POWER WIRELESS SENSORS VIA REGENERATIVE ELECTROMAGNETIC TMD

W.A.Shen
The Hong Kong Polytechnic University,
Kowloon, Hong Kong, China

S. Zhu
The Hong Kong Polytechnic University,
Kowloon, Hong Kong, China

Y.L.Xu
The Hong Kong Polytechnic University,
Kowloon, Hong Kong, China

Lack of sustainable power source prevents wireless smart sensors (WSS) from widespread application in long-term structural health monitoring (SHM). Some efforts have been reported in literatures to solve this problem by using solar energy, micro-wind turbine technology and vibration-based energy harvester. In particular, a variety of mechanisms or materials have been explored for vibration-based energy harvesting techniques, including electromagnetic induction, piezoelectricity, electrostatic generation, dielectric elastomers and so on. However, there still exists a gap between the power output of most existing vibration-based energy harvesting devices and the power demand of commercially available WSS. This paper presents an experimental study on a novel energy harvesting solution to WSS—utilizing regenerative electromagnetic tuned mass dampers (EMTMD). The EMTMD, as a key element in the system, is composed of a pendulum-type TMD and a rotary electromagnetic damper. When connected to an energy harvesting circuit (EHC), it converts vibration energy of structures to electrical energy, and functions in both structural vibration reduction and sensor power supply. The functionality of the regenerative EMTMD system was validated in this study through shaking table tests of a single-story steel frame model equipped with an integrated EMTMD, EHC and WSS system. The experimental results revealed that the proposed regenerative EMTMD system can provide regenerative and economical power to WSS. The harvested power under random ground motions (RMS acceleration – 0.05g) reaches up to 312.4mW. The proof-of-concept experiments clearly demonstrate the novel EMTMD is a promising device to be exploited as a sustainable and regenerative power source to WSS.

S.Zhu : ceszhu@polyu.edu.hk

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W.A.Shen[1], S.Zhu[1], and Y.L.Xu[1]

[1] Department of Civil & Structural Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China

ABSTRACT: Lack of sustainable power source prevents wireless smart sensors (WSS) from widespread application in long-term structural health monitoring (SHM). Some efforts have been reported in literatures to solve this problem by using solar energy, micro-wind turbine technology and vibration-based energy harvester. In particular, a variety of mechanisms or materials have been explored for vibration-based energy harvesting techniques, including electromagnetic induction, piezoelectricity, electrostatic generation, dielectric elastomers and so on. However, there still exists a gap between the power output of most existing vibration-based energy harvesting devices and the power demand of commercially available WSS. This paper presents an experimental study on a novel energy harvesting solution to WSS—utilizing regenerative electromagnetic tuned mass dampers (EMTMD). The EMTMD, as a key element in the system, is composed of a pendulum-type TMD and a rotary electromagnetic damper. When connected to an energy harvesting circuit (EHC), it converts vibration energy of structures to electrical energy, and functions in both structural vibration reduction and sensor power supply. The functionality of the regenerative EMTMD system was validated in this study through shaking table tests of a single-story steel frame model equipped with an integrated EMTMD, EHC and WSS system. The experimental results revealed that the proposed regenerative EMTMD system can provide regenerative and economical power to WSS. The harvested power under random ground motions (RMS acceleration = 0.05g) reaches up to 312.4 mW. The proof-of-concept experiments clearly demonstrate the novel EMTMD is a promising device to be exploited as a sustainable and regenerative power source to WSS.

