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OPTIMAL ANALYSIS, DESIGN AND TESTING OF AN ELECTROMAGNETIC DAMPER WITH RESONANT SHUNT CIRCUIT FOR VIBRATION CONTROL OF A CIVIL STRUCTURE

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Control of vibration serviceability problems in civil engineering structures has received considerable attention in recent years. Most of this has been focused on classical technologies such as tuned mass dampers, viscous dampers, viscoelastic dampers and friction pendulum systems, which in many cases are able to provide satisfactory vibration suppression performance. By contrast, electromagnetic actuators and electromagnetic dampers (EMD) have been more extensively used in mechanical applications as a means of attenuating unwanted vibration.

In this study, the use of an EMD is investigated for vibration suppression of a civil engineering structure. A voice coil motor is utilised as an EMD in which the terminal ends are connected with a shunt circuit and resonant shunt circuit to improve the damping performance. Therefore, the basic resistor series circuit and resistor, inductor and capacitor (RLC) oscillating circuit are chosen in this application, with both the H_∞ and H_2 optimisation techniques being used to determine the required shunt circuit components.

The resulting electromagnetic shunt damper (EMSD) is experimentally employed for enhancing the damping performance of a five storey aluminium frame structure under random and harmonic excitation. In line with the analysis and design of the damper, it is found that the EMSD experimentally demonstrates good vibration suppression performance.

1. Introduction

The use of electromagnetic dampers (EMDs) to generate electromagnetic damping forces is based on electromagnetic induction theory and the fundamental electromagnetic damping concept of EMD was described by [1] and [2]. A induced small shunt voltage is generated passively and actively via relative motion of conductive material and permanent magnet. The induced shunt voltage go through a shunt impedance circuit. It can activate electromagnetic damping and use it to reduce the host structure's vibration.

A flexible aluminium cantilever beam was studied by [3]. An electromagnetic shunt damper (EMSD) was passively suspended to the end of the beam to reduce vibration and an RC resonant shunt circuit was selected to connect with the EMD. An RLC resonant shunt circuit was also selected by [4] and [5] to improve the vibration suppression of the flexible cantilever beam.

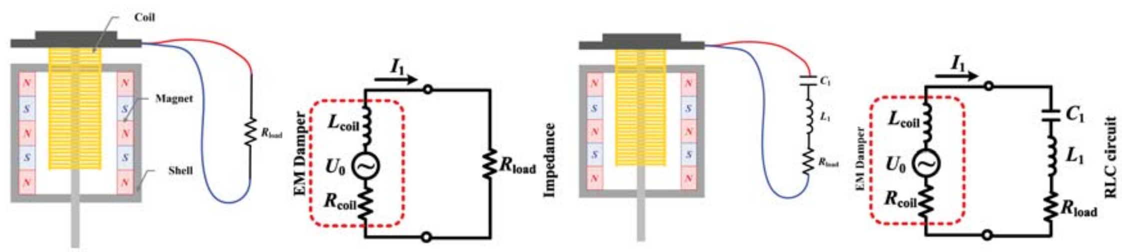
Paper [6] examined the performance of an EMD connected in series with an RLC resonant circuit, which was shown to be analogous to an equivalent TMD. Zhu [6] introduced the concept of the TMD analogue and examined H_∞ optimisation design. [7] carried out analysis of resonant shunt damper using both H_∞ and H_2 robust optimisation design methods and used the results in an application on a laboratory scale structure to verify the damper design methodology and practical performance.

The first part of this paper discusses the motivation behind this study. The second section introduces the specification of an electromagnetic damper, describes its dynamic behaviour and examines the use of shunt circuits to create EMSD devices. The next section introduces a laboratory scale moment resisting frame and data acquisition system for experimental evaluation of the EMSD design, as well as its modal testing and experimental evaluation of EMSD performance. The last section will provide some conclusions from this EMSD study.

