Materials and Structures*. 25(11), p.11LT04.
2. **Gu, X.**, Li, J., Li, Y. & Askari, M., 2016. Frequency control of smart base isolation system employing a novel adaptive magneto-rheological elastomer base isolator. *Journal of Intelligent Material Systems and Structures*. 27(7), pp.849-858.
3. **Gu, X.**, Yu, Y., Li, J., Li, Y., & Alamdari, M. M. 2016. Semi-active storey isolation system employing MRE isolator with parameter identification based on NSGA-II with DCD. *Earthquakes and Structures*, 11(6), 1101-1121.
4. **Gu, X.**, Yu, Y., Li, J. & Li, Y. 2017. Utilising optimal general regression neural network (GRNN) inverse model for modelling and control of magnetorheological elastomer base isolation system. *Journal of Sound & Vibration*. (Accepted)
5. Yu, Y., Li, Y., Li, J. & **Gu, X.**, 2016. Self-adaptive step fruit fly algorithm optimized support vector regression model for dynamic response prediction of magnetorheological elastomer base isolator. *Neurocomputing*. 211, pp.41-52.
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7. Yu, Y., Li, Y., Li, J., **Gu, X.** & Royel, S., 2016. Dynamic modelling of magnetorheological elastomer base isolator based on extreme learning machine. *Mechanics of Structures and Materials: Advancements and Challenges*. pp. 703-

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8. Askari, M., Li, J., Samali, B. & **Gu, X.**, 2016. Experimental forward and inverse modelling of magnetorheological dampers using an optimal Takagi–Sugeno–Kang fuzzy scheme. *Journal of Intelligent Material Systems and Structures*. 27(7), pp.904-914.

Conference Paper

1. **Gu, X.**, Li, J. & Li, Y. 2014. Adaptive base isolation system with magneto-rheological elastomer base isolators: numerical investigations. *Proceeding of the sixth World Conference on Structural Control and Monitoring (6WCSCM)*, Barcelona, Spain.
2. **Gu, X.**, Li, J., Askari, M. & Li, Y. 2014. Semi-active control of an innovative adaptive base isolation system. *14th International Conference on ER Fluids and MR Suspensions (ERMR2014).* Spain.
3. **Gu, X.**, Li, J. & Li, Y., 2014. Innovative semi-active storey isolation system utilising novel magneto-rheological elastomer base isolators. *Proceeding of 23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23)*. Byron Bay, Australia

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ABSTRACT

Most of current researches on controllable or "smart" base isolation systems have been based on the hybrid of conventional base isolation system with active or semi-active dampers. Although supplementary dampers may help to reduce maximum displacement of base isolation systems and provide adjustable damping to suppress vibrations of the protected structure, it suffers some setbacks such as introduction of undesirable acceleration, limited performance due to the passive nature of base isolation, etc. Moreover, those "smart" supplementary dampers failed to add "smartness" or controllability toward working mechanism of isolation systems, i.e. decoupling ground motion from superstructures. In recent years, the development of adaptive base isolator utilising magnetorheological elastomer (MRE) shed light on "truly" smart base isolation systems in which isolators' lateral stiffness can be controlled in real time by varying applied current. To this end, the MRE base isolation system exhibits a promising potential for ultimate seismic protection of civil infrastructures due to its ability to maximise, in real time, level of decoupling between ground motion and the superstructure. However, there have been only limited researches reported in this area. In addition, there is lack of throughout investigations, especially experimental investigation, on critical issues and feasibility related design and implementation of such MRE-based smart base isolated system, which is much needed for future development and application.

This thesis is aimed at filling aforementioned research gap in development and application of MRE-based smart base isolated system by contributing new knowledge in the fields in terms of: i) modelling of the MRE isolator to capture its forward and inverse dynamic characteristics; ii) comprehensive investigation on the response time of MRE isolator and exploration of approaches to minimise the lag; iii) overcome

obstacles in experimental realisation of smart base isolation system; iv) other innovations in seismic protection of civil infrastructures employing MRE isolator.

First, the modelling of the MRE isolator is conducted for dynamic response prediction of the device. Two forward models of the isolator are proposed and compared, namely, a phenomenological model based on hysteresis Bouc-Wen model and innovative strain-stiffening model identified by least square (LS) function. Performance evaluation of the model has been conducted based on the experimental testing data from MRE isolator. Furthermore, due to the inherent nonlinearity and hysteretic characteristics of the devices, it is challenging to obtain a less complicated mathematical model to describe the inverse dynamics of MRE base isolators and hence to perform control synthesis of the MRE base isolation system. Therefore, an optimal general regression neural network (GRNN) inverse model has been proposed to depict the inverse dynamics of the isolator. With the inverse model, the nonlinearity and phenomenological hysteresis brought into control system by the MRE isolator can be neutralised for the classic control algorithm like LQR to be feasible.

Real-time control of the MRE isolators holds the key to unlock MRE materials' unique characteristics, i.e. instantly changeable shear modulus in continuous and reverse fashion. However, one of the critical issues for the applications of real-time control is the response time delay of MRE vibration isolators, which has not yet been fully addressed and studied. Therefore, the next topic of this thesis is to identify the inherent response time of the MRE isolator and explore feasible approaches to minimise the response time delay. The definition and experimental measurement of the response time of MRE isolator is presented, followed by three response time reduction approaches, i.e. PWM servo current drive, modification of isolator's solenoid and innovative configuration of solenoid excitation.

A three-storey shear building model is then designed as the testing bed of proposed MRE base isolation system. Various control algorithms are proposed, developed and formulated to explore the capability of the smart isolation system, includingnon-

dominated sorting genetic algorithm optimised neural fuzzy logic control (NSGA-NFLC), Bang-Bang control, LQR control with GRNN inverse model, frequency control and Lyapunov-based current selection control. Comprehensive investigation of seismic protection performance of the MRE isolation system has been conducted numerically and experimentally. Promising vibration suppression performance has been observed in most controlled solation scenarios, particularly in NSGA-NFLC and Lyapunov controller.

Finally, an innovative storey isolation system utilising MRE isolator has been proposed and numerically evaluated. The advantage of storey isolation system lies in that it can distribute the deformation of base isolation system into different levels, leading to effective solution of extensive base displacement issue faced by conventional base isolation system. The NSGA-II is utilised to seek for the optimal placement of isolators and current input of each device. The Lyapunov-based current selection control is employed for the control of the storey isolation system. A comprehensive numerical testing compares the seismic responses of bare building, building with passive controlled MRE base isolation system, building with optimal MRE storey isolation system and controlled storey isolation system. Simulation results indicate that the controlled storey isolation system is capable of significantly mitigating the floor acceleration and base displacement as well as avoiding whipping effect problem in passive storey isolation system.