1 INSTRUCTIONS

Emerging wireless sensor technology has seen growing applications in the health monitoring of mechanical, aerospace and civil structures. The limited lifespan of batteries has motivated researchers to seek alternative and reliable power supply to wireless smart sensor (WSS) from ambient light, wind, heat, strain, radio and vibrations (Park 2008). Many vibration-based energy harvesting techniques, e.g. electromagnetic (EM) induction (Glynne-Jones *et al.* 2004), piezoelectricity (Anton & Sodano 2007), electrostatic generation (Mitcheson *et al.* 2004), dielectric elastomers, has been developed for the power source of WSS. The output power of such micro devices usually ranges from µWs to mWs (Mitcheson 2005), whereas the typical power consumption of a WSS is from tens of to hundreds of mWs (Lynch 2006). Therefore, further development of vibration-based energy harvesters with considerably larger output power is necessary in order to successfully power WSS in real applications. On the other hand, the dissipative energy by dampers installed in civil structures has been wasted in the past. These dampers actually provide an appealing power source in consideration of a large amount of vibration energy they absorb. This paper proposes a regenerative electromagnetic tuned-mass damper (EMTMD) system, consisting of a pendulum-type TMD, a rotary EM damper and an energy harvesting circuit (EHC), to provide not only the vibration mitigation of structures but also the regenerative power source of WSS. Though the principle of the regenerative EMTMD is similar to resonant oscillators commonly used in micro energy harvesting devices, they are different in the sense that the EMTMD would affect the vibration of controlled structures to a great extent, and the input vibration to the EMTMD system can no longer be treated as excitations independent with the EMTMD system. A series of shaking table experiments were carried out for a proof of concept, in which a single-story steel frame model equipped with an integrated EMTMD-EHC-WSS system was tested. The functionality of the self-powered vibration control and monitoring system was successfully verified through shaking table test results, and the performance of structural vibration control, energy harvesting, and vibration monitoring was discussed respectively.

2 REGENERATIVE EM-TMD SYSTEM

2.1 Description of regenerative EM-TMD system

Figure 1 illustrates a schematic of a structure equipped with an integrated EMTMD-EHC-WSS system. A simple pendulum is a common form of TMD, in which an auxiliary mass is attached to a primary structure through a pendulum. It is a resonant device oscillating in a 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.* 2011a; Zhu *et al.* 2010). A gearbox is often needed to amplify the damping capacity and output power. Figure 2 shows the principle of the EMTMD-EHC-WSS system, in which the EMTMD is connected to the EHC, and the latter one is further connected to a WSS. The core component in this system is the subsystem composed of the rotary EM damper and the EHC, termed electromagnetic damping and energy harvesting (EMDEH) subsystem [Figure 2]. With the aid of EMDEH subsystem, the dissipative energy by the TMD is converted to electrical energy, stored in rechargeable batteries and further used to power one or more WSS that closely monitor the dynamic response of the structure. WSS could either transmit the raw data back to the central server for system identification or structural condition assessment, or conduct on-line diagnosis using the embedded algorithm and send back the processing results only (Lei *et al.* 2010). Therefore, a self-powered vibration control and monitoring system for civil structures can be realized using the salient features of the EMTMD.

2.2 Energy harvesting circuit

Harvested energy needs to be stored in energy storage elements such as supercapacitors and rechargeable batteries. In this study, a rechargeable battery was selected because of its more stable voltage during charge process and lower self-discharging rate in comparison with a supercapacitor. Examples of rechargeable batteries include Li-ions, NiMH, NiCd, SLA, Li Polymer, etc. A Li-ions battery (capacity: 1840mAh, nominal voltage:3.7V) was used in this study to store energy and power a WSS. However, the AC voltage and current output from the EMTMD needs to be massaged before it is used to charge the Li-ions battery. Figure 3 shows the EHC with a three-phase bridge rectifier and a typical DC-DC converter used in this study. The EHC regulates the random output voltage and maintains a stable charge voltage on the Li-ions battery. As the output voltage from the EMTMD in full-scale civil structures is expected to much higher than those of rechargeable batteries (Shen *et al.* 2011b), a Buck or Buck-boost converter need to be used in most applications. A non-isolated Buck-boost converter (LDO03-005W05-VJ) is selected in the experiment described in the next section. The allowed input voltage of LDO03 is 3-13.8V, and the output voltage is 0.59-5.1V, tuned by the resistor R_{trim}. The switching Buck-boost converter adjusts the duty cycles according to the changing input voltage via a fixed-frequency pulse-width-modulator (PWM). Figure 4(c) shows the tested EHC on a breadboard.