2. Electromagnetic damper with resonant shunt circuit (EMSD) optimisation design

This section discusses the use of an electromagnetic damper (EMD), which makes use of a linear voice coil motor, as seen in Figure 1a. The concept is to use EMD to facilitate vibration suppression in a civil engineering structure. The EMD can be expressed as a circuit containing a coil inductor, coil resistor and power source. In this study, passive control is chosen to address the vibration problem. Therefore, the power source at the beginning is zero until the conductive material (copper coil) moves within permanent magnet pairs. Then, according to electromagnetism theory, an induced current (eddy current) will be generated, which can provide the electrical energy to drive the circuit system.

The circuit of the EMD needs to be closed and then the current can run through the circuit to provide the electrical energy. The external connecting circuit is called the shunt circuit. In this study, two shunt circuits are chosen. One is purely an impedance series circuit while the other is an RLC oscillating circuit, as seen in Figure 1.



(a) EMD (linear voice motor) with impedance.

(b) Circuit expression of EMD with impedance.

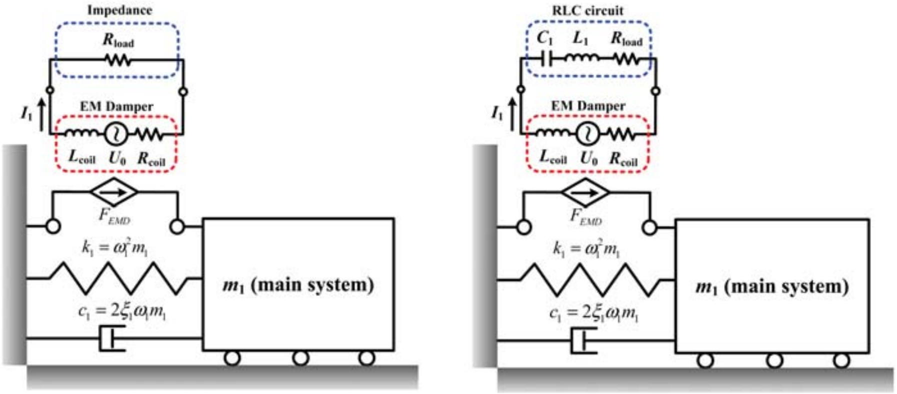
(c) EMD (linear voice motor) with RLC circuit.

(d) Circuit expression of EMD with RLC circuit.

Figure 1: Schematic of electromagnetic shunt damper (EMSD) devices.

The EMD is connected with a shunt circuit to form an EMSD, which is connected with the structural system. A relative motion is required between the two terminals of the EMSD and hence this is achieved by connection with the structure on two levels. The mounting configuration is similar to a classical viscous damper, as seen in Figure 2a. The impedance is selected for the shunt circuit contribution. To determine the performance of the EMSD, it is necessary to examine the relevant electromagnetic induction theory and structural mechanics to derive the equation of motion of the combined system. Hence, the governing equation of motion of the structure with attached EMSD is given by:

$$\begin{bmatrix} m_1 & 0 \\ 0 & L_{coil} \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{q} \end{Bmatrix} + \begin{bmatrix} c_1 & K_{emN} \\ -K_{emV} & R_{coil} + R_{load} \end{bmatrix} \begin{Bmatrix} \dot{x}_1 \\ q \end{Bmatrix} + \begin{bmatrix} k_1 & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} x_1 \\ q \end{Bmatrix} = \begin{Bmatrix} f \\ 0 \end{Bmatrix} \quad (1)$$



(a) SDOF system with EMSD (connecting with impedance).

(b) SDOF system with EMSD (connecting with RLC).

Figure 2: Electromagnetic damper (EMD) device.

By taking the Laplace transform, the transfer function of the SDOF structure with EMSD is given by:

$$\frac{X(s)}{F(s)} = \frac{sL + R}{s^3 m_1 L + (m_1 R + c_1 L)\, s^2 + (c_1 R + k_1 L + K_{emN} K_{emV})\, s + k_1 R} \tag{2}$$

