VIBRATION REDUCTION AND ENERGY HARVESTING OF BUILDING STRUCTURES USING ELECTROMAGNETIC MULTIPLE TUNED MASS DAMPERS

GING LONG LIN¹, CHI-CHANG LIN², YU-JING CHEN², and TA-CHIH HUNG²

¹Dept of Construction Engineering, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan
²Dept of Civil Engineering, National Chung Hsing University, Taichung, Taiwan

This study investigated the use of electromagnetic multiple tuned mass dampers (EM-MTMDs) to decrease the dynamic responses of building structures when subjected to earthquake ground motions. By using a rotary electromagnetic damper, the vibration energy of each TMD unit is able to be converted into electrical energy. To validate the vibration reduction and energy harvesting abilities of the constructed prototype EM-MTMD, it was installed on a scale-down primary structure. Shaking table tests were classified into three stages. In the first stage, the scale-down primary structure was tested and its dynamic parameters were identified. In the second stage, each of the EM-TMD units underwent harmonic excitations to identify their EM damping ratios. In the third stage, the primary structure was installed with the prototype EM-MTMD under the selected ground motions. The results indicated that the proposed EM-MTMD could decrease the dynamic responses of the primary structure and generate power under earthquake ground motions.

Keywords: Electromagnetic damper, Shaking table test, Vibration control, Dynamic response.

1 INTRODUCTION

A tuned mass damper (TMD) system is one kind of passive structural control device, it often be utilized to mitigate vibrations in building structures. However, a TMD system is susceptible to frequency uncertainties in the primary structure, leading to the detuning of the TMD, which can significantly diminish its control effectiveness. To address this issue, multiple-tuned-mass-dampers (MTMDs) with a broader frequency bandwidth were proposed, providing a more robust control performance (Lin et al. 2001). Additionally, when implementing TMD/MTMD systems in a long-period structure, a significant TMD stroke is anticipated, which can be hindered by traditional viscous dampers with limited stroke. Rotational dampers without stroke limitations are a potential solution to this problem.

In recent years, researchers have been focusing on developing dampers that have multi-functional capabilities, which not only mitigate structural dynamic vibrations but also generate a substantial amount of energy under external forces. For instance, Zhu et al. (2012) studied an energy dissipation device that can both mitigate vibrations and harvest energy. Researchers Tang and Zuo (2012), Shen et al. (2012), and Liu et al. (2016) have also created their prototype...
electromagnetic TMD systems and control algorithm for theoretical and experimental studies. By incorporating a rotary EM damper in each TMD unit of an MTMD system, Lin et al. (2021) investigated a novel EM-MTMD system. This conference paper extends the above research, focusing on the relevant experimental details.

2 A PRIMARY STRUCTURE INSTALLED WITH AN EM-TMD

A primary structure equipped with an EM-TMD is presented in Figure 1. The EM damper can provide a damping force to the movement of TMD. Figure 2 shows the schematic and photo of the EM damper, which consists of a direct-current (DC) motor, a gearbox, a guide rack, and a pinion. The DC motor is utilized as the rotational electric generator. In addition, due to the low relative velocity between TMD and the building floor, the gearbox is necessary to accelerate the angular momentum of the DC motor to increase the damping effect. Moreover, the rack and pinion are utilized to convert the torque of the rotary EM damper into the required translational force in a TMD. This translational force \( F(t) \) can be expressed by (Lin et al. (2021)):

\[
F(t) = \left( \frac{l_{\text{pin}}}{r_{\text{pin}}^2} + \frac{n_{gb}^2 l_{gb}}{\rho_{\text{pin}}^2 r_{\text{pin}}^2} + \frac{n_{gb}^2 l_{mo}}{\rho_{gb} \rho_{\text{pin}}^2 r_{\text{pin}}^2} \right) \dot{v}_s(t) + \left( \frac{k_e k_t n_{gb}^2}{\rho_{gb} \rho_{\text{pin}}^2 r_{\text{pin}}^2} \cdot \frac{1}{R_{\text{circ}}} \right) \ddot{v}_s(t)
\]

where,

\[
R_{\text{circ}} = R_{\text{mo}} + R_{\text{load}}
\]

