EXPERIMENTAL STUDY OF REGENERATIVE EM-TMD SYSTEM FOR BUILDING VIBRATION CONTROL

W. A. Shen [1], S. Zhu [2], Y. L. Xu [2], X. Shi [2] and W. C. Lee[2]
[1] Department of Civil and Structural Engineering,
The Hong Kong Polytechnic University, China.
Email: Wenai.shen@polyu.edu.hk
[2] Department of Civil and Structural Engineering,
The Hong Kong Polytechnic University, China.

ABSTRACT

This paper proposes a novel tuned mass damping (TMD) system in building structures with hybrid functions—vibration control and energy harvesting. The regenerative electromagnetic TMD (EM-TMD) system comprises a pendulum-type TMD, a rotary electromagnetic (EM) damper and an energy-harvesting circuit. The structural vibration energy induced by earthquake or wind, which is a great amount, is absorbed by EM-TMD and converted to electrical energy by the EM damper, and stored in energy storage elements (such as supercapacitors and rechargeable batteries) by the energy harvesting circuit. As a result, the proposed EM-TMD systems can not only effectively protect building structures against excessive vibrations, but also provide regenerative and economical power sources to smart wireless sensing system or other electronic devices. This paper presents a proof-of-concept shaking table experiment in which a single-degree-of-freedom (SDOF) model equipped with a regenerative EM-TMD system has been tested. A prototype of rotary EM damper connected with two types of energy harvesting circuits, were tested and compared in this study. Three important properties, i.e., energy conversion efficiency, output power and control effect, were investigated and discussed. The results successfully validate the feasibility of conducting vibration control and energy harvesting simultaneously using regenerative EM-TMD system in buildings.

KEYWORDS

energy harvesting, electromagnetic damper, energy conversion efficiency, vibration control, TMD

INTRODUCTION

Substantial researches have been done on structural vibration mitigation through energy dissipation strategy, in which various damping devices were successfully used, e.g. friction dampers, metallic yield dampers, buckling-restrained braces, viscous fluid dampers, visco-elastic dampers, tuned mass damper (TMD), electromagnetic (EM) dampers, magneto-rheological (MR) fluid dampers, and so on (Housner *et al*., 1997; Palomera-Arias *et al.*, 2008; Soong and Dargush, 1997; Soong & Spencer, 2002). Among them, TMD, a resonant energy absorber, becomes an effective vibration control device seeing wide applications in civil and mechanical structures, e.g. in high-rise building, tall chimney (Soong 1997; Xu et al. 1992). A recent well-known example is the pendulum-type TMD (730 tons) in Taipei 101 tower (Kourakis 2007). In conventional energy dissipation strategy, a great amount of vibration energy is converted to heat, and it is thus often associated with the self-heating of dampers. On the other hand, emerging wireless sensor technology has seen growing applications in the health monitoring of civil structures. The limited lifespan of batteries has motivated researchers to seek alternative and reliable power supply to wireless sensing nodes (WSN) from ambient light, wind, heat, strain, radio and vibrations (Bogue 2010; Lynch 2006; Park 2008).In particular, most of the vibration-based energy harvesting devices using micro or small resonance structures (cantilever beam or simple supported beam with a proof mass), consequently, the inherent limitation of the power constrains the amounts of their output power, which arrange from μWs to mWs (Mitcheson 2005), cannot meet most of electronics devices requirements. A WSN node of approximately 10 meters away from the central node (receiver) is estimated power consumption of approximately 100 milliwatts (Roundy *et al*. 2005). Further, the power consumption of smart wireless sensor with on-board computing function can be higher than 100 miliwatts, usually up to several hundreds of miliwatts (Lynch 2006). In this regards, a generator with much more output power should be developed to meet this requirement. In fact, many flexible and lightly damped civil structures (such as high-rise buildings, long-span bridges, stay cables, etc.) are vulnerable to excessive vibrations induced by traffics, wind, waves or earthquakes. To harvest the energy dissipated or wasted by passive control devices is rarely considered and the development of corresponding self-powered system attracts few attention in area of civil engineering. Tang *et al.*(Tang 2010) proposed the regenerative semi-active series TMD and a simulation study employing Taipei 101 model. Tang's research shows that the potential energy harvesting capacity by regenerative TMD is huge, because the output power in this full-scale model simulation is up to the order-of magnitude of kWs. This paper presents a proof-of-concept shaking table experiment in which a single-degree-of-freedom (SDOF) model equipped with a regenerative EM-TMD system has been tested. A prototype of rotary EM damper connected with two types of energy harvesting circuits, termed, three-phase rectifier connected with a constant resister or a super-capacitor, are tested and compared in this study. Three important properties, i.e., energy conversion efficiency, output power and control effect, are investigated and discussed.