On the other hand, if the shunt circuit is an RLC resonant circuit, as seen in Figure 2b, the relevant equation of motion is:

$$\begin{bmatrix} m_1 & 0 \\ 0 & L_{coil} + L_1 \end{bmatrix} \begin{Bmatrix} \ddot{x}_1 \\ \ddot{q} \end{Bmatrix} + \begin{bmatrix} c_1 & K_{emN} \\ -K_{emV} & R_{coil} + R_1 \end{bmatrix} \begin{Bmatrix} \dot{x}_1 \\ \dot{q} \end{Bmatrix} + \begin{bmatrix} k_1 & 0 \\ 0 & \frac{1}{C_1} \end{bmatrix} \begin{Bmatrix} x_1 \\ q \end{Bmatrix} = \begin{Bmatrix} f \\ 0 \end{Bmatrix} \tag{3}$$

and hence the transfer function of the SDOF structure with EMSD using resonant shunt circuit is given by:

$$\frac{X_1(s)}{F(s)} = \frac{s^2 L + sR + \frac{1}{C}}{s^4 m_1 L + (m_1 R + c_1 L)\, s^3 + \left(\frac{m_1}{C} + c_1 R + k_1 L + K_{emN} K_{emV}\right) s^2 + \left(\frac{c_1}{C} + R k_1\right) s + \frac{k_1}{C}} \tag{4}$$

Meanwhile, [6] and [7] observed that it is possible to carry out robust optimisation design of the structure and EMSD system using the H_∞ approach. From this, the optimal frequency ratio $\bar{\gamma}$ and damping ratio $\bar{\zeta}$ can be expressed as follows:

$$\bar{\gamma}_{opt} = \sqrt{\frac{2}{2 + \bar{\mu}}} \qquad \bar{\zeta}_{2,opt} = \sqrt{\frac{3\bar{\mu}}{8}} \tag{5}$$

In addition, [7] proposed also to use the H_2 robust optimisation control method, which results in frequency and damping ratios as follows:

$$\bar{\zeta}_{2,opt} = \frac{1}{2}\sqrt{\bar{\gamma}^2 + \bar{\mu}\bar{\gamma}^2 - 2 + \frac{1}{\bar{\gamma}^2}} \qquad \bar{\gamma}_{opt} = 1 \tag{6}$$

Both robust optimisation methods show that the optimal design ratios are functions of the equivalent mass ratio $\bar{\mu}$.

3. Experimental validation

To validate the above theory, a programme of experimental work was undertaken using a laboratory scale model of a multi-storey building constructed using an aluminium moment resisting frame. A linear voice coil motor was utilised as an EMSD, which was operated in series with a shunt impedance circuit and an RLC shunt circuit.

3.1 Aluminium moment resisting frame

A six storey aluminium moment resisting frame (MRF) was chosen to imitate a building structure, as seen in Figure 3. Each floor plate is $400 \times 400 \times 25$ mm and each level has 400 mm height. The four columns connect through floor plates at each level, with dimensions of $20 \times 2012.5 \times 6.25$ mm. On each floor plate, there are 49 M4 threaded holes to provide equipment mounting.

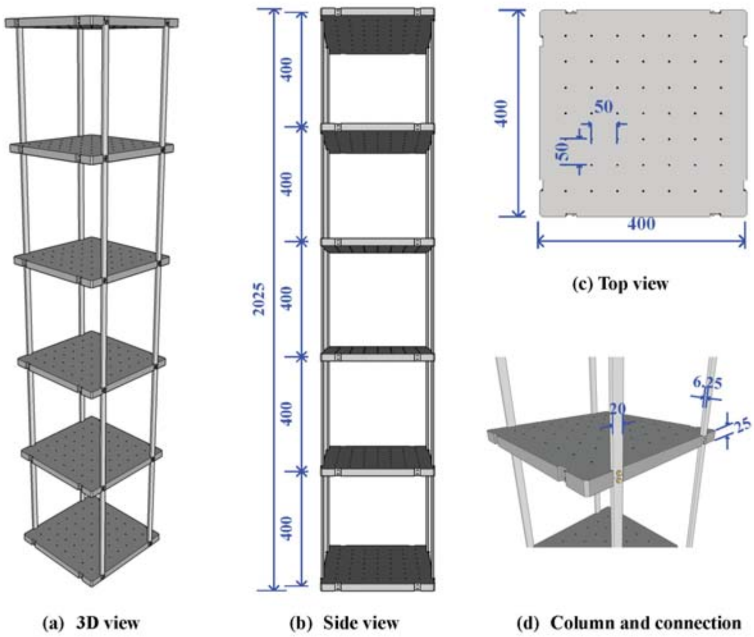


Figure 3: 6 floor aluminium MRF and dimension.

