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

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Abstract

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A Variable Resonance Magnetorheological-Fluid-Based Pendulum Tuned Mass Damper for Seismic Vibration Suppression

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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.

Keywords: magnetorheological fluid, building protection, vibration absorber, tuned mass damper, differential

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.

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 Figure 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 Equations 1-2 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.

When electric current is supplied to the internal coils of the damper, this induces a magnetic field which can increase the damping torque of the device. If no current is applied, there is minimal

damping torque produced, and hence through the differential gearbox, rotational motion of the mass is primarily transmitted to the free-spinning damper, rather than the torsion spring. As current is increased from 0 A to the full-scale range of 3 A, the damper increasingly resists motion transfer to its rotor, hence increasing the transmission of motion to the torsion spring. While this will be better elaborated on in the following sub-sections, this basic working should highlight that the continuous control of the MR damper can essentially add stiffness to the pendulum mass, thereby yielding variable resonance in the device. In contrast to the alternative tuning of pendulum length l_p to set PTMD resonance, for example through motor-driven support cable adjustment [27], this MR-based design: possesses a rapid response rate which is not influenced by the pendulum mass inertia, does not suffer a trade-off between power consumption and drive-system response rate, and offers a rapid transition between resonant frequencies without the need to gradually shift from one to another.

Figure 1 – MR-PTMD prototype CAD model (dims in mm)

2.2. Rotary MR Damper Design

Illustrated through the CAD model of Figure 2 is the rotary MR damper which facilitates control of the TMD's resonance. The damper itself is quite compact with a maximum diameter of 47 mm and a body length of 38 mm. The MRF (MRF-140CG, produced by LORD Corp.) in the joint surrounds a rotor adjacent to two electromagnetic coils wired in series. These coils of 120

turns each can supply magnetic flux through the magnetic circuit made of high-permeability low carbon steel when current is input. The MRF in the 0.5 mm wide radial gaps inside and outside of the rotor drum is then subject to an increased yield stress and viscosity, increasing the braking torque between the aluminium shaft and outer-body, i.e. yoke, of the damper. Regarding the behaviour of the ‘T-shaped’ drum, this design essentially acts as a normal drum-type damper, however with a larger active area of MRF and less unnecessary geometry, reducing weight. Furthermore, this design trades the requirement of the large radial area needed in MR disc-type dampers for a more manageable increase in axial length of the damper, facilitating a more compact prototype than would have otherwise been possible.

Figure 2 – Rotary MR damper schematic (dims in mm)

As for the considerations that went into the design of the damper, a 2D axisymmetric field study was developed in the FEM software COMSOL Multiphysics ver. 5.1. Within this simulation, the MRF was defined by the B-H curve LORD Corp. has provided in the material data sheet for MRF-140CG [28], and the steel of the magnetic circuit was set to possess a relative permeability μ_r of 300. All other materials as detailed in Figure 2 were defined by the built-in properties of the software package. Through iteration, the geometry of the joint was revised to meet an optimal trade-off between weight and magnetic flux penetrating the MRF. Plotted in Figure 3(a) is the simulated mean flux through the inner and outer gaps of the damper under the application

of a 0 A to 3 A current range, with these regions highlighted in the model shown in Figure 3(b). Within this result, it is seen that under a 3 A current, the maximum flux through the MRF achieved is 1.184 T in the inner gap, along with 0.673 T in the outer gap. The seemingly large deviation amongst these flux densities of the two gaps is primarily due to the inverse proportionality between flux density and area, with the area increasing radially outwards. It should be noted, however, that due to the increasing moment arm at a larger radius as well as a larger shear area, the torque contribution of what would be a region of relatively low shear-stress MRF in the outer gap, is in fact similar to that of the inner gap.

Figure 3 – Magnetic field FEM analysis: (a) mean flux through MRF, (b) joint model

2.3. MR-PTMD Working Mechanism

In itself, the presented MR damper is capable of varying the resistance to rotation through an increased level of damping torque that may be output. When connected to one of the three ports of a planetary gearbox, as illustrated in Figure 4, this effectively governs the relative motion between the other two. With the MR damper connected to the planet carrier, and a torsional spring of stiffness k_t connected to the sun gear, the pendulum mass m_p is affixed to the ring gear, serving as an input to the system as it rotates an angle θ due to the linear input displacement x_{in} . At first disregarding the relative gear ratios between these three ports of the gearbox, the basic behaviour of the MR-PTMD can be explained by considering the torque balance between the damper and the spring. As the mass swings, this would then drive both the damper and spring to rotate together, with the torque between the two elements at the gear-mesh being balanced.