REGENERATIVE EM-TMD SYSTEM

Description of Regenerative EM-TMD System

A novel TMD system, termed regenerative EM-TMD system, is proposed in building structures with hybrid functions—vibration control and energy harvesting. The regenerative EM-TMD system comprises a pendulum-type TMD, a rotary EM damper and an energy-harvesting circuit. Figure 1 illustrates a schematic of a structure equipped with a regenerative EM-TMD system. A simple pendulum is a common form of TMD, which attaches an auxiliary mass to a primary structure through a pendulum. It is a resonant device oscillating at similar frequency of the structure but with a phase shift, and it actually adds another degree-of-freedom (DOF) to the structure. The damping characteristic of the TMD is mainly contributed by a rotary electromagnetic damper in this study. It should be noted that according to Faraday's Law and Lorentz's Law, any permanent-magnet motors or generators, either DC or AC and either linear or rotary, can function as passive electromagnetic damper (Palomera-Arias *et al.,* 2008; Shen *et al.,* 2011; Zhu *et al.*, 2010). A gearbox is often needed to amplify the damping capacity and output power. In this system, the rotary EM damper is connected with the energy-harvesting circuit, which known as electromagnetic damping and energy harvesting (EMDEH) system [Figure 2], plays a key role in the proposed regenerative EM-TMD system. With the aid of EMDEH system, the EM-TMD could dissipate structural vibration energy and convert it to electrical energy, which is further harvested and stored by energy harvesting circuits and used to power one or more wireless sensor nodes (e.g. Imote2 in Figure 1) that closely monitor the dynamic response of the structure.

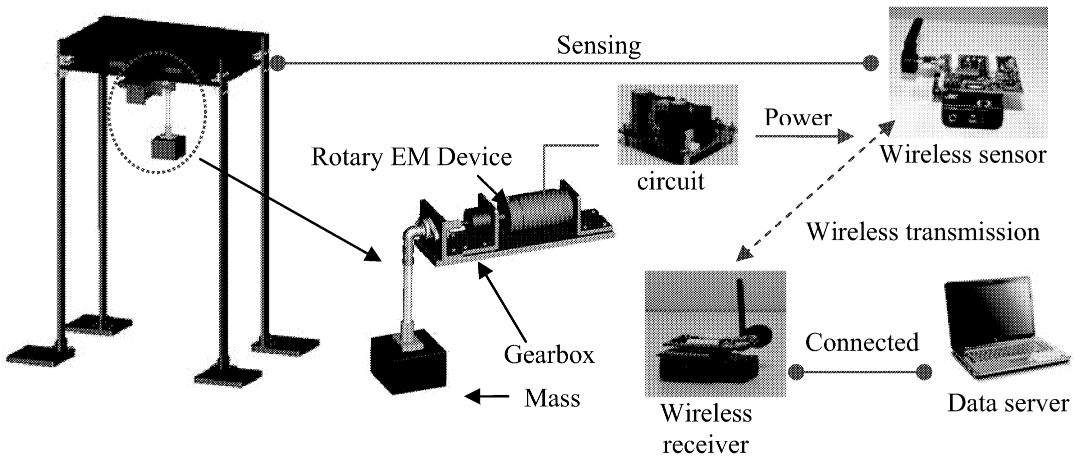


Figure 1 Regenerative EM-TMD system with wireless sensor

Power Flow

Figure 2 indicates the power flow from the input excitations to the ultimate power consumption by wireless sensors. In the first stage, the input power is divided into four parts, that is, power of the kinetic energy of structural mass, the power of elastic strain energy, the dissipative power by structural inherent damping, and the power absorbed by TMD. The power absorption by TMD is composed of two parts—the vibration power of the auxiliary mass and the damping power. Unlike in conventional TMDs, the damping power in EM-TMD becomes the input power P_{in} to the EMDEH system. If the pendulum-type TMD with minor swing, it can be linearized to be a lateral motion TMD, then P_{in} is given by

