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# Theoretical modeling, simulation and experimental study of hybrid piezoelectric and electromagnetic energy harvester

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In this paper, performances of vibration energy harvester combined piezoelectric (PE) and electromagnetic (EM) mechanism are studied by theoretical analysis, simulation and experimental test. For the designed harvester, electromechanical coupling modeling is established, and expressions of vibration response, output voltage, current and power are derived. Then, performances of the harvester are simulated and tested; moreover, the power charging rechargeable battery is realized through designed energy storage circuit. By the results, it's found that compared with piezoelectric-only and electromagnetic-only energy harvester, the hybrid energy harvester can enhance the output power and harvesting efficiency; furthermore, at the harmonic excitation, output power of harvester linearly increases with acceleration amplitude increasing; while it enhances with acceleration spectral density increasing at the random excitation. In addition, the bigger coupling strength, the bigger output power is, and there is the optimal load resistance to make the harvester output the maximal power. 
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## I. INTRODUCTION

Vibration energy harvester, which can convert mechanical energy into electric energy, has been focused by researchers in recent years,[1–3] and three working mechanisms have been proposed: piezoelectric, electromagnetic and electrostatic energy harvesting.[4] However, PE and EM energy harvester got more attention than electrostatic energy harvester, as they have high electromechanical coupling and no external voltage source requirement.[5] Furthermore, much works have been done for these harvesters, for example, theoretical analysis by lumped parameter model and distributed parameter model,[6–8] structural design by linear and nonlinear methods,[9–11] fabrication technologies based MEMS process,[12,13] and energy storage circuit.[14–16]

In order to combine the benefits of single harvesting mechanism simultaneously, hybrid energy harvesters were proposed by researchers. Wacharasindhu designed a hybrid PE and EM energy harvester for harvesting energy from pressing keyboard, and the structure was fabricated by MEMS process. By experimental test, output power of PE and EM elements were 40.8μW and 1.15μW respectively.[17] Hybrid energy harvester proposed by Yang can output 176μW and 0.19μW for PE and EM elements respectively.[18] Challa proposed a coupling PE-EM meso harvester using the moving magnet as mass block, and the experimental results showed that output power of harvester was 332μW, while the corresponding single PE and EM harvesting devices were 275μW and 244μW respectively.[19] Besides, Chen illustrated a MEMS hybrid PE and EM energy harvester based on the four fixed beam-mass structure, and the output voltage was 94mV and 8mV for PE and EM

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elements respectively.[20] Bryn proposed a low frequency vibration hybrid PE and EM energy harvester, and average output power were 46.2μW and 3.6μW at the excitation frequency of 5Hz from the electromagnetic and piezoelectric transducers respectively.[21] Mahmoudi developed a multiphysics model of hybrid piezoelectric-electromagnetic vibration energy harvester including the main sources of nonlinearities, and showed that the hybrid transduction permitted enhancement of the power density by up to 84%.[22] Furthermore, Chen designed a hybrid energy harvester integrated with piezoelectric and electromagnetic mechanism for powering wireless sensor nodes in smart grid, and with the total output power of 341.9μW, the power density was much higher than the one generated only by conventional piezoelectric energy harvester under the same condition.[23] Therefore, compared with PE and EM single harvesting mechanism, hybrid energy harvester can output bigger power.

In addition, Li investigated the influence of electromechanical coupling effect on performances of hybrid piezoelectric and electromagnetic energy harvester by theoretical analysis, and results showed that the bigger coupling coefficient, the greater resonant frequency shifting, output power and conversion efficiency.[24] Tandesse reported that for hybrid PE and EM energy harvester, EM and PE elements can output the high power at low and high vibration frequency respectively. Thus, combining these two systems together can improve the function of devices over the wide frequency range.[25] Besides, Shan presented the mathematical model of output power by taking the secondary piezoelectric effect into account, and compared with the single piezoelectric power generator. From the analysis results, the optimized external load increases the system power output of the hybrid energy harvester by 13.3%.[26]

From above references, the research works for hybrid PE and EM energy harvester mainly focused on the structure design and performances validation at present, and performances were tested at the harmonic excitation. Moreover, the coupling effect between two harvesting elements was less considered in their model and analysis. Therefore, in this paper, a hybrid PE and EM energy harvester was designed, and the working model considering the electromechanical coupling between two energy harvesting elements was proposed. Then, expressions of output voltage, current and power were derived by lumped parameters model, and the coupling effect between PE element and EM element was studied by simulation and experimental test. For the designed hybrid energy harvester, performances under harmonic and random excitation were tested. Lastly, the energy storage circuit for hybrid PE and EM energy harvester was designed, and the power charging the rechargeable battery was realized.