Suppose then the case in which the MR damper is turned off, with zero current passing through the internal coils. With quite a low output torque, the damper shaft would easily rotate at an angle θ_1 , whereas the spring would balance this torque with a small, near-zero rotation angle θ_2 . In this case, the spring would essentially be inactive, meaning the TMD stiffness would be given only by the pendulum mass, with a natural frequency dependant only on the pendulum length l_p , as described in Equation 1:

$$\omega_{n,min} = \sqrt{\frac{g}{l_p}}. \quad (1)$$

On the other hand, if the damper was turned on with a high current, the large output torque would need to be balanced by a similarly large spring torque, meaning the spring would then be active, with the spring stiffness adding to that of the pendulum mass, assuming the damper to be relatively very stiff. This would result in a natural frequency given by the following [29], Equation 2:

$$\omega_{n,max} = \sqrt{\frac{g}{l_p} + \frac{k_t}{m_p l_p^2}}. \quad (2)$$

For anywhere in between these two extremes, the amount of stiffness added by the spring would exist within these limiting cases, with the damper-controlled gearbox governing this amount.

Regarding the behaviour of the planetary gearbox, not only does it allow the damper to govern the effective PTMD stiffness in a compact overall design, but the gear ratios between the elements connected also influence its operation. The ring, planet, and sun gears have the teeth numbers of $N_R = 42$, $N_p = 16$, and $N_S = 9$, respectively. From these, the gear ratios from the MR damper and spring relative to the pendulum mass input can be established from Equation 3:

$$GR_s = \frac{N_R}{N_S}, \quad (3)$$

giving a ratio of 4.667 in the case of the spring (connected to the sun gear), and from Equation 4:

$$GR_{PC} = \frac{N_R}{N_R + N_S}, \quad (4)$$

giving a ratio of 0.8235 for the MR damper (connected to the planet carrier). The justification for connecting the damper to the low torque side and the spring to the high torque side is that a lower initial torque for the damper is desirable to set a minimum PTMD stiffness, and the spring gear ratio effectively increases the spring stiffness without requiring a larger spring, or one that is shorter and under a higher stress.

Figure 4 – MR-PTMD working mechanism diagram

3. Harmonic Vibration Analysis

3.1. Experimental Investigation of the Variable Resonance Property

A series of tests were conducted on the prototype MR-PTMD, using a single-axis shaker table, as depicted in the experimental setup of Figure 5. These were performed in order to characterise its vibration attenuation and frequency shift capabilities under the application of varied current to the damper. As shown, an electrodynamic shaker (VTS VC100-8) connected to a table resting upon linear bearings provided the harmonic input displacement to the affixed device, utilising a laser displacement sensor (Micro-Epsilon ILD1700-50) for input measurement and PID feedback

control. To measure the response of the TMD mass, another laser displacement sensor (Keyence LB-11/LB-70) was targeted at the centre of the mass, measuring its absolute displacement, i.e. relative to ground. To control the shaker and record the measured data, a data acquisition (DAQ) board (NI PCI-6221) was used, connected to a computer running a LabVIEW program to orchestrate the tests. Within the program, staged frequency sweeps can be performed, with the device allowed to settle sufficiently before testing the next frequency increment. Internally, both the transmissibility Q and phase ϕ of the TMD mass were computed using the following equations [23], Equations 5-6, respectively:

$$Q = \sqrt{\frac{1 + (2\varepsilon\lambda)^2}{(1 - \lambda^2)^2 + (2\varepsilon\lambda)^2}}, \quad (5)$$

and:

$$\phi = \tan^{-1}\left(\frac{-2\varepsilon\lambda^3}{1 - \lambda^2 + (2\varepsilon\lambda)^2}\right), \quad (6)$$

where $\lambda = f/f_n$, i.e. the ratio of the input frequency f to natural frequency f_n of the TMD. This natural frequency comes from $f_n = \sqrt{k_e/m_p}/2\pi$, where k_e is the effective stiffness in the linear translation axis, and m_p is the pendulum mass. The last term is computed as $\varepsilon = c_e/4m_p\pi f_n$, where c_e is the equivalent damping coefficient in the linear translation axis of the device.