$$P_{in} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} C_d \cdot \dot{x}^2(t)dt = 2m\omega_n\xi_d \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \dot{x}^2(t)dt = 2m\omega_n\xi_d\dot{x}_{rms}^2 \tag{1}$$

where C_d is the total damping coefficient of TMD, N·s/m; $x(t)$ is the linear velocity of mass, $x(t) \approx L\theta(t)$, m/s, m is the mass of TMD, kg; ω_n is the natural frequency of TMD, rad; ξ_d is the total damping ratio of TMD, final, $\dot{x}_{rms}$ is the RMS value of the velocity of TMD.

Usually the damping of EM damper consists of electromagnetic damping C_{em} and parasitic damping C_p. As a result, part of the input power P_{in} is dissipated by the parasitic damping, whereas the other is converted into electrical power in the circuit.The corresponding conversion efficiency from mechanical power to electrical power is defined as η_1, or named as mechanical coupling efficiency, which is given by

$$\eta_1 = \frac{C_{em}}{C_p + C_{em}} = \frac{\xi_{em}}{\xi_p + \xi_{em}} = \frac{\xi_{em}}{\xi_d} \tag{2}$$

where ξ_p , ξ_{em} is the parasitic and electromagnetic damping ratio of the pendulum (EM-TMD), respectively. In electrical domain, there still exits some power loss in the power flow path, some dissipated by internal coils of EM device, and the other is lost in the energy harvesting circuit. Consequently, the output power of the regenerative EM-TMD system is given by

$$P_{out} = \eta \cdot P_{in} = \eta_1\eta_2\eta_3 \cdot P_{in} \tag{3}$$

Where η is the energy conversion efficiency, (%). Especially, in the impedance-matching condition of constant resistor scenario, a further simplified formula could be employed to estimate the average output power of the regenerative EM-TMD system, that is

$$P_{out} = \omega_n m\xi_d\eta_1\dot{x}_{rms}^2 \tag{4}$$

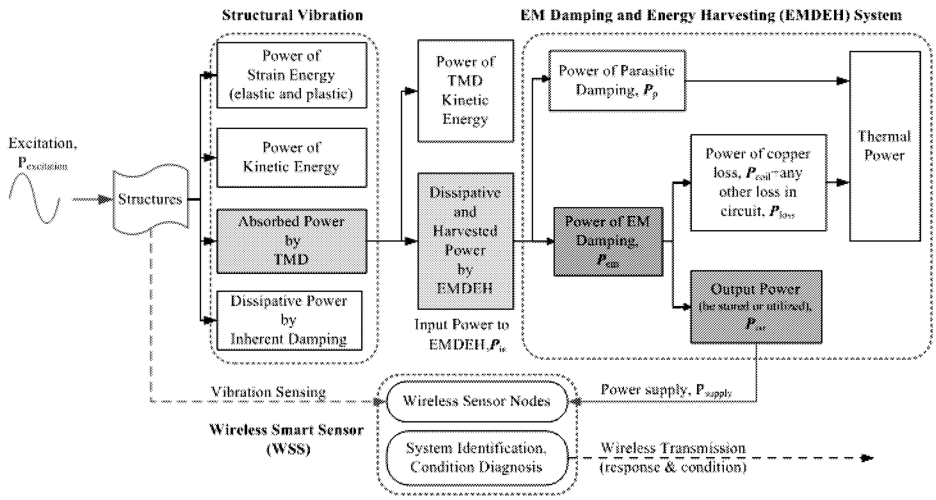
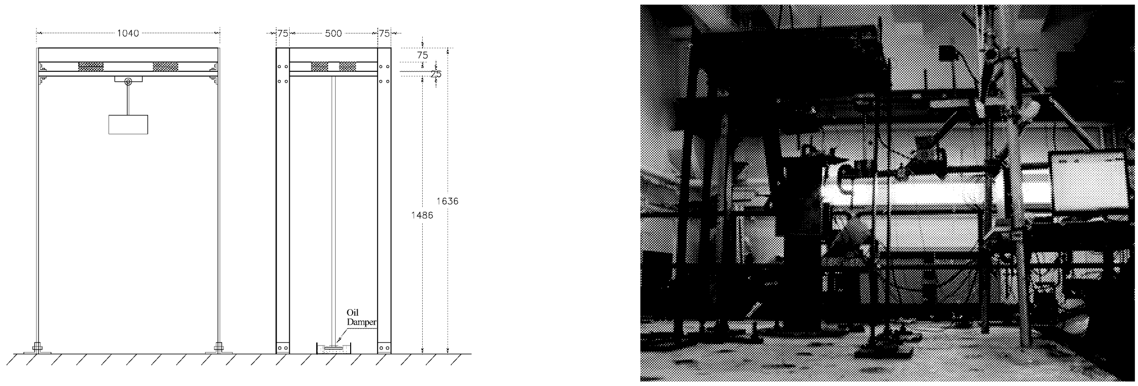