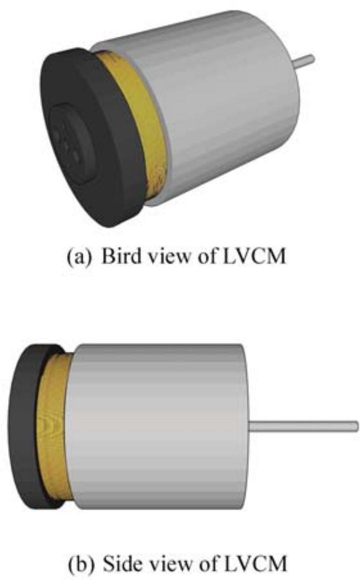


Figure 4: Electromagnetic linear voice coil motor.

From a passive control energy point of view, the external excitation energy from the ground propagates through all levels of the building. The two terminals of an EMD connected between adjacent levels can therefore dissipate vibration energy and reduce dynamic response throughout the structure.

3.2 Electromagnetic damper (Linear voice coil motor)

The EMD selected was a Moticont Linear Voice Coil Motor (LVCM) GVCM-095-089-01S06, as seen in Figure 4, which is widely used in industrial production lines. The LVCM in this study is used as the EMD and contains three main components; the outside shell of the motor, a copper coil and a permanent magnet connected to the core part of the shell case.

The copper coil is a conductive material. In this case, when the coil moving within the core magnet and wire up the motor terminal cable to the shunt circuit, it can achieve the EMSD vibration suppression concept.

Figure 5 shows the mounting of the EMD, which consists of two parts. The first one is the EMD stand which is attached to the bottom level of the shear frame. The second part is a triangular plate, which connect to the first level of the shear frame.

Table 1 shows relevant data for the LVCM. The previous studies [6] and [7] mentioned two machine constants (force constant and back emf constant) required in the design of an EMSD. The force

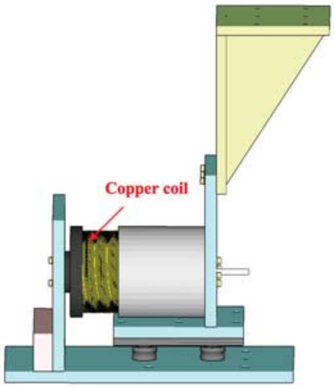


Figure 5: Linear voice coil motor with standard carriage system.

Intermittent force 10% duty cycle	351.1 (N)
Continuous force	111.2 (N)
Force constant	22.2 (N/A)
Back EMF constant	22.2 (V/m/s)
Stroke	63.5 (mm)
Body Mass	4.1 (kg)
Coil resistance	3 (Ohms)
Coil inductance	2.1 (mH)

Table 1: Technical characteristics of Linear Voice Coil Motor (adopted from catalogue of Moticont.

constant is expressed as current converting to force while the back emf constant is represented by velocity converting to voltage.

Otherwise, the other properties of LVCM such as inherent resistance and coil inductance values are used in the EMSD design process. They are $3\ \Omega$ and 2.1 mH, respectively.

3.3 Excitation and data acquisition

Figure 6a shows all the sensors and LVCM set up. Endevco 7754-1000 accelerometers, an Imetrum optical measurement system and MTS R-Series RHM0150MD601A01 magnetostrictive position sensors have all been used to measure the acceleration and displacement. The accelerometers were set up in the horizontal direction parallel to the MTS sensors. The chosen excitation source is an APS Dynamics Model 400 shaker, which provides the input loading at the second level.

(a) 6 stories aluminium frame and all measuring sensors.

(b) MRF with connect the LVCM.