Figure 5 – Shaker frequency sweep experimental setup

The tests were performed at a constant displacement amplitude of 10 mm, over a frequency range of 1.5 Hz to 10 Hz, with the damper current incremented in 0.5 A steps from 0 A to 3 A. Highlighted in Figure 6, the variable resonance property of the TMD is demonstrated, with the device being capable of a 104% increase from the base (0 A) resonance at 2.24 Hz, to the maximum (3 A) resonance at 4.58 Hz. This added absorption bandwidth is a clear indication of an increased effectiveness over a larger frequency range, provided an appropriate control approach is utilised to control damper current.

Figure 6 – MR-PTMD resonance shift under varied current

3.2. Controller Design

3.2.1. Short-time Fourier transform control algorithm

In order to control the resonance of the MR-PTMD, short-time Fourier transform (STFT) was selected for its relative simplicity in implementation and its successful use reported in similarly

semi-active TMD's [7, 23, 30, 31]. Through appropriate adjustment of window time, STFT can yield the dominant frequency of a signal in a given time-frame, from which, in this case, an optimal damper current can be selected such that the TMD best attenuates the input vibration for any frequency within its tuneable range [30]. Such analysis is governed by the following equations describing STFT, Equations 7-10, starting with the segmentation of the input signal $x(t)$:

$$x_\tau(t) = x(t)h(t - \tau), \quad (7)$$

where $x_\tau(t)$ is the input signal segment, t is time, and $w(t - \tau)$ is a window function with a fixed window time τ . The Fourier transform of the windowed segment of the input is then performed:

$$X_\tau(\omega) = \frac{1}{\sqrt{2\pi}} \int x_\tau(t) e^{-j\omega t} dt, \quad (8)$$

where $X_\tau(\omega)$ is the Fourier transform of the windowed signal, and ω is angular frequency. The energy density spectrum, denoted by $P(\tau, \omega)$, of this signal for a given window time τ is equal to the square of the determined Fourier transform:

$$P(\tau, \omega) = |X_\tau(\omega)|^2. \quad (9)$$

From this definition, the instantaneous dominant frequency $\langle \omega_\tau \rangle$ can be computed from:

$$\langle \omega_\tau \rangle = \frac{1}{|x(\tau)|^2} \int \omega P(\tau, \omega) d\omega. \quad (10)$$

With the dominant frequency known, a function that maps input frequency to output current for the MR damper within the MR-PTMD then needs to be experimentally determined for STFT to be implemented in this work.

3.2.2. Experimental control-function development

To experimentally determine the frequency-current relationship, the 5-story scale building constructed for later seismic protection testing was utilised. Pictured in Figure 7 is the experimental setup for these tests, with the MR-PTMD mounted on the top floor of the 5-story

building atop a 6-DOF linear-actuator excited shaker platform. The scale building itself was constructed based on a ~20 m tall building according to dimensional scaling laws [32], built with a length scale factor of 1:20 and a corresponding mass scale factor of 1:20³, resulting in floor spacing of 180 mm, and a floor mass of 3.6 kg. Regarding the input motion, the shaker platform provided harmonic or pre-configured (seismic) input signals along a single translational axis, while acceleration data was collected using two accelerometers (ADXL 203EB), with one placed at the ground level and another placed at a probe location on one of the five floors. Additionally, displacement data relative to ground was collected using a laser displacement sensor (Micro-Epsilon ILD1302-100), with adjustable height to target a selected floor. With this data feeding into a DAQ (NI cDAQ-9174 with NI 9201 module) for logging, an NI myRIO-1900 was used to control the damper current, using an amplifier to provide the necessary power output.

Figure 7 – Scale building experimental setup

In this first mode of testing using the scale building setup, a series of harmonic loadings tests were conducted from 1 Hz to 6 Hz, capturing the resonance of the structure, and the working range of the MR-PTMD. Within these experiments, current was set manually between each test run over a 0 A to 3 A range; analysing the time-response of the top-floor and ground-floor

accelerations, the transmissibility was calculated for each test frequency and current. Included in Figure 8 are the normalised test results obtained, with the optimal control points highlighted; given the target is to minimise or best attenuate transmissibility of ground-level vibrations, these minima correspond to the optimal control currents for each test frequency. As anticipated from previous shaker testing, and in-line with a heuristic understanding of similar MR-based systems, this ideal control current shifts from 0 A to 3 A in a positive relationship with input frequency.