Figure 2 Power flow of a structure with a regenerative EM-TMD system

SHAKING TABLE TEST

SDOF Model with Pendulum-type TMD

Shaking table tests of a single-story frame equipped with a regenerative EM-TMD system were carried out for a proof of concept. The single-story steel frame represents a generic single-degree-of-freedom (SODF) model, and the regenerative EM-TMD system comprises a pendulum-type TMD, a rotary electromagnetic damper, an energy harvesting circuit [Figure 3(b)]. Table 1 shows the dimensions, frequencies and damping ratios of the standalone steel frame without TMD and the pendulum-type TMD. Due to the light damping feature of the steel frame, its inherent damping ratio without TMD was enhanced to 0.95% by adding another oil damper to mimic real-world examples. The ratio of the TMD mass to the frame mass is 3.3%. According to (Soong 1997), the optimal frequency and damping ratio can be calculated as 1.033 Hz and 11.07%. The measured frequency ratio and damping ratio are close these optimal values, as shown in Table 1. The damping characteristic of the TMD is mainly contributed by an electromagnetic damper with a length of 94mm and a diameter of 78mm. It is composed of pairs of permanent magnets and coils, and its configuration is essentially the same as a conventional three-phase alternator. The machine constant of EM damper, K_m ,is easy to be estimated by experiment, which value is 0.7921 V·s/rad. And the equivalent resistance of the EM damper, R_{coil}, is 34.0Ω. A gearbox with a ratio of 1:8 is used to enhance the rotational speed of the rotary electromagnetic damper. As a result, it also magnifies the damping of the EM-TMD n^2 times, where the gear box ratio n = 8.



(a) Dimensioned drawing of SDOF model (b) Photograph of SDOF model with EM-TMD

Figure 3 Shaking table experimental setup diagrams and photograph

Table 1 Properties of SDOF model and the pendulum-type EM-TMD

SDOF model without EM-TMD		Pendulum-type EM-TMD	
Height, *h* (m)	1.636	Length of pendulum L (mm)	186
Mass (kg)	527.9	Mass of TMD , *m* (kg)	17.6
Width b_1 (m)	1.04	Mass ratio of TMD, (%)	3.3
Width b_2 (m)	0.65	Frequency of TMD* (Hz)	1.06
Frequency (Hz)	1.078	Frequency ratio of TMD	0.99
Damping ratio (%)	0.95	Damping ratio of TMD* (%)	10.2

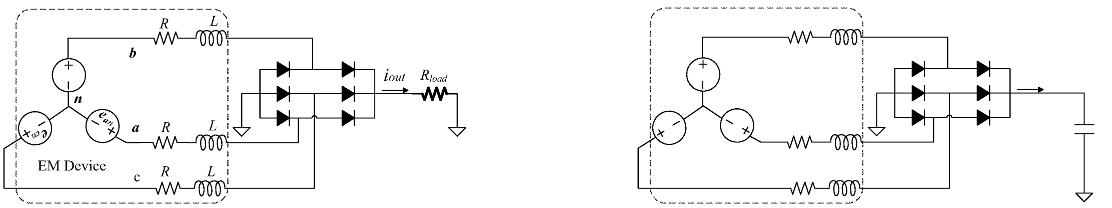
* measured when EM-TMD was connected with Circuit A.

Energy Harvesting Circuits

The AC voltage output of the three-phase EM damper was converted to DC output by a three-phase rectifier comprising six Schottky diodes. The relatively small forward voltage drop of Schottky diodes (around 0.22 V) minimizes the power loss due to the rectifier. Two different circuits shown in Figure 4 were connected to the EM-TMD and tested individually.