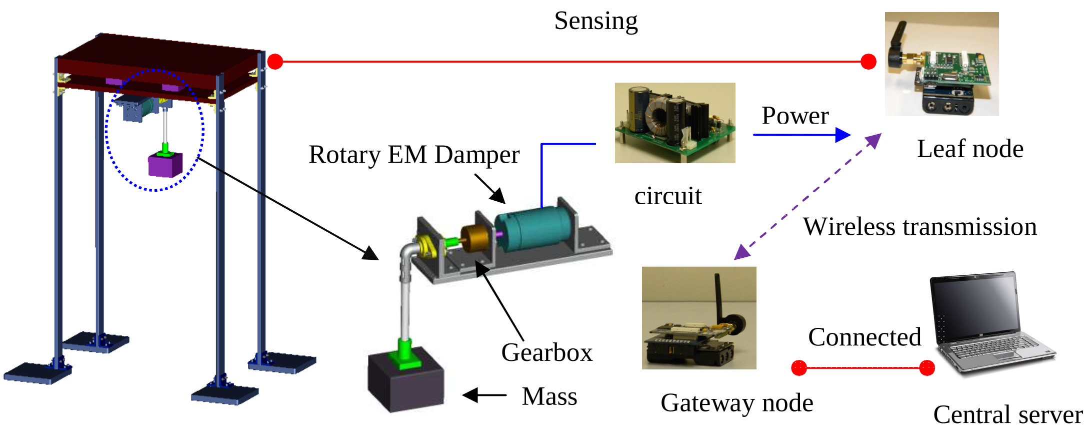


Figure 1. Regenerative EM-TMD system with wireless sensor

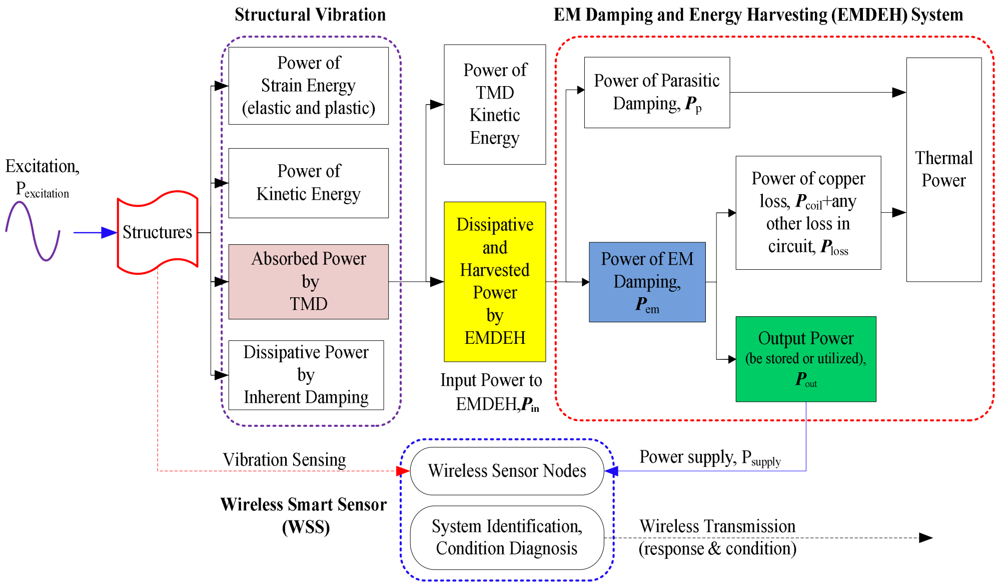


Figure 2.The power flow in a structure equipped with the EMTMD-EHC-WSS system

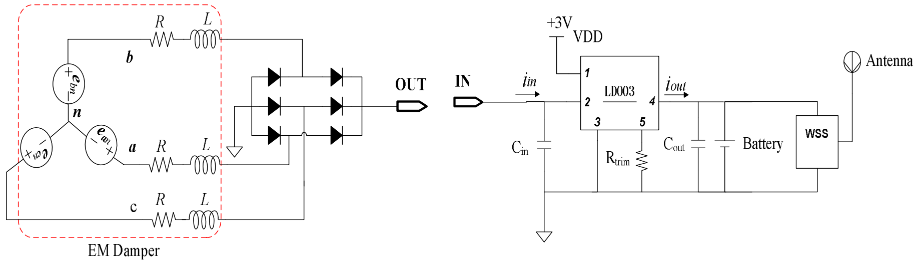


Figure 3 Energy harvesting circuit with a DC-DC converter

2.3 Power flow

Figure 2 indicates the power flow from the input excitations to the ultimate power consumption by a WSS. 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 EMTMD becomes the input power P_{in} to EMDEH subsystem [Figure 2].

$$P_{in} = P_p + P_{em} = P_p + P_{coil} + P_g = P_p + P_{coil} + P_{ehc} + P_{out} \tag{2}$$

where, P_p is the average parasitic damping power; P_{em} is the average EM damping power; P_{coil} is average power due to copper loss; P_g is the average gross output power from the EM dampers, P_{ehc} is the average power loss in the EHC, P_{out} is the average output power to the battery. The pendulum-type TMD can be simplified as a linear motion TMD if its swing amplitude is small. Consequently, P_p can be estimated by

$$P_p = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} C_p \cdot \dot{x}^2(t)dt = 2m\omega_n\xi_p \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \dot{x}^2(t)dt = 2m\omega_n\xi_p \dot{x}_{rms}^2 \tag{3}$$