These control currents, also listed in Table 1 along with their corresponding minimum normalised transmissibility, were then fit with a 3rd order polynomial saturating at 0 A and 3A, as illustrated in Figure 9. The function describing this behaviour and governing the control output $I(f)$ can be expressed using a series of if statements, Equations 11-13, to bound the polynomial within the saturation frequencies 2.62 Hz and 4.43 Hz:

if $f < 2.62$ Hz,

$$I(f) = 0 \text{ A}, \quad (11)$$

else if $f > 4.43$ Hz,

$$I(f) = 3 \text{ A}, \quad (12)$$

else,

$$I(f) = -0.4519f^3 + 4.6547f^2 - 13.907f^1 + 12.611f^0. \quad (13)$$

As for the evident ‘S-bend’ in the control curve, this is typical of MR devices, primarily due to internal magnetic saturation, however in this case should also largely be due to the reaching of mechanical stiffness limits in the device. Regarding the 1.8 A optimal current determined for the 3.4 Hz case which appears not to match the fit curve well, it is suspected that the apparent deviation is due to the steep slope of the cubic at the inflexion point occurring in this region.

Figure 8 – Optimal control current search in 5th floor transmissibility curves

Table 1 – Experimentally optimal MR damper control currents

	Input frequency (Hz)									
	1	2	2.5	3	3.2	3.4	3.6	4	5	6
Control current (A)	0	0	0	0.25	0.60	1.80	1.80	2.20	3	3
Min. norm. trans. (%)	0	-10.4	-8.05	-22.4	-26.8	-21.0	-22.9	-26.1	-0.77	0

Figure 9 – Current control curve for STFT

3.2.3. Controller performance evaluation

To then verify the effectiveness of the STFT controller using the developed current control function, the scale building was first loaded harmonically at its resonant frequency of 3.60 Hz in a staged test to demonstrate the rapid response-time and building-vibration decay rate of the MR-PTMD. As evident in Figure 10, after the building was allowed to settle to a stable oscillation magnitude with the MR-PTMD in the passive-off (0 A) control mode, a command was sent to turn the TMD on to the semi-active control mode. When in this mode, STFT is applied to the sampled ground-level acceleration signal on-board the NI myRIO controller, using the established control function to output an appropriate control signal to the MR damper of the device. From when the device was switched on, the response showed an immediate reduction in magnitude, leading to a 74.1% reduction across peaks once settled, occurring at a calculated decay rate λ_D of 2.35 s^{-1} .

Figure 10 – MR-PTMD semi-active response and decay rate

Following this were frequency sweep experiments conducted over a 1 Hz to 10 Hz range, using three comparable control modes: passive-off (0 A), passive-on (optimal TMD tuning at building resonance: 1.8 A), and semi-active control. As can be seen in Figure 11, consistent improvement over passive-off and passive-on tunings is demonstrated through these results in analysing the 5th floor transmissibility, determined using the recorded acceleration data. Where passive-off tuning yielded greater attenuation performance than passive-on towards lower frequencies, and the passive-on tuning performed better than passive-off nearby the building's resonance at 3.60 Hz, the semi-active control regime offered optimal attenuation across the entire tested frequency range. The benefit of such control is particularly apparent around the building's resonance, where a similar full-scale structure would be most vulnerable to potentially disastrous vibration. At best, this semi-active control led to a maximum reduction in transmissibility of 79.1% at 3.52 Hz when compared to the passive-off case, and a maximum reduction of 53.3% at 2.80 Hz when compared to the passive-on case. Regarding peak transmissibility, optimal TMD tuning, i.e. passive-on, saw a reduction of 49.8% to a peak of 5.721 from the passive-off peak of 11.39, further improved to a 60.4% reduction to 4.508 in the semi-active control case.

Figure 11 – Scale building 5th floor transmissibility

4. Scale Building Seismic Protection Testing

Using the same experimental setup illustrated in Figure 7, seismic excitation experiments were conducted to evaluate the MR-PTMD's capability to attenuate structural vibration with the scale building. To do so, the E-W component of the 1994 Northridge ($M_w = 6.7$) earthquake was selected, using a 1:4 timescale, corresponding to the scale factor used in the building construction. The reason this specific record was chosen is that it possesses a relatively wide frequency spectrum, with apparent high and low frequency segments over the 15 s duration of the signal, as labelled in Figure 12(a).