Circuits A – A single resistor was connected to the rectifier, representing a general electrical load with constant resistance [Figure 4(a)]. According to the impedance-match principle is commonly accepted in energy harvesting research community, the external resistance R_{load} was tuned to be equal to the internal resistance, namely, 34 Ω. Therefore, the power of R_{load} represents the output power in this case.

Circuit B – It consisted of the three-phase rectifier and a supercapacitor of 23.5F, representing a quite simple energy harvesting circuit. The latter one was employed to store the generated electric energy for powering the electronics devices such as a wireless sensor.



(a) Circuit A: Constant resister (b) Circuit B: Super-capacitor

Figure 4 Energy harvesting circuits

Test Scenarios

Total four testing scenarios were set in this experimental study, which can be seen in Table 2. The responses were collected by KYOWA EDX-100A data acquisition system with a sampling frequency of 100Hz, including the accelerations of the shaking table and frame, the displacement of the shaking table, frame and the pendulum, the corresponding voltages and currents within the energy harvesting circuits. A series of shaking table tests were carried out under random excitations with a bandwidth of 0.5-10 Hz, in which the SDOF model without TMD, the SDOF model with EM-TMD connected with different circuits were tested individually. Ground motions of two different levels, namely, the root mean square (RMS) accelerations equal to 0.03g and 0.05g, were applied during the tests.

Table 2 Testing Scenarios

Scenarios No.	Description	Random Excitation		Circuit
		RMS $\ddot{x}_g$ (m/s^2)	Freq (Hz)	
1	Without control	0.03g	0.5-10	----------
2	With EM-TMD	0.03g	0.5-10	A
3	With EM-TMD	0.05g	0.5-10	A
4	With EM-TMD	0.05g	0.5-10	B

RESULTS AND DISCUSSIONS

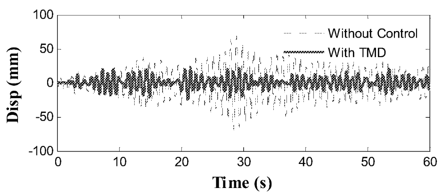
Scenarios 1 2 &3: Without control and with EM-TMD (Circuit A)

Circuit A is designed to validate and assess the control efforts, output power and corresponding energy conversion efficiency of the regenerative EM-TMD system. Significant control efforts were observed in this shaking table testing. The root-mean-square values of displacement and acceleration are reduced by 61.27% and 59.28% respectively. Meanwhile, peak responses of the SDOF model are successfully under controlled; acceleration and displacement are mitigated by 68.63% and 65.33% respectively [Table 3]. This significant effort also can be seen in Figure. 5, all the peak responses under 0.03g ground random excitation are suppressed. Besides, in frequency domain, the control effects are vividly shown in the displacement power spectral density (PSD) function, in which the single peak (43.5dB/Hz) becomes two lower peaks (30.2 dB/Hz,25.8 dB/Hz) with a wider band width (0.989~ 1.148Hz) [Figure 6(a)]. Similarly, the same phenomenon is observed in acceleration PSD [Figure 6(b)]. The PSD figures indicate that the EM-TMD successfully control the structural responses in the narrow frequency range nearby the natural frequency of the control target mode, but fail to control the response in other frequencies.

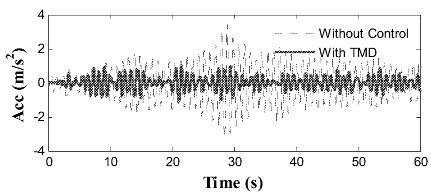
Traditionally, the mechanism of TMD is regarded as by the way of increasing damping ratio of structure, which has been observed, from 0.95% (without control) increasing to 4.9% (with EM-TMD), in this testing too. However, other observations could provide another way to explain it. The vibration power without TMD is 6355.5mW, after introducing TMD (pendulum), that value is down to 819.8 mW, which has been cut down by 87.05%. Furthermore, the total power of the modified system (with EM-TMD), including structural vibration power (819.8mW), TMD vibration power (792.9mW), TMD damping power (629.1mW), which sum (2241.8mW) is only one third of the original system's vibration power (6355.5mW), approximately. This phenomenon indicates that, under the same input, the power of the modified system is becoming much smaller. It turned out that the impedance of the modified system is much larger than that of the original system (SDOF model without control), which with the aid of adding another DOF to it. Put it in another way, adding an EM-TMD (or TMD) is to add a DOF to the structure and make it have larger impedance so that the structural responses are significantly suppressed.

