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A variable resonance magnetorheological-fluid-based pendulum tuned mass damper for seismic vibration suppression

M.D. Christie [a], S. Sun [a,*], L. Deng [a], D.H. Ning [b], H. Du [b], S.W. Zhang [c,*], W.H. Li [a]

[a] School of Mechanical, Materials Mechatronic and Biomedical Engineering, University of Wollongong, New South Wales 2522, Australia
[b] School of Electrical, Computer & Telecommunications Engineering, University of Wollongong, New South Wales 2522, Australia
[c] Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, Hefei, Anhui Province 230026, China

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ABSTRACT

Seismic events leading to catastrophic outcomes around the world, particularly in built-up regions surrounding fault lines, often have high death tolls and cause costly damages to societies' existing infrastructure. To suppress damaging vibrations in multi-story buildings across a wide frequency spectrum, much research has been put into the study of variable-resonance tuned mass dampers, which maintain their usefulness across a range of frequencies, unlike passive alternatives. As a novel implementation of fast responsive magnetorheological materials to enable variable resonance, this paper presents a prototype magnetorheological-fluid-based pendulum tuned mass damper, integrating a differential gearbox to yield a damper-controlled transmission between the pendulum mass and a mechanical spring. The device is demonstrated to be highly effective, at its best reducing peak relative displacement by 12.8%, and peak acceleration by 22.0%, in contrast to comparable passive tuning modes in scale-building seismic experiments. This is owed to its controllable resonance which can be increased by 104% from its base value at 2.24 Hz. Further, other performance benefits are demonstrated in RMS structure displacement, and interstory drift ratio.

1. Introduction

Urban areas with high population density and large infrastructure nearby fault lines are at high risk of catastrophic failure where large structures and multi-story buildings are not well-protected against seismic activity. Techniques that may be used for such protection against ground-level disturbances include vibration isolation and vibration absorption. The approach of vibration isolation involves the mechanical decoupling of the structure from the input, i.e. the ground, to attenuate the input at its source [1]. A more common approach to suppress damaging vibrations in multi-story buildings, in-part due to these structures having long periods of vibration thereby making low-stiffness isolators impractical [2], is the implementation a vibration absorber or tuned mass damper (TMD) into the structure, which absorbs energy to attenuate the motion [3]. These systems primarily consist of a mass to absorb energy, along with mechanical or implicit stiffness and some form of damping to eventually dissipate the energy stored in the mass.

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* Corresponding authors.
E-mail addresses: ssun@uow.edu.au (S. Sun), swzhang@ustc.edu.cn (S.W. Zhang).

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With the description of what constitutes a tuned mass damper being quite general, it should come as no surprise that a variety of functional TMDs exist, with numerous prototypes having been proposed and many seeing implementation. Taiwan's Taipei 101 skyscraper is one of the more well-known instances where a TMD has been implemented into a structure where a high level of seismic activity, in addition to strong winds, must be compensated for [4,5], with this device being a pendulum-TMD (PTMD): a large oscillating mass supported by links or cables [3,6]. Another variant of TMD is the tuned liquid column damper (TLCD), essentially a reservoir of water which can absorb vibrational energy and dissipate it through internal water motion [3]. A remaining sub-class of TMD which is the conventional sliding or shear-mode TMD, which primarily consists of a mass constrained to move in the direction of the motion to be attenuated [3,7,8].

Such devices, which may differ in their design and working mechanism, are by definition passively tuned to resonate at (typically) a single given frequency. With the dominant frequency of earthquakes varying over their span of occurrence and from case to case, however, such passive devices have limited effectiveness across the possible frequency spectrum of these events. This is further exacerbated in regions where both near-field and far-field seismic activity may occur, due to their unique characteristics and greater uncertainty in the dominant frequencies of these events [9,10]. It is for this reason that a large aspect of research in this field is targeted at variable resonance devices and control efforts to compensate for unpredictable seismic activity. This variable resonance can be achieved for TMDs through one of two ways: active control of force using actuators, or control of system mechanical properties (semi-active control). While active control typically yields somewhat greater performance than comparable semi-active systems, it tends to lack the robustness and predictable behaviour of the semi-active systems [11,12], which also tend to have lower operating costs due to lower energy requirements [11–13]. It is in this area of semi-active control that magnetorheological (MR) materials have seen effective use and implementation.

Magnetorheological materials are a class of smart material which exhibit altered rheological properties under the application of a magnetic flux. Of the variants of these materials fabricated, the main two families that exist are MR-fluids (MRFs), and MR-elastomers (MREs). As a magnetic field is applied to either class of material, suspended micro-scale iron particles tend to align to the magnetic field lines, which in the case of MRFs results in increased viscosity and damping during flow, and for MREs this primarily causes an increase in stiffness [14,15]. Given the ease of generating a magnetic field using an electromagnet, along with a rapid response rate in the order of milliseconds [14,16], control of devices making use of these materials is exceptionally simple. Consequently, MR dampers have been studied for some time now in structural vibration control, among other uses, with reportedly reasonable success [17–20]. More recently however, due to the improved versatility offered by variable resonance, use of stiffness-controllable MRE in TMD designs has increasingly been reported [7,21–24]. Where MR fluid lacks the direct ability to provide variable stiffness and hence variable resonance, the fluid may have greater practicality and viability for use, given MR elastomer could potentially yield while in use, whereas MR fluid typically operates in a state of constant yield. With this in mind, variable stiffness has previously been achieved using MR dampers connected with mechanical springs, as recently reported in the linear shock absorbers presented by Sun et al. [25,26]. Exploiting this concept for vibration absorption specifically, however, has seen limited implementation and testing. Enabled through an innovative stiffness variation mechanism with MRF materials, such variable resonance is one of the key aspects of the design presented in this work, the magnetorheological pendulum tuned mass damper (MR-PTMD).

Through the use of a rotary MR damper coupled with a differential gearbox, the MR-PTMD couples an additional torsional spring to the pendulum mass through a variable transmission. This allows effective and simple control of TMD resonance through the control of electric current fed into the damper's electromagnetic coils. Applying short-time Fourier transform (STFT), feedback control is used to set the resonance to match any given input signal over the tuneable range of the device. Aside from exploring this relatively new and unconventional concept of variable stiffness using MR fluid, the innovative MR-based differential gearbox design utilised offers appreciable improvement over the alternative passive tuning modes for the device.

Following this section, the remainder of the paper is organised as follows. Section 2 details the design, magnetic field modelling, and working mechanism of the MR-PTMD. Section 3 includes experimental characterisation and controller development of the device under harmonic loading. Section 4 then details the performance of the device in scale-building experiments under seismic loading. Conclusions are lastly outlined in Section 5.

2. Design and working mechanism of the MR-PTMD

2.1. MR-PTMD structure

With the prototype MR-PTMD design illustrated in the CAD model of Fig. 1, the device has a frame constructed out of aluminium extrusion, housing a rotary MR damper coupled to a mechanical spring and hanging mass through a planetary gearbox. The pendulum mass m_p has a design weight of 1.75 kg, with its centre at a distance l_p of 70 mm from its rotation axis. The spring of the device is a compression spring used in torsion, possessing a torsional stiffness k_t of 1.67 N·m/rad, which is held under a slight axial pre-load to maintain constant gear-meshing inside the gearbox as the spring rotates. These design parameters as listed were selected under the assumption of a typical mass ratio of approximately 0.1 [6], as a guideline. This was followed by a small degree of heuristic tuning, utilising Eqs. (1) and (2) to establish an acceptable frequency shift range. Supporting the internal assembly are light-weight 3D printed Nylon supports, with the mass hanger being made similarly.