Regarding the uni-directional nature of the input excitation, this serves as an underlying assumption for the device to function well in its existing form, similar to other seismic performance evaluations of conventional MR dampers [17, 33]. While in practice unpredictable hypocentre locations would make bi-directional TMDs more practical, for preliminary studies, uni-directional loading is reasonable. For this prototype design to function bi-directionally, a multiple TMD (MTMD) system would need to be employed [34, 35], or alternatively a mechanism such as a rotational base-plate could be used to target the device. In the case of the MTMD system using two uni-directional TMDs, however, this may not have as good attenuation performance as a truly bi-directional PTMD, also with additional issues arising from having multiple independent TMD structures. Showing this improved performance of a bi-directional PTMD over an MTMD system, a comparative study involving vibration suppression of a wind turbine was recently conducted [36]. To further improve the bi-directional performance of the MR-PTMD, a 'joystick' coupling mechanism could be utilised, with a single mass and a damper-spring transmission for each direction.

To evaluate the performance of the semi-active controlled TMD, as done in previous transmissibility tests, this was again compared to the passive-off (0 A), and passive-on (1.8 A) tunings. To acquire sufficient data to analyse the building response, for each control mode a series of five experiments were conducted, shifting the location of the response accelerometer and laser displacement sensor between each test. In doing so, excitation acceleration signals were compared to ensure the results to be valid for comparison.

Focussing first on the displacement response of the building, included in Figure 12(a) is the relative displacement of the 5th floor over the roughly 15 s duration of the time-scaled Northridge earthquake, showing the three control modes. Quite notably, early on in the response it is obvious that the passive-on tuning tends to have higher peak displacement than both the passive-off and semi-active case. This is until about 4.3 s has elapsed and the passive-off case appears to have typically higher peak amplitudes than the other two control modes. This is due to the earthquake signal possessing a lower dominant frequency early on, eventually increasing in dominant frequency from about 4.3 s thereon.

As can be seen in Figure 12(b), upon detection of this shifting dominant frequency, the STFT algorithm and paired control function result in a generally increasing damper control current for the semi-active control mode. This reflects the fact that over the 17 s run time of the tests, the semi-active control mode tends to possess the minimum relative displacement when compared to both passive control modes in the low and high frequency regions of the seismic event due to capability of variable resonance. It should also be noted that there is apparent clipping in the control signal of Figure 12(b), due to the relatively small time-window selected for use in the STFT algorithm. This resulted in a very rapid shift in apparent dominant frequency, and hence the control current adjusting the setpoint stiffness was shifted at a similarly fast rate. It has been suggested that such clipping may lead to exacerbated vibrations in some cases, and may be remedied by more complex control approaches [37], however this was not experienced in the experiments conducted here.

Figure 12 – Northridge earthquake (a) 5th floor relative displacement time-trace, and (b) semi-active damper control signal time-trace

To quantify this analysis, RMS relative displacement and peak relative displacement for each floor have been compiled and illustrated in Figure 13 and Figure 14, respectively, with this data and percent reductions due to semi-active control also being included in Table 2. Evident in Figure 13, over the entire duration of the test runs, the passive tuning cases coincidentally possessed very similar RMS displacements. This is contrast to the appreciable improvement that can be seen in the semi-active result for all floors, being smaller in magnitude than both passive tuning modes in all cases. Across all floors, this is an average 12.7% reduction over the passive-off tuning mode, and an average of 13.0% reduction over the passive-on tuning mode. Similarly, Figure 14 shows the semi-active control mode to yield the optimal result, however due to more

apparent variation in peak values of displacement rather than the averaged RMS values, by no coincidence the results are not as uniform across floors.

Figure 13 – Northridge earthquake RMS relative displacement response

Figure 14 – Northridge earthquake peak relative displacement response

Table 2 – Experimental relative displacement seismic response data

Floor	RMS displacement (mm)				
	Passive-off tuning	Passive-on tuning	Semi-active control		
			Mag.	% reduction (rel. passive-off)	% reduction (rel. passive-on)
1	0.325	0.329	0.276	15.2%	16.3%
2	1.255	1.231	1.153	8.10%	6.30%
3	1.844	1.852	1.584	14.1%	14.5%
4	2.401	2.414	2.065	14.0%	14.4%
5	2.687	2.736	2.364	12.0%	13.6%
Floor	Peak displacement (mm)				
	Passive-off tuning	Passive-on tuning	Semi-active control		
			Mag.	% reduction (rel. passive-off)	% reduction (rel. passive-on)
1	1.451	1.540	1.422	2.01%	7.61%
2	5.777	6.882	5.310	8.08%	22.8%
3	9.347	8.333	8.118	13.2%	2.58%
4	12.64	11.22	10.61	16.1%	5.42%
5	12.62	13.33	11.63	7.90%	12.8%