where C_p is the parasitic damping coefficient of the TMD; $\dot{x}(t)$ is the linear velocity of the mass, $x(t) \approx L\theta(t)$, m is the mass of TMD; ω_n is the natural frequency of TMD; ξ_p

is the parasitic damping ratio of the TMD, $\dot{x}_{rms}$ is the RMS velocity of the TMD. The average power P_{coil} and P_{gross} are defined as

$$P_{coil} = I^2_{coil,rms} \cdot R_{coil} = I^2_{in,rms} \cdot R_{coil} \tag{4}$$

$$P_g = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} u_{in}(t) \cdot i_{in}(t) dt \tag{5}$$

where, $I_{coil,rms}$ is the RMS current in the coil; $I_{in,rms}$ is the RMS value of the input current shown in Figure 3; u_{in} is instantaneous voltage of the input capacitor; i_{in} is instantaneous current of the input capacitor. The average output power shown in Figure 3 can be estimated by

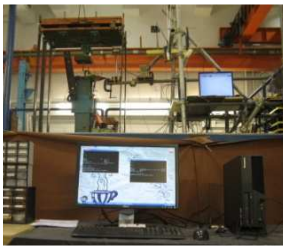
$$P_{out} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} u_b(t) \cdot i_{out}(t) dt \tag{6}$$

where u_b is the charge voltage of the battery; i_{out} is the charging current.

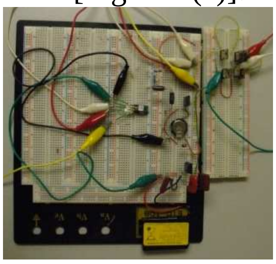
3 SHAKING TABLE TESTS

3.1 Testing setup

Shaking table tests of a single-story steel frame equipped with an EMTMD-EHC-WSS system were carried out for a proof of concept. The single-story steel frame represents a generic single-degree-of-freedom (SODF) model [Figure 4(a)].



