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

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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.

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 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

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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 produce 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.