Table 3 Control effects of EM-TMD (Circuit A, R_{load}=34Ω, Excitation: 0.03g random input)

Scenarios	Root-mean-square Responses		Peak Responses	
	$\ddot{x}$ (m/s^2)	x(mm)	$\ddot{x}$ (m/s^2)	x(mm)
Without control	0.941	20.155	3.446	69.842
With EM-TMD	0.365	8.207	1.081	24.230
Reduction (%)	61.27	59.28	68.63	65.33

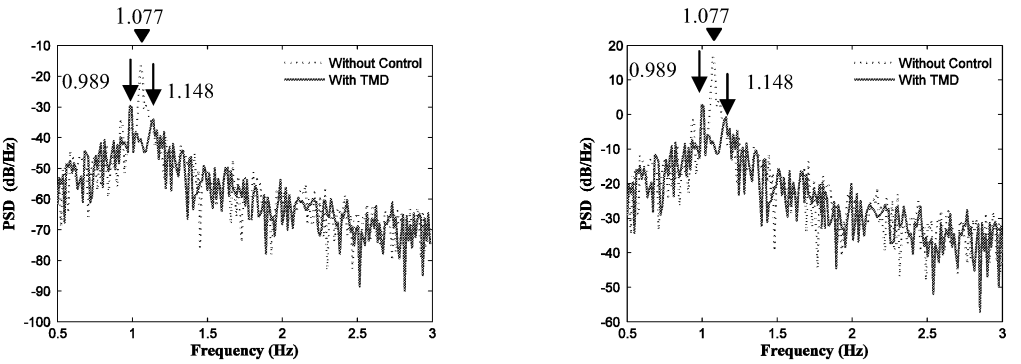


(a) Structural displacement



(b) Structural acceleration

Figure 5 Comparisons of structural response time histories of without control and with EM-TMD.



(a) PSD of structural displacement signals (b) PSD of structural acceleration signals

Figure 6 Comparisons of power spectral density functions of without control and with EM-TMD

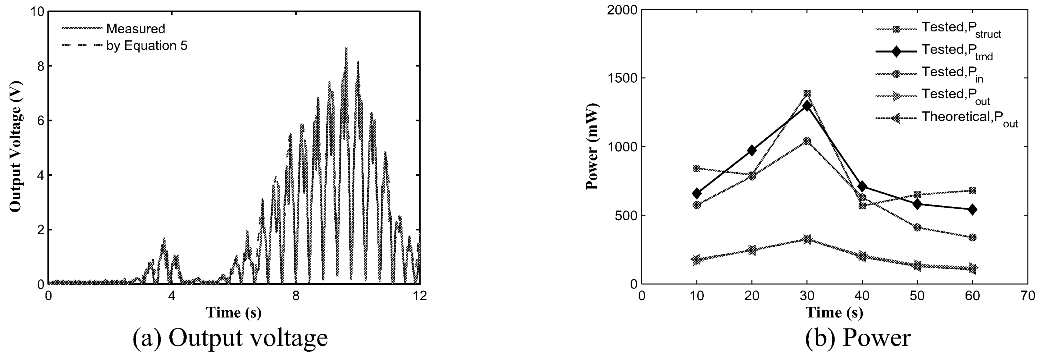
Another issue is the energy harvesting. Firstly, the output voltage (voltage of R_{load}) under impedance-matching condition can be estimated by

$$U_{load}(t) = \sqrt{\omega_n m \xi_d \eta_1 R_{coil}} \cdot \left|\dot{x}(t)\right| \tag{5}$$

where, η_1=61.96% in this experiment.