## II. STRUCTURE DESIGN

A hybrid energy harvester is designed and shown in Figure 1, which integrated with piezoelectric and electromagnetic conversion mechanisms simultaneously. Magnets are supported by a

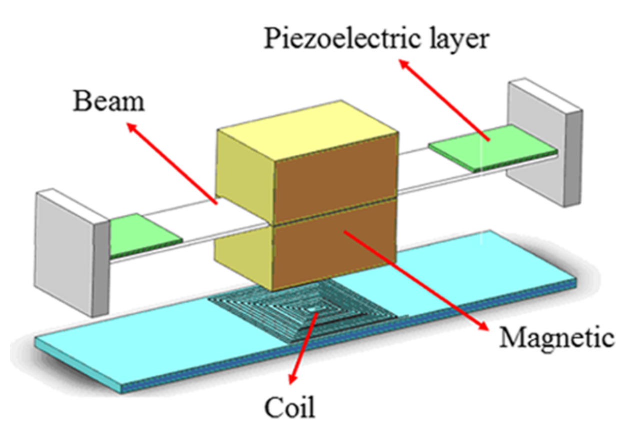


FIG. 1. Hybrid PE and EM energy harvesting.

double-fixed beam, and piezoelectric layers (PZT) polarized in the beam thickness direction are attached on the top surface of beams. Others, coils are placed under the magnets. It consists of the PE harvesting element, EM harvesting element and the mechanical structure, and PE and EM elements connect with load resistors. Under the excitation, PE and EM elements output power based on piezoelectric effect and Farady's Law respectively.

In the analysis, the harvester is modeled as a SDOF (single degree of freedom) system. Let z(t) be the amplitude of the magnet, $V_p(t)$ as the output voltage of PE element, $I_{em}(t)$ as the output current of EM element, and the governing equations considering the electromechanical coupling can be established, as shown in equations (1)–(3).

$$m_e\ddot{z}(t) + c_m\dot{z}(t) + kz(t) + g_{em}i_{em}(t) + \theta V_p(t) = \mu_1 m_e a(t) \tag{1}$$

$$L_c\frac{di_{em}(t)}{dt} + (R_c + R_m)i_{em}(t) - g_{em}\frac{dz(t)}{dt} = 0 \tag{2}$$

$$\frac{V_p(t)}{R_p} + C_p\dot{V}_p(t) - \theta\frac{dz(t)}{dt} = 0 \tag{3}$$

where $a(t)$ is the excitation acceleration, and $\mu_1$ is the correction factor of single degree of freedom system compared with the distributed-parameter model.[27] $R_p$ and $R_m$ are load resistance of PE and EM element respectively; $C_p$ is equivalent capacitance of PE layer; $V_p$ is output voltage of PE energy harvesting element; $I_{em}$ is output current of EM energy harvesting element; $R_c$ and $L_c$ refer to resistance and inductance of coils; $\theta$ and $g_e$ are PE and EM transfer factors respectively. These parameters are dependent on the material constants and the structures of the energy harvester, which can be derived by standard model analysis.[5]

The application environment of vibration harvester is usually the low frequency vibration. Therefore, the inductance of coil can be neglected in the analysis. Then, Fourier transform is carried on equations(1)–(3), and it can be obtained that

$$z(\omega) = \frac{\mu_1 m_e}{m_e(i\omega)^2 + (c_m + \frac{g_{em}^2}{R_c+R_m})i\omega + \mathrm{k} + \theta\frac{i\omega\theta R_p}{1+i\omega C_pR_p}}a(\omega) \tag{4}$$

$$\mathrm{i}_{em}(\omega) = \frac{g_{em}}{R_c + R_m}z(\omega)i\omega \tag{5}$$

$$V_p(\omega) = \frac{\theta R_p}{1 + j\omega C_pR_p}z(\omega)i\omega \tag{6}$$

So the amplitude of magnet at any frequency $\omega$ is

$$z_M = \frac{\mu_1 m_e a_M}{\sqrt{[-m_e\omega^2 + k + \frac{\omega^2R_p^2\theta^2C_p}{1+(\omega C_pR_p)^2}]^2 + \{\omega[c_m + \frac{g_{em}^2}{R_c+R_m} + \frac{\theta^2R_p}{1+(\omega C_pR_p)^2}]\}^2}} \tag{7}$$

where $a_M$ is the magnitude of acceleration. From Equation (7), it can be concluded that the coupled PE and EM elements can alter the vibration response of harvesting system, which affects the power obtained from energy harvesting system conversely. However, the governing equations for hybrid energy harvester in literatures[17,19] do not consider this electromechanical coupling effect.

