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Semi-active control of magnetorheological elastomer base isolation system utilising learning-based inverse model

Xiaoyu Gu, Yang Yu, Jianchun Li*, Yancheng Li*

Centre for Built Infrastructure Research, School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology, University of Technology Sydney, NSW 2007, Australia

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ABSTRACT

Magnetorheological elastomer (MRE) base isolations have attracted considerable attention over the last two decades thanks to its self-adaptability and high-authority controllability in semi-active control realm. Due to the inherent nonlinearity and hysteresis of the devices, it is challenging to obtain a reasonably complicated mathematical model to describe the inverse dynamics of MRE base isolators and hence to realise control synthesis of the MRE base isolation system. Two aims have been achieved in this paper: i) development of an inverse model for MRE base isolator based on optimal general regression neural network (GRNN); ii) numerical and experimental validation of a real-time semi-active controlled MRE base isolation system utilising LQR controller and GRNN inverse model. The superiority of GRNN inverse model lays in fewer input variables requirement, faster training process and prompt calculation response, which makes it suitable for online training and real-time control. The control system is integrated with a three-storey shear building model and control performance of the MRE base isolation system is compared with bare building, passive-on isolation system and passive-off isolation system. Testing results show that the proposed GRNN inverse model is able to reproduce desired control force accurately and the MRE base isolation system can effectively suppress the structural responses when compared to the passive isolation system.

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1. Introduction

Magnetorheological elastomer (MRE) with magnetisable particles being dispersed in a rubber-like solid matrix [10,20], possesses changeable shear modulus that can be instantly controlled in a real time fashion through applying external magnetic field [19]. Such unique feature has been widely utilised in research and development of MRE-based devices as semi-active controllable elements for vibration isolation in mechanical engineering, such as MRE based tunable stiffness and damping vibration isolator [19], MRE seat suspension isolator [11], engine vibration isolator [1], etc. In civil engineering, MRE has been proposed to develop semi-active base isolation systems to protect civil structures against earthquakes [17,18,29,5].

One of the key challenges to achieve such development lays on design and implementation of real time feedback control of MRE base isolation system utilising its controllable change of shear stiffness. Semi-active control is considered to be superior to both passive control and active control as it enables high authority control for high performance and flexibility as

* Corresponding author.
E-mail addresses: Jianchun.li@uts.edu.au (J. Li), Yancheng.li@uts.edu.au (Y. Li).

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that of active control without compromising reliability and energy requirement [22,31]. However, the design of adequate semi-active controller to enable control effectiveness and efficiency imposes a challenge due to the nature of the semi-active control, i.e. the control action, which is also a function of the system status, can only be indirectly achieved by adjusting mechanical properties of semi-active devices such as stiffness or damping. On the other hand, most semi-active devices, such as MRF dampers or MRE isolators are known to be highly nonlinear and hysteretic by nature. A great deal of research efforts have been made to explore semi-active control of MRF dampers, such as modal based LQG controller (Wang and Dyke, 2013), [24] Lyapunov-based control methods [16,30,23,4], turbo-Lyaounov control (Cha and Agrawal, 2013) [7], optimal control (Hiemenz et al. 2003), [15] genetic algorithm optimised fuzzy logic control [28]. In comparison to MRF dampers, since research on real time control of MRE base isolation system is still at a conceptual and feasibility proof stage, there have been only limited control strategies explored for MR elastomer base isolation system [6,13,29]. Different from MRF dampers or other semi-active devices, the principle of controlling MRE base isolators to protect structures is to produce instant motion decoupling between the harmful vibration source and the protected structures.

To control a structure equipped with semi-active devices, such as MRF dampers, the design of controllers often requires two stage actions in order to generate the required control: (i) determining the desired primary control action (such as actuation force) based on the feedback responses; (ii) determining required control command (i.e. the current/voltage) to drive the semi-active devices in order to generate primary control action [27]. In other words, the control action required by the semi-active system relies on not feedbacks of the system but the inversed dynamics of the semi-active devices under a given status of the devices (i.e. instant displacements, velocities and accelerations).

When it comes to semi-active control approaches, a good demonstration is the clipped-optimal control (COC) proposed by Dyke et al. (1996) [12] for real-time control of structures equipped with the MR dampers. In this control strategy, a simple clipped algorithm is used to generate the control command (zero or maximum voltage) to drive MR dampers based on the measured force feedback. The control strategy combines H_2/LQG optimal controller for calculating the desired control force and a voltage selecting algorithm for driving MR damper. In another word, two feedback loops are required: one for determining the desired control force from the system feedbacks and the other one for determining control command (voltage to drive the devices) from the measured force feedback [16]. There are two major drawbacks in these kinds of control strategies: firstly, the measurement of feedback actuation force might not be always feasible, e.g. in the case of MRE base isolator and secondly, the control efficiency is greatly compromised due to simple clipped control (zero or maximum). To this end, utilising inverse models that describes inverse dynamics between command signals and actuator force for determining control command to drive the device based on system feedbacks becomes popular in recent semi-active control research [3,8,26]. However, due to inherent highly nonlinear and hysteretic nature of semi-active devices, it is not feasible to obtain explicit inverse dynamic model of semi-active devices. Taking advantage of neural network (NN) models in emulating arbitrary function at various accuracy levels (Cybenko, 1989), [9] several neural network based inverse models have been investigated for applications of MR dampers. Chang et al. (2002) explored the possibility of utilising the recurrent NN models to estimate the inverse dynamics of the MR dampers. Xia [27] has developed an inverse model for MR damper utilising optimal multi-layer NN and system identification. Weber et al. [25] utilised a neural network-trained inverse model of MR damper and applied the scheme on the vibration control of a five storey shear model. Askari et al. [2] investigated an NN inverse model optimised by Takagi-Sugeno-Kang fuzzy scheme and such inverse model can well recurrent the desired control force. However, inverse models published so far are complicated and unsuitable for real-time control applications. For example, they often require information not only at the present moment but also in previous time history [27], 2 historical time instants tracked; [25], 4 historical time instants tracked; [2], 5 variables with 3 historical time instants tracked each). The more retroactive information required, the longer inevitable delay tolerance will be produced. Some require a wide range of system inputs as training signal and extremely careful selection of regressor set. In addition, there is neither inverse model nor current selecting strategy being reported for real-time control of the MR elastomer base isolation systems.

To address the aforementioned challenges, this paper proposes a novel semi-active control for real-time feedback control of a MRE base isolation system. A classical LQR controller is selected as the primary controller to calculate desired control force based on the structural response. To generate the desired force, an inverse model based on general regression neural network (GRNN) is developed to determine the applied current to the MR elastomer isolator.

The main superiority of the proposed GRNN-based inverse model is summarised as follows:

- The model structure of GRNN-based inverse model is free of assumptions, which avoids complicated model identification.
- the proposed GRNN inverse model only requires inputs of displacement, velocity, force at present and one previous time instant, which will result in much less delay tolerance in the control.
- The GRNN adopts one-pass-learning algorithm which makes it much faster to form the conditional mean regression surface than commonly used back propagation (BP) algorithm, which is beneficial to online model training in the practical application.
- Different from other neural networks, the predictions of GRNN is always apt to converge to the global optimal solution and will not fall into the local optimum.
- The time interval from the calculation of optimal control force to the generation of the desired applied current is less than 1 ms, satisfying the requirement of real-time structural control.

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