(a) Test setup on shaking table



(b) Energy harvesting circuit on a breadboard

Figure 4. Test setup of regenerative EM-TMD system

Table 1 shows the dimensions, frequencies and damping ratios of the standalone steel frame without TMD and the corresponding properties of the pendulum-type EMTMD. 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 and Dargush (1997), the optimal frequency and damping ratio is calculated as 1.033 Hz and 11.07%. The measured frequency ratio and damping ratio is close to the optimal values, as shown in Table 1. The damping capacity of the TMD is mainly contributed by an electromagnetic damper with a length of 94mm and a diameter of 78mm. It comprises 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 was estimated by an experimental calibration as K_m=0.7921 V·s/rad, and the equivalent resistance of the EM damper is R_{coil}=34.0Ω. A gearbox with a ratio of 1:8 was used to enhance the rotational speed of the damper. As a result, it also magnified the damping of the EMTMD by n^2 times, where the gear box ratio n=8. The output voltage of Buck-Boost converter LDO03 was tuned to 4.2 volts, a standard charge voltage for Li-ion batteries. It corresponds to R_{trim}=334 Ω in the EHC. A wireless sensor consisting of Imote2 wireless sensing platform and a SHM-A multi-metric sensor board (Rice et al. 2010) was installed to measure the acceleration response of the frame. The allowable input voltage range is from 3.7V to 4.7V.

Table 1. Properties of SDOF model and the pendulum-type EMTMD

SDOF model without EMTMD		Pendulum-type EMTMD	
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 EMTMD was connected with a rectifier and a constant resistor (R_{load}=34Ω)

3.2 Testing Scenarios

Table 2 shows the four different scenarios in the shaking table tests. 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 displacements of the shaking table, frame and the pendulum, the voltages and currents within the EHC. A series of shaking table tests were carried out under random excitations with a bandwidth of 0.5-10 Hz. The building model without TMD and the building model with EMTMD were tested individually. Ground motions of two different levels, namely, the RMS accelerations equal to 0.03g and 0.05g, were applied during the tests.

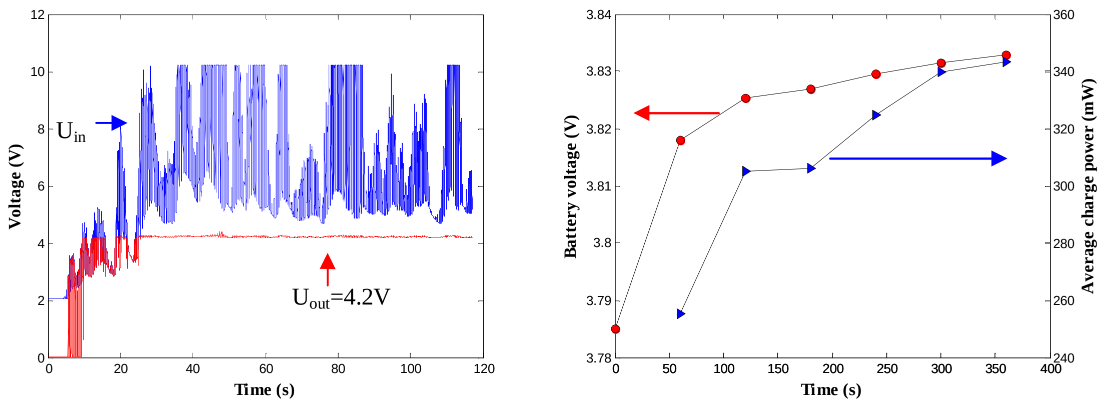
Table 2. Testing Scenarios

Scenarios No.	Description	Random Excitation RMS $\ddot{x}_g$ (m/s2)	Random Excitation Freq (Hz)	Circuit
1	Without control	0.03g	0.5-10	----------
2	Without control	0.05g	0.5-10	----------
3	With EMTMD	0.05g	0.5-10	Without WSS
4	With EMTMD	0.05g	0.5-10	With WSS