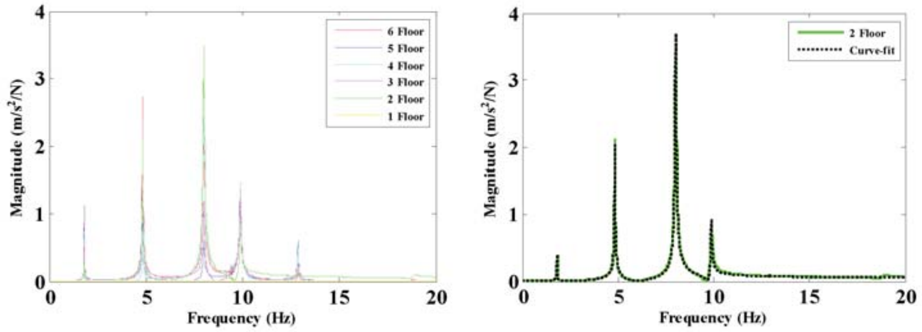
(c) Zoom in the LVCM level.

Figure 6: Aluminium frame with LVCM and all sensors.

3.4 Modal testing

The MRF modal properties can be established using general modal testing procedures, as shown in Figure 6b. The APS dynamic shaker is attached to the ground and pushes the second level of the MRF using a random signal input.

The measured FRF curve is shown in Figure 7a. Figure 7b shows the second floor test point curve-fitting result. It can be seen that the curve fitting results have good agreement in comparison with the original measurement data.



(a) Power response spectrum in absolute value.

(b) Cruve fitting power response spectrum in absolute value.

Figure 7: Dynamic response of 6 stories structure under uniaxial excitation.

The mode shapes of the MRF is shown in Figure 8. Table 2 gives the modal properties from the measurement. It can be seen that the first mode is a pure being mode; the natural frequency is 1.81 Hz, the damping ratio is 0.33 %, and modal mass is 36.59 kg. This mode will be targeted for EMSD robust control.

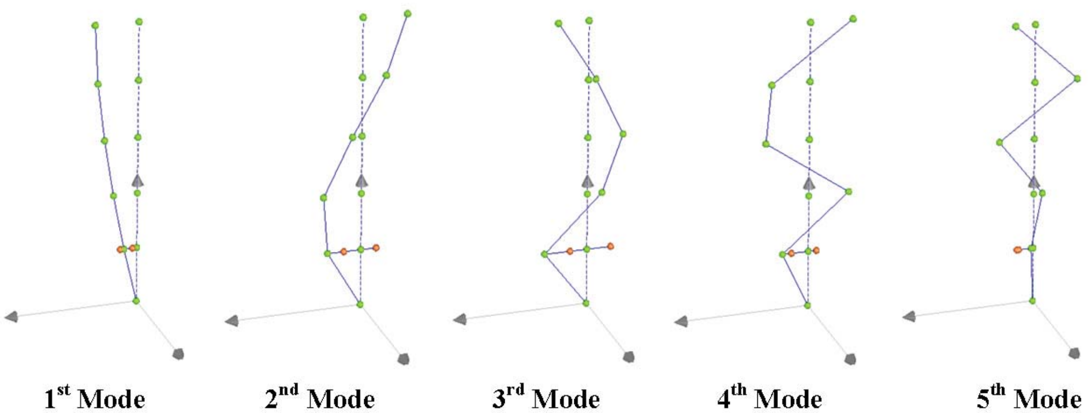


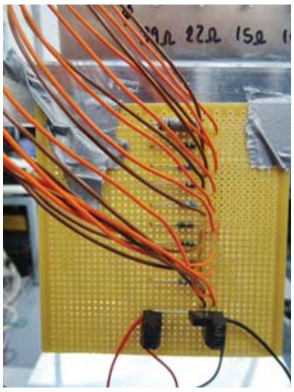
Figure 8: Mode shape of aluminium MRF.