The load voltage (output voltage) is up to 8.664V, and the proposed Equation (5) can predict the load voltage time histories under impedance-matching condition accurately [Figure 7(a)]. From Equation (5), the output voltage in impedance-matching condition is decided by three factors, that is, the structure itself (ω_n, m, ξ_d), the EM damper features (η_1, R_{coil}), and the excitations ($\dot{x}(t)$). The most essential is the structural constrain, because the parameters (m,ω_n,ξ_d) of TMD are determined by a specific structure and which mode shape is attempted to be controlled. It demonstrates that, the EM-TMD system in building vibration control will produce a much larger output voltage than conventional electromagnetic harvester, because its mass is huge comparing to common electromagnetic harvester. Moreover, the architecture of the EM damper, including the bearing, gearbox, is another influence factor. A higher mechanical coupling η_1 will lead to a higher output voltage, which can be achieved by using a low friction bearing, gearbox and EM damper. Additionally, the output voltage potentiality could be improved by employing a higher internal resistance R_{coil}. The final factor is the velocity of TMD, which is related to the external excitation to the structure, such as the wind, earthquake and traffic loads in civil infrastructure. Higher excitation can produce a higher voltage output. A high output voltage is one of the advantages of the proposed energy-harvesting via EM-TMD. This is a way out of a low AC voltage of a few hundred millvolts of existing electromagnetic energy-harvesting techniques (Dayal et al. 2011).

If the voltage is given, it is easy to estimate the output power in scenario 2. Average output power of the load (R_{load}=34Ω) is 200.9mW, the corresponding power density is 0.446 mW/cm^3 or 11mW/kg, and the normalized power density (NPD) (Priya and Inman 2009) is 1.516 mW/cm^3·ms^2.An approximately same trend between TMD vibration power, TMD damping power (P_{in}), and output power is observed in Figure 7(b). The theoretical Equation (4) was found to give very accurate predictions of the output power comparing with the experimental results. As indicated in Equation (4), the output power of the regenerative EM-TMD system for an impedance-matching condition will be proportional to the mass of TMD, which consistent with literature (Mitcheson 2005). In addition, the average energy conversion efficiency η=31.93% could be calculated based on the data of Figure 7(b), which range from 29.28% to 35%.



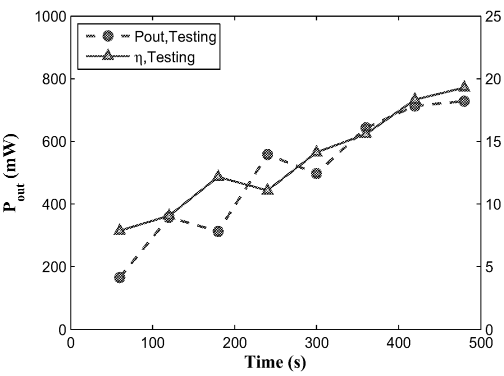
(a) Output voltage (b) Power

Figure 7 Output voltage and power of regenerative EM-TMD (R_{load}=34Ω, random excitation: 0.03g)

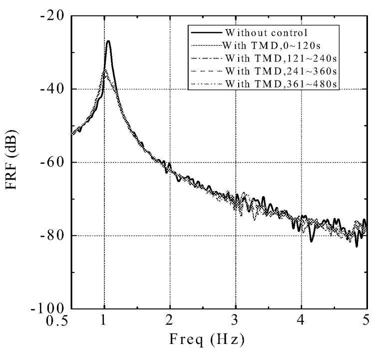
Due to the limitation of the paper length, it is not allowed to present the details of scenario 3 here. The average output power of scenario 3 (R_{load}=34Ω, random excitation 0.05g) is 930.3mW, and the corresponding power density is 2.07 mW/cm^3, 52.9 mW/kg, and 4.2 mW/cm^3·ms^2. In addition, the average open-circuit voltage of scenario 3 is 9.07 volts, which will be employed for the discussion in next section.