As additional metrics to evaluate the performance of the MR-PTMD, the peak interstory drift ratio (IDR) of the scale building under the seismic loading, as well as the peak acceleration response have been analysed. The peak interstory drift ratio is taken as the peak interstory drift, i.e. the difference in relative displacement between two consecutive floors, divided by the spacing between them [38]. This serves as an important qualifier as to the harmfulness of relative motion between building floors, and as such has been plotted in Figure 15, with the data tabulated in Table 3. Note for percentage reductions due to semi-active control included in Table 3, negative values indicate the semi-active case to possess the larger value in the comparison. For all but two floors, floors 3 and 4, it can be seen that the semi-active control mode has an IDR lower in magnitude than the passive-on tuning, tracking closely with the passive-off tuning. Where the semi-active control mode appears to struggle to improve IDR around the middle of the building, along with the passive-off case, this is likely a consequence of improved suppression of the 5th floor's motion where the MR-PTMD is affixed, exaggerating another harmonic vibration mode. This may suggest that employing another TMD system at the mid floor of the building, or an alternative control approach may lead to greater performance for this system.

Taking the maximum calculated IDR, found in floor 2 for the passive-on tuning as a point of comparison, the semi-active control mode resulted in a reduced maximum IDR by 8.27%, albeit then occurring upon floor 3. In comparison to the passive-off tuning mode to which the semi-active control mode yields a similar result. While no appreciable difference is observed in terms of IDR, it should be reiterated that the semi-active case maintains a substantially lower displacement response and peak transmissibility, making it more versatile in managing unpredictable seismic activity.

Figure 15 – Northridge earthquake peak interstory drift ratio

Table 3 – Experimental scale building interstory drift ratio under seismic loading

Floor	Interstory drift ratio ($\times 10^{-3}$)				
	Passive-off tuning	Passive-on tuning	Semi-active control		
			Mag.	% reduction (rel. passive-off)	% reduction (rel. passive-on)
1	11.52	12.21	9.065	21.3%	25.8%
2	24.13	30.77	23.84	1.24%	22.5%
3	28.32	19.55	28.23	0.32%	-44.4%
4	18.84	17.74	18.67	0.92%	-5.26%
5	13.77	19.99	14.93	-8.45%	25.3%

Regarding inertial effects felt by the structure, the peak acceleration for each floor is reported in Figure 16, with data listed in Table 4. It can be seen that the semi-active control mode generally

results in reduced peak accelerations between the three modes tested, with a reduction of as much as 33.5% for the 5th floor when compared to the passive-off tuning mode. The most notable exception to this, however, is for the 2nd floor in which is the semi-active peak acceleration is 13.5% larger than the minimum of 0.928 g obtained under the passive-off tuning mode, which again may be a result of induced harmonic vibration modes. Although, this is not the absolute maximum peak acceleration, with the overall maximum being 1.092 g, resulting from the passive-on tuning occurring in floor 3, in which case the semi-active mode produces a 3.58% smaller maximum floor acceleration.

Figure 16 – Northridge earthquake peak acceleration response

Table 4 – Experimental peak acceleration seismic response data

Floor	Peak acceleration (g)				
	Passive-off tuning	Passive-on tuning	Semi-active control		
			Mag.	% reduction (rel. passive-off)	% reduction (rel. passive-on)
1	0.577	0.566	0.586	-1.51%	-3.49%
2	0.928	0.934	1.053	-13.5%	-12.7%
3	0.936	1.092	0.951	-1.65%	12.9%
4	0.565	0.543	0.467	17.4%	14.2%
5	0.850	0.725	0.566	33.5%	22.0%

5. Conclusions

A novel MR-damper-controlled variable resonance pendulum tuned mass damper, the MR-PTMD, was designed, modelled, and tested in its ability to suppress seismic vibrations in a scale 5-story building. Through frequency sweep testing, the device was shown to be capable of a 104% increase in resonant frequency. Later, utilising a semi-active STFT control scheme, the device demonstrated a reduction of 79.1% and a reduction of 53.3% in ground-vibration transmissibility when compared to passive-off and passive-on tuning modes, respectively. When using the same semi-active control scheme in seismic loading experiments with the 1994 Northridge earthquake, the MR-PTMD was demonstrated to perform generally better than both the passive-off and passive-on control modes in attenuating building motion, particularly in terms of RMS relative displacement wherein average reductions of 12.7% over the passive-off tuning mode and 13.0% over the passive-on tuning mode were observed.