4 TESTING RESULTS AND DISCUSSIONS

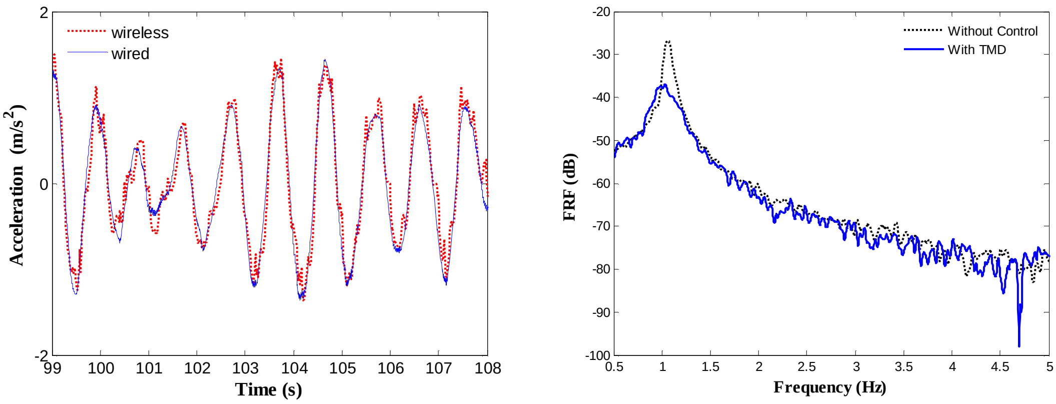
The performance of the self-powered vibration control and monitoring system using the regenerative EMTMD was evaluated in this section based on the experimental results. Figure 5 shows the energy harvesting performance in Test No. 3. Figure 5(a) is the time histories of input and output voltage of the DC-DC converter when the battery was not connected to any electric load. Though the input voltage shows a substantial fluctuation (voltage higher than 10V is beyond the measurement range), the DC-DC converter could well maintain a stable output voltage of 4.2V, with a minimal ripple observed. Figure 5(b) shows the time histories of the battery voltage and average charge power during the shaking table test. The voltage of Li-ion battery gradually increased from 3.785V to 3.833V, and the corresponding average charge power is 312.4mW. Meanwhile, the Imote2 wireless sensor was powered by the Li-ion battery in the Testing No. 4. Figure 6(a) shows the comparison of the acceleration signals collected by the wireless and wired systems, and the measurement by the wireless sensor could agree with the wired system very well. The current in the wireless sensor was around 55mA in standby state, and it went up to 162 mA when it started sensing. Therefore, the standby power and the sensing power of the Imote2 WSS is around 204 mW and 626 mW respectively. In practice, WSS usually works alternately in standby and sensing states. It is also as such in this experimental study. The average power consumption of the Imote2 WSS was 299 mW in this test. The output power from the EHC demonstrates a promising feasibility of using the regenerative EMTMD to power one or more WSS. It should be noted that the output power of the EMTMD in real-scale civil engineering structures is expected to be considerably larger than those described in this experimental study.

The regenerative EMTMD also functions like conventional TMD devices with regard to the vibration mitigation of structures. Figure 6(b) shows the frequency response function (FRF) of the building accelerations estimated from the experiments. The control effect of the regenerative EMTMD is evidenced by the considerable reduction of the FRF peak by around 10dB. The damping ratio of the frame model was increased from 0.95% to 4.6% after the installation of the regenerative EMTMD that was connected to the EHC. It testifies that the regenerative EMTMD is an effective damping device for the vibration control of civil engineering structures.



(a) Input and output of Buck-boost converter without load (b) Battery voltage and average charge power

Figure 5 Energy harvesting performance of the regenerative EMTMD in testing scenario 3



(a) Structural acceleration signals (b) Frequency Response Function

Figure 6 Wireless sensor performance and control effects of testing scenario 4

5 CONCLUSIONS

This paper proposes a novel regenerative EMTMD, which functions as vibration dampers and energy harvesters simultaneously. Based on it, a self-powered vibration control and monitoring system which integrates the regenerative EMTMD, EHC and WSS has been proposed, designed and validated by a series of shaking table tests. The experimental results demonstrated the integrated system can achieve an effective performance in vibration control and a good accuracy in wireless sensing simultaneously. More important, the output power from the regenerative EMTMD can be successfully harvested by the EHC and further used to power a WSS during the test. The average output power was 312.4mW for the ground motion levels of 0.05g (RMS accelerations). Considering much greater output power in its applications in full-scale civil engineering structures, the proposed regenerative EMTMD is a promising device as a green, economic and sustainable power source to WSS. It provides a great potential to establish a self-powered smart system with the functions of online health diagnosis, energy harvesting and adaptive vibration control for civil engineering structures.

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