\( \dot{v}_s(t) \): relative acceleration between TMD and structure
\( \ddot{v}_s(t) \): relative velocity between TMD and structure
\( R_{\text{mo}} \): resistance of the DC motor
\( R_{\text{load}} \): external electrical resistance
\( l_{\text{mo}}, l_{gb}, l_{\text{pin}} \): rotational inertia of the DC motor, and gearbox and pinion
\( \beta_{gb}, \beta_{\text{pin}} \): efficiency (transmission) of the gearbox and the pinion
\( k_e, k_t \): motor electrical constant and torque constant
\( R_{\text{circ}} \): total resistance of the closed circuit
\( n_{gb} \): gear ratio of the gearbox
\( r_{\text{pin}} \): radius of the pinion

In Eq. (1), \( k_e \) and \( k_t \) have the same value and unit \((V \cdot s/rad, N \cdot m/A)\). From Eq. (1), the inerterance \( b_s \) (Smith 2002) and EM damping coefficient \( c_e \) are listed below:

\[
b_s = \frac{l_{\text{pin}}}{r_{\text{pin}}^2} + \frac{n_{gb}^2 l_{gb}}{\rho_{\text{pin}}^2 r_{\text{pin}}^2} + \frac{n_{gb}^2 l_{mo}}{\rho_{gb} \rho_{\text{pin}}^2 r_{\text{pin}}^2}
\]

\[
c_e = \frac{k_e k_t n_{gb}^2}{\beta_{gb} \beta_{\text{pin}}^2 r_{\text{pin}}^2} \times \frac{1}{R_{\text{circ}}}
\]

Based on Eq. (4), the coefficient \( c_e \) is a function of \( R_{\text{load}} \). In Eq. (3), the inerterance \( b_s \) is a function of the rotational parameters of the EM damper; it can lead to a change in the frequency of the EM-TMD. The component tests will identify the actual values of \( b_s \) and \( c_e \).
3 SHAKING TABLE TEST PROGRAM

3.1 The Scale-down Primary Structure

This section aims to create a scaled-down version of a high-rise building; its dynamic parameters were designed to replicate the fundamental behavior of a 40-story building. Figure 3(a) illustrates the shaking table test setup that subjects the scaled-down primary structure to a sweep sine excitation. The experimental and theoretical frequency response functions of the structural displacement are shown in Figure 3(b), and good agreement between the theoretical simulation and experimental results was observed. Table 1 presents the parameters of the primary structure, including a mass of 6,046 kg, a stiffness achieved by curved guides and rollers, as shown in Figure 3(a), an identified natural period of 3.53 s, and a damping ratio of 2%.

Table 1. Dynamics parameters of the scale-down primary structure.

<table>
<thead>
<tr>
<th>Mass (kg)</th>
<th>Stiffness (N/m)</th>
<th>Damping ratio (%)</th>
<th>Frequency (Hz)</th>
<th>Period (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6046</td>
<td>188,899</td>
<td>2</td>
<td>0.28</td>
<td>3.53</td>
</tr>
</tbody>
</table>
3.2 The EM-MTMD

The EM-MTMD prototype was optimized by minimizing the scaled-down primary structure’s RMS displacement, as Lin et al. (2001) described. The component test setup for the EM-MTMD is presented in Figure 4. The identified parameters of each EM-TMD unit are listed in Table 2, based on sweep sine excitations and the theoretical model of the EM-TMD. It is worth noting that the frequencies of the EM-TMDs are tuned to the frequency of the scaled-down primary structure.

Table 2. Dynamic parameters of the EM-MTMD.