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References

- [1] I. G. Buckle and R. L. Mayes, "Seismic Isolation: History, Application, and Performance—A World View," *Earthquake Spectra*, vol. 6, no. 2, pp. 161-201, 1990/05/01 1990.
- [2] N. R. Fisco and H. Adeli, "Smart structures: Part II - Hybrid control systems and control strategies," *Scientia Iranica*, Review vol. 18, no. 3 A, pp. 285-295, 2011.
- [3] M. Gutierrez Soto, "Tuned Mass Dampers," *Archives of computational methods in engineering*, vol. 20, no. 4, pp. 419-431, 2013.
- [4] H. Fan, Q. S. Li, A. Y. Tuan, and L. Xu, "Seismic analysis of the world's tallest building," *Journal of Constructional Steel Research*, vol. 65, no. 5, pp. 1206-1215, 2009/05/01/ 2009.
- [5] Q. S. Li, "Dynamic Behavior of Taipei 101 Tower: Field Measurement and Numerical Analysis," *Journal of structural engineering (New York, N.Y.)*, vol. 137, no. 1, pp. 143-155, 2011.
- [6] R. R. Gerges, "Optimum design of pendulum-type tuned mass dampers," *The structural design of tall and special buildings*, vol. 14, no. 4, pp. 353-368, 2005.
- [7] S. Sun *et al.*, "Development of magnetorheological elastomers-based tuned mass damper for building protection from seismic events," *Journal of Intelligent Material Systems and Structures*, p. 1045389X17754265, 2018.
- [8] C. Bedon and C. Amadio, "Enhancement of the seismic performance of multi-storey buildings by means of dissipative glazing curtain walls," *Engineering Structures*, vol. 152, pp. 320-334, 2017/12/01/ 2017.
- [9] 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, no. 3, p. 035005, 2013.
- [10] S. Zhang and G. Wang, "Effects of near-fault and far-fault ground motions on nonlinear dynamic response and seismic damage of concrete gravity dams," *Soil Dynamics and Earthquake Engineering*, vol. 53, pp. 217-229, 2013/10/01/ 2013.
- [11] L. Kela and P. Vähöja, "Recent studies of adaptive tuned vibration absorbers/neutralizers," *Applied Mechanics Reviews*, vol. 62, no. 6, p. 060801, 2009.

- [12] J. Yang *et al.*, "Experimental study and modeling of a novel magnetorheological elastomer isolator," *Smart Materials and Structures*, Article vol. 22, no. 11, 2013, Art. no. 117001.
- [13] M. Behrooz, X. Wang, and F. Gordaninejad, "Modeling of a new semi-active/passive magnetorheological elastomer isolator," *Smart Materials and Structures*, Article vol. 23, no. 4, 2014, Art. no. 045013.
- [14] I. Bica, Y. D. Liu, and H. J. Choi, "Physical characteristics of magnetorheological suspensions and their applications," *Journal of Industrial and Engineering Chemistry*, vol. 19, no. 2, pp. 394-406, 3/25/ 2013.
- [15] Y. Li, J. Li, W. Li, and H. Du, "A state-of-the-art review on magnetorheological elastomer devices," *Smart Materials and Structures*, Review vol. 23, no. 12, 2014, Art. no. 123001.
- [16] J. M. Ginder, M. E. Nichols, L. D. Elie, and S. M. Clark, "Controllable-stiffness components based on magnetorheological elastomers," 2000, vol. 3985, pp. 418-425.
- [17] S. J. Dyke, B. F. Spencer Jr, M. K. Sain, and J. D. Carlson, "Modeling and control of magnetorheological dampers for seismic response reduction," *Smart Materials and Structures*, Article vol. 5, no. 5, pp. 565-575, 1996.
- [18] H. Yoshioka, "'Smart' Base Isolation Strategies Employing Magnetorheological Dampers," *Journal of engineering mechanics*, vol. 128, no. 5, pp. 540-551, 2002.
- [19] O. Yoshida, "Seismic Control of a Nonlinear Benchmark Building Using Smart Dampers," *Journal of engineering mechanics*, vol. 130, no. 4, pp. 386-392, 2004.
- [20] K.-M. Choi, "Semi-active fuzzy control for seismic response reduction using magnetorheological dampers," *Earthquake engineering & structural dynamics*, vol. 33, no. 6, pp. 723-736, 2004.
- [21] J. M. Ginder, "Magnetorheological elastomers in tunable vibration absorbers," 2001, vol. 4331, pp. 103-110: The Society.
- [22] H. X. Deng and X. L. Gong, "Adaptive tuned vibration absorber based on magnetorheological elastomer," *Journal of Intelligent Material Systems and Structures*, Conference Paper vol. 18, no. 12, pp. 1205-1210, 2007.
- [23] S. Sun *et al.*, "An adaptive tuned vibration absorber based on multilayered MR elastomers," *Smart Materials and Structures*, Article vol. 24, no. 4, 2015, Art. no. 045045.
- [24] S. Sun, H. Deng, J. Yang, W. Li, H. Du, and G. Alici, "Performance evaluation and comparison of magnetorheological elastomer absorbers working in shear and squeeze modes," *Journal of Intelligent Material Systems and Structures*, Conference Paper vol. 26, no. 14, pp. 1757-1763, 2015.
- [25] S. Sun, "Development of a novel variable stiffness and damping magnetorheological fluid damper," *Smart materials and structures*, vol. 24, no. 8, p. 085021, 2015 2015.
- [26] S. Sun *et al.*, "A Compact Variable Stiffness and Damping Shock Absorber for Vehicle Suspension," *IEEE/ASME Transactions on Mechatronics*, Article vol. 20, no. 5, pp. 2621-2629, 2015, Art. no. 7086317.