Mode Number	Natural Frequency (Hz)		Damping ratio (%)	Modal Mass (kg)
	Ansys	Measurment		
1	1.80	1.81	0.33	36.59
2	5.27	4.83	0.35	41.97
3	8.35	8.00	0.36	37.64
4	10.76	9.86	0.27	74.68
5	12.31	12.87	0.18	21.59

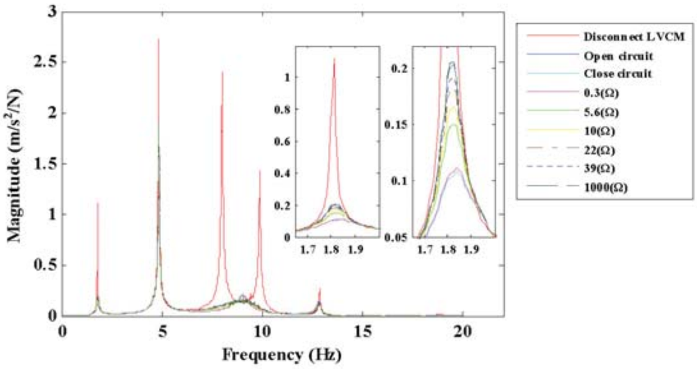
Table 2: Measured dynamic properties of the six storey aluminium resistant frame structure.

3.5 LVCM validation

Figures 6c and 9a show the connected LVCM and series of impedance circuits which form the EMD. The resistors used had resistances of 0.3, 5.6, 10, 22, 39 and 1000 Ω. The inherent resistance of the EMD is an additional 3 Ω. After this, closing the EMD wire can create the shunt circuit which is a closed circuit.



(a) Photo of impedance series circuit.

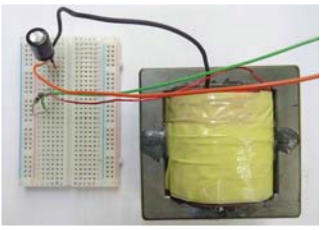


(b) 6 floor frequency response function.

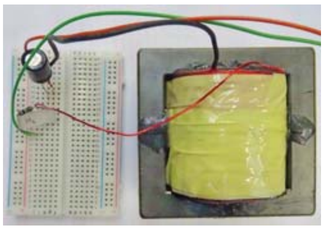
Figure 9: Impedance series circuit and frequency response function at level 6.

Figure 9b shows the FRF curve at the top level of MRF under random signal input. The lower resistances demonstrate better reduction particularly in the closing circuit; the highest value 1000 Ω has no damping effect. From the FRF response, this type of energy dissipation feature seems to purely increase the system damping in a similar way to the viscous damper.

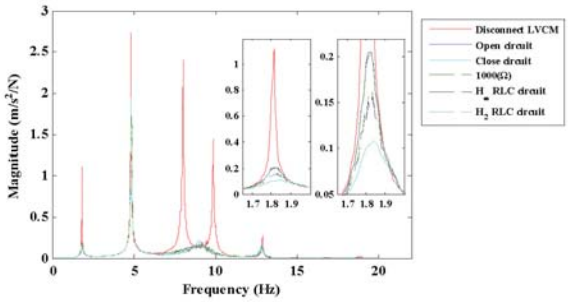
On the other hand, the resonant RLC shunt circuit is chosen to connect with the EMD. Figure 10a shows the H_∞ RLC circuit and 10b shows the H_2 RLC circuit components design uses the section 2 equations to obtain the component values. Therefore, the FRF response can be represented in Figure 10c.



(a) Photo of H_∞ RLC circuit.



(b) Photo of H_2 RLC circuit.



(c) 6th floor FRF.

Figure 10: RLC circuit and frequency response function at level 6.

The FRF shows the RLC optimal design does not have as satisfactory a reduction as TMD. In fact, it has only a slight reduction. This de-tuning could come from non-linear effects such as friction and geometry connection problems.

4. Conclusions

In this paper, the main objective is to investigate the effects of connecting the electromagnetic damper (EMD) with a resonant shunt circuit (EMSD). A linear voice coil motor was used as an electromagnetic damping device. A simple impedance shunt circuit was used to connect the EMSD with a laboratory scale frame. The experimental results showed that connecting the low value of resistance achieves a better control performance.

Otherwise, when the EMD is connected to an optimally designed RLC oscillating shunt circuit, theoretically, the dynamic performance could be the same as the TMD. However, the results do not show the expected performance. As a slight tuning effect, the EMSD has a de-tuning effect in comparison with the TMD which might come from some unknown non-linear behaviour of the damper and connection. Further experimental studies are needed to verify this.

5. Acknowledgement

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