<table>
<thead>
<tr>
<th>TMD No.</th>
<th>$m_s$ (kg)</th>
<th>$b_s$ (kg)</th>
<th>$f_s$ (Hz)</th>
<th>$T_s$ (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMD 1</td>
<td>49.14</td>
<td>0.74</td>
<td>0.26</td>
<td>3.91</td>
</tr>
<tr>
<td>TMD 2</td>
<td>43.47</td>
<td>0.74</td>
<td>0.27</td>
<td>3.68</td>
</tr>
<tr>
<td>TMD 3</td>
<td>37.67</td>
<td>0.74</td>
<td>0.29</td>
<td>3.44</td>
</tr>
</tbody>
</table>

Figure 5 illustrates the identified correlation between the total damping ratio $\xi_{total}$ (including EM damping ratio $\xi_e$ and inherent damping ratio $\xi_{inh}$) and $R_{circ}$ of each EM-TMD. Notably, the EM damping ratio $\xi_e$ of each EM-TMD can be modified by adjusting $R_{load}$, as shown in Eq. (4). Table 3 presents three EM-MTMD systems with different levels of EM damping ratio for each EM-TMD, called optimal, inherent and 2×opt. In Table 3, “optimal” refers to the EM-MTMD with the ideal damping ratio of each EM-TMD, which is a relatively small damping ratio. Meanwhile, the shaking table test identifies the “inherent” damping ratio without the EM circuit. This indicates that the inherent damping ratio of each TMD is slightly larger than its ideal damping ratio. The shaking table test identified the “2×opt” damping ratio with the EM circuit ($R_{circ1} = 70\Omega$, $R_{circ2} = 180\Omega$, $R_{circ3} = 146\Omega$), the case of “2×opt” representing twice the optimal damping ratio.

Figure 5. Identified the relationship of the total damping ratio vs. $R_{circ}$ of each EM-TMD.
Table 3. Levels of damping ratios of EM-MTMD systems.

<table>
<thead>
<tr>
<th>Type</th>
<th>Damping ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TMD 1</td>
</tr>
<tr>
<td>Optimal damping</td>
<td>3.4%</td>
</tr>
<tr>
<td>Inherent damping</td>
<td>4.7%</td>
</tr>
<tr>
<td>$2 \times$ opt damping</td>
<td>7.1%</td>
</tr>
</tbody>
</table>

3.3 The (Primary Structure) – (EM-MTMD) Combined System

Figure 6 shows the test setup and the theoretical model of the (scale-down primary Structure) – (EM-MTMD) combined system. The control effectiveness of the EM-MTMD “$2 \times$ opt” under the 1992 Landers earthquake, scaled to a PGA of 240 gal, is presented in Figure 7. The results show a significant reduction in both structural displacement and acceleration. In addition, Figure 8 illustrates the power generation waveform of each EM-TMD when subjected to the same ground acceleration, which is calculated based on the measured electric current in each closed circuit of the EM-TMD. This confirms that the EM-MTMD is a dual-functional device capable of reducing structural vibration and generating electric energy.

(a) Test setup
(b) Theoretical model

Figure 6. Shaking table test of (primary structure) – (EM-MTMD) combined system.

(a) Structural disp.
(b) Structural acc.

Figure 7. Structural responses w/ and w/o EM-MTMD (1992 Landers, PGA=240gal).
CONCLUSIONS

This study aims to assess the feasibility of a novel MTMD system known as the electromagnetic tuned mass damper (EM-MTMD). By incorporating a rotary EM damper into each single TMD of an MTMD system, the EM-MTMD system offers the potential to mitigate vibration and harvest electric energy concurrently. A prototype of the EM-MTMD system was designed and fabricated, and its control performance was evaluated through a shaking table test. The results demonstrate that the EM-MTMD can significantly reduce the excessive vibration of the primary structure. Moreover, the test results reveal that the EM-MTMD system can effectively decrease structural responses while simultaneously generating power.

Acknowledgments

The authors would like to express their gratitude for the financial support from the Ministry of Science and Technology of the Republic of China (Taiwan): MOST 108-2218-E-992-313-MY2.

References