- [27] R. Lourenco, "Design, construction and testing of an adaptive pendulum tuned mass damper," 2011.
- [28] LORD Corp. (2008). *LORD TECHNICAL DATA: MRF-140CG Magneto-Rheological Fluid*. Available: <http://www.lordfulfillment.com/upload/DS7012.pdf>
- [29] R. C. de Barros and C. M. A. Sousa, "Pendulum TMD's in Building Vibration Control," in *CONTROLO 2016: Proceedings of the 12th Portuguese Conference on Automatic Control*, P. Garrido, F. Soares, and A. P. Moreira, Eds. Cham: Springer International Publishing, 2017, pp. 559-569.
- [30] S. Nagarajaiah, "Short time Fourier transform algorithm for wind response control of buildings with variable stiffness TMD," *Engineering structures*, vol. 27, no. 3, pp. 431-441, 2005.
- [31] S. Shuaishuai, Y. Jian, L. Weihua, D. Huaxia, D. Haiping, and A. Gursel, "Development of an MRE adaptive tuned vibration absorber with self-sensing capability," *Smart Materials and Structures*, vol. 24, no. 9, p. 095012, 2015.
- [32] R. S. Mills, H. Krawinkler, and J. M. Gere, "Model Tests on Earthquake Simulators - Development and Implementation of Experimental Procedures," 1979.
- [33] S. J. Dyke, B. F. Spencer Jr, M. K. Sain, and J. D. Carlson, "An experimental study of MR dampers for seismic protection," *Smart materials and structures*, vol. 7, no. 5, p. 693, 1998.
- [34] J. L. Lin, K. C. Tsai, and Y. J. Yu, "Bi-directional coupled tuned mass dampers for the seismic response control of two - way asymmetric - plan buildings," *Earthquake Engineering & Structural Dynamics*, vol. 40, no. 6, pp. 675-690, 2011/05/01 2010.
- [35] J. L. Almazán, C. Juan, J. A. Inaudi, D. López-García, and L. E. Izquierdo, "A bidirectional and homogeneous tuned mass damper: A new device for passive control of vibrations," *Engineering Structures*, vol. 29, no. 7, pp. 1548-1560, 2007.
- [36] C. Sun and V. Jahangiri, "Bi-directional vibration control of offshore wind turbines using a 3D pendulum tuned mass damper," *Mechanical Systems and Signal Processing*, vol. 105, pp. 338-360, 2018/05/15/ 2018.
- [37] M. E. Uz and M. N. S. Hadi, "Optimal design of semi active control for adjacent buildings connected by MR damper based on integrated fuzzy logic and multi-objective genetic algorithm," *Engineering Structures*, vol. 69, pp. 135-148, 2014/06/15/ 2014.
- [38] X. Gu, Y. Yu, J. Li, and Y. Li, "Semi-active control of magnetorheological elastomer base isolation system utilising learning-based inverse model," *Journal of Sound and Vibration*, vol. 406, pp. 346-362, 2017/10/13/ 2017.