In particular, the coupling effect of PE element changes the effective stiffness and damping coefficient of the harvesting system, while that of EM element just influences the effective damping coefficient. Thus, the effective stiffness and damping coefficient of hybrid energy harvester at any excitation frequencies $\omega$ are shown respectively as

$$K_{ef} = K + \frac{\omega^2R_p^2\theta^2C_p}{1 + (\omega C_pR_p)^2} \tag{8}$$

$$c_{ef} = c_m + \frac{k_{em}^2}{R_{coil} + R_m} + \frac{\theta^2R_p}{1 + (\omega C_pR_p)^2} \tag{9}$$

Similarly, the amplitude of PE output voltage and EM output current are derived through Equation (10), as illustrated respectively

$$|I_{em}| = \frac{\omega k_{em}}{R_m + R_{coil}} z_M, \left|V_p\right|^2 = \frac{\omega^2 R_p^2 \theta^2}{1 + (\omega C_p R_p)^2} z_M^2 \tag{10}$$

Then, the average power of PE and EM elements are illustrated as equations (11) and (12) respectively, which are calculated from the root-mean-squared (RMS) values of output voltage and current.

$$P_{em} = \frac{R_m k_{em}^2 \omega^2}{2(R_m + R_{coil})^2} z_M^2, P_p = \frac{R_P \omega^2 \theta^2}{2 + 2(\omega C_p R_p)^2} z_M^2 \tag{11}$$

So the total output power of hybrid energy harvester is

$$P_e = P_{em} + P_p = [\frac{R_m k_{em}^2 \omega^2}{2(R_m + R_{coil})^2} + \frac{R_P \omega^2 \theta^2}{2 + 2(\omega C_p R_p)^2}] z_M^2 \tag{12}$$

In Equation (12), for hybrid energy harvester, it can be concluded that power output of PE element is not only decided by piezoelectric properties, but also affected by electromagnetic properties because of coupling effect. And vice versa, the power of EM element is also influenced by PE properties.

## III. SIMULATION STUDY AND DISCUSSION

From above analysis results, for hybrid energy harvester, electric output has the coupling effect on the response of harvesting system. In this section, the effect is studied by simulation method.

As the influence of PE element is obvious, effects of EM parameters and resonant frequency on performances of hybrid energy harvester are mainly simulated. In the simulation, the output voltage of PZT is obtained by ANSYS software, while the output current of coil is achieved with Ansoft Maxwell software. The structural parameters and materials properties are shown in Table I. In the simulation, the excitation acceleration is 0.6g and the excitation frequency is 83Hz.

### A. Effect of space between coil and magnet on performances

By Equations (7) and (12), the average amplitude and output power of hybrid energy harvester are related with magnet properties and the space between coil and magnet. Therefore, magnetic field distribution of magnet is simulated through Ansoft Maxwell software, and the result is shown in Figure 2. It can be concluded that the closer distance to the magnet, the bigger magnetic field intensity. Meanwhile, the magnetic flux in coil is different when the space between magnet and coil changes. For the designed harvester, the output performances are simulated at the different spaces. From the simulation results in Figure 3, EM output power increases firstly and then decreases with the space increasing; moreover, EM element outputs maximal power when the space between magnet and coil is -2mm.

According to Equation (7), electromechanical coupling effect of EM element on harvesting system is caused by equivalent electric damping, which are illustrated in Table II for different spaces. In this case, the output power of PE element is shown in Figure 4. It is found that PE element outputs

TABLE I. Structural parameters and materials properties.

| EM energy harvesting element | | PE energy harvesting element | |
|---|---|---|---|
| Mass magnet (NdFeB) | 15mm*20mm | Beam of one side (stainless steel) | 28mm*8mm*0.36mm |
| Residual magnetism | 1T | PZT layer | 10mm*8mm*0.2mm |
| Inner diameter of coil | 16.5mm | Piezoelectric coefficient | $-100^{*}10^{-12}$m/V |
| Coil height | 7mm | PZT density | 7700 kg/m$^3$ |
| Coil diameter | 0.15mm | PZT elastic modulus | 60GPa |
| Coil turns | 360 | PZT poisson ratio | 0.3 |

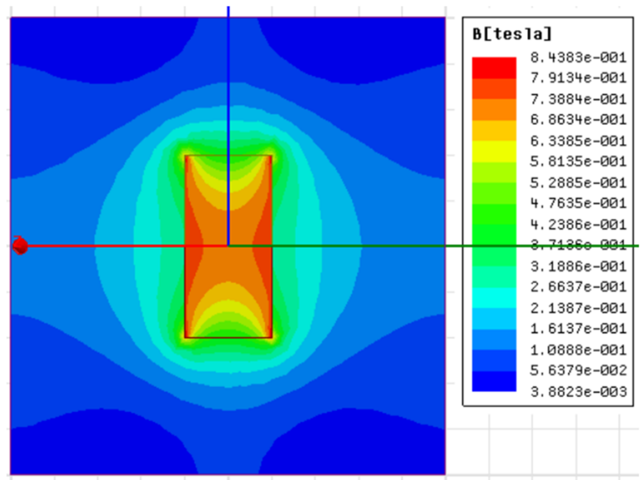


FIG. 2. Magnetic induction lines distribution of magnet.