Scenario 4: Circuit B; Supercapacitor

Circuit B is a simple and typical energy harvesting circuit. Supercapacitor can stand a high voltage change rate, which is employed here for storing the generated electrical energy by the EM damper. The super-capacitor is a 23.5F (by two 47F in series) aluminium electrolytic capacitor. When the open-circuit voltage is higher than the super-capacitor's voltage , there exists a current flows through the coils, thereby, the super-capacitor is charging [Figure 4(b)].As a results, under the random excitation (0.05g RMS) for 480 seconds duration, the supercapacitor had been charged from 0.8 volts up to 4.25 volts, so the total stored energy was 204.7 J. The significant characteristic of the circuit B is that, its voltage will increase in the charging process, which leads to an increase of the corresponding equivalent impedance. In addition, the electromagnetic damping will decrease with the voltage of super-capacitor rising in the same excitation condition (Shen *et al.,* 2011). Consequently, although with a constant RMS value random input, the output power and its corresponding energy conversion efficiency perform time-varying characteristics. This phenomenon is shown in the Figure 8(a), when the voltage of super-capacitor is charging from 0.8 to 1.2V, its output power and the corresponding efficiency is 165.5 mW and 7.88%; on contrary, when the voltage of super-capacitor is about 4.2 volts, its output power and corresponding energy conversion efficiency are 728.3mW and 19.3%, respectively. It turned out that, the output power and efficiency are influenced by the voltage of super-capacitor. When the voltage of super-capacitor is less than half of the open-circuit voltage (U_o≈9 volts in scenario 3&4, RMS value), the output power and energy conversion efficiency will increase with the rising of the voltage of the super-capacitor; however, when it across the half of the open-circuit voltage, the trend of output power and efficiency needs further investigation. In summary, under a higher excitation than scenario 2, a higher output power, 497 mW, is obtained in this case. However, the output power obtained in this scenario 4 is half of that of scenario 3, approximately. In addition, the corresponding energy conversion efficiency is 13.4%, which is much less than that of the impendence-matching case of the constant resistor scenario (e.g. scenario 2). The power densities of this scenario are listed in the following: 1.1 mW/cm^3 or 28.2 mW/kg, and 2.25 mW/cm^3·ms^2. In addition, the super-capacitor used in this experiment has a big current leakage (about 25mA), which is a significant drawback of the super-capacitor. On the other hand, the control effect shows little time-varying feature. The peak of frequency response functions of without control and with EM-TMD is decreased from -27dB to -35 dB approximately [Figure 8(b)]. As aforementioned, the increasing of the voltage of super-capacitor changes the damping characteristic of the pendulum-type TMD, but cannot change its frequency. Therefore, Figure 8(b) indicates that the control effect of EM-TMD is less affected by the damping characteristic (damping ratio) of TMD, in other words, the control effect of EM-TMD will not change significantly in the charging process of the super-capacitor.



(a) Output power and efficiency



(b) FRF function

Figure 8 The energy harvesting characteristics and the control effect of regenerative EM-TMD (Circuit B, random excitation:0.05g)

CONCLUSIONS

In summary, this paper investigates the novel regenerative EM-TMD system through a series of shaking table tests. This integrated vibration control and energy-harvesting system is operated on low-frequency mode, considering the interaction between harvester (EM-TMD) and the structure. The harvester performs as a damping device for the structure. High output voltage and output power can be achieved by this regenerative

EM-TMD system; which is larger than that of conventional electromagnetic harvester. In impendence-matching condition of constant resistor loading (scenario 2 & 3), the harvested average power under the ground motion levels of 0.03g and 0.05g (RMS) reaches 200.9 mW and 930.3 mW ,respectively. The corresponding energy conversion efficiency is 31.93%. In addition, a high power density has been observed. In details, 2.07 mW/cm^3, 52.9 mW/kg, and 4.2 $mW/cm^3 \cdot ms^2$ have been achieved in scenarios 3 (Circuit A). On the other hand, the harvester—EM-TMD, has a great interaction with the structure. The control effects of EM-TMD are significant, in which, a 61.27% reduction of acceleration RMS value is achieved with a 3.3% mass ratio. However, the output power and energy conversion efficiency showed the time-varying characteristics through the charging process of super-capacitor. In scenario 4 (Circuit B), the output power and energy conversion efficiency are only half of that in scenario 3 (Circuit B), when the super-capacitor charged from low voltage to half of the open-circuit voltage. This phenomenon is negative for the energy harvesting. Anyway, the output power of regenerative EM-TMD system using energy harvesting circuit B is 497 mW under 0.05g ground random motion, which is enough to power one or several wireless sensor nodes. Furthermore, because the output power is proportional to the mass of EM-TMD and the full scale EM-TMD in civil structure is several hundreds to tens of thousands times larger than that of the small scale experimental model which presented in this paper, the full scale structure equipped with the regenerative EM-TMD system is expected to generate a tremendously higher output power. In conclusions, the experimental results indicate that the potential avenue of developing the self-powered sensing and control system is open for civil infrastructures.

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