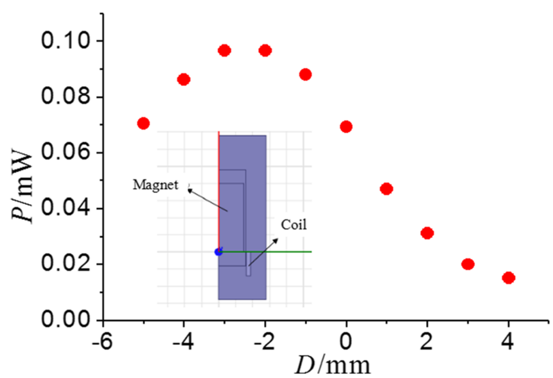


FIG. 3. EM Output power at different magnet position.

TABLE II. EM damping for different spaces between coil and magnet.

| Space | -5mm | -2mm | 4mm |
|---|---|---|---|
| EM damping | 0.052 | 0.0715 | 0.0112 |

the minimal power when the space between magnet and coil is -2mm. However, compared with EM element, the variation of space has less influence on PE element performance. When the spaces vary from 4mm to -2mm, the enhancing power of hybrid energy harvester is 0.07mW. Therefore, it is necessary to calculate the optimal space between coil and magnet when designing the hybrid energy harvester.

### B. Effect of coil turns on performances

For coils in the harvester, when the inner diameter, height and wire diameter are fixed, the electromagnetic damping for different coil turns are shown in Table III, and the output power of EM and PE elements are simulated, whose results are illustrated in Figures 5 and 6. When the coil turns are 45, 560 and 1000, the output power of PE and EM elements are 0.01mW, 0.095mW, 0.15mW and 0.144mW, 0.136mW, 0.128mW respectively. Furthermore, it shows that EM power increases with coil turns increasing while PE power decreases, and the variation of PE element is much less than

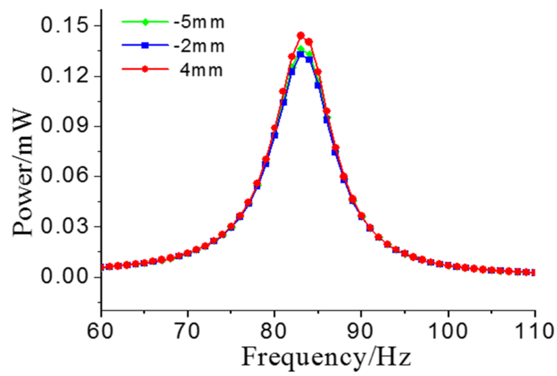


FIG. 4. PE output power for different spaces between coil and magnet.

TABLE III. EM damping for different coil turns.

| Coil turns | 45 | 360 | 1000 |
|---|---|---|---|
| EM damping | 0.0074 | 0.0512 | 0.1034 |

that of EM element. Besides, for hybrid energy harvester, the total power enhances with the coil turn increasing. Therefore, when designing the hybrid energy harvester, the coil turns should be increased in order to improve the output power.

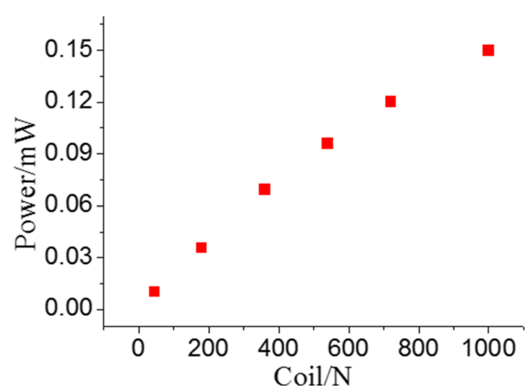


FIG. 5. EM output power for different coil turns at fixed coil wire diameter.

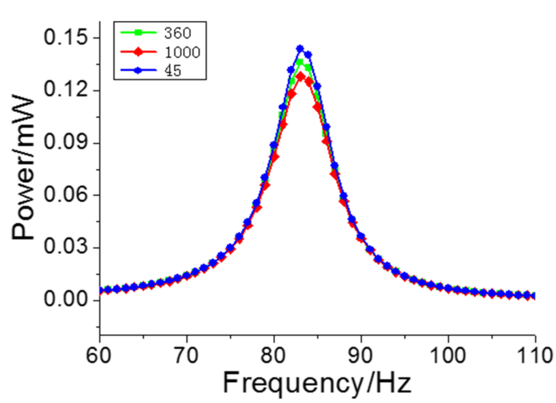


FIG. 6. PE output power for different coil turns at fixed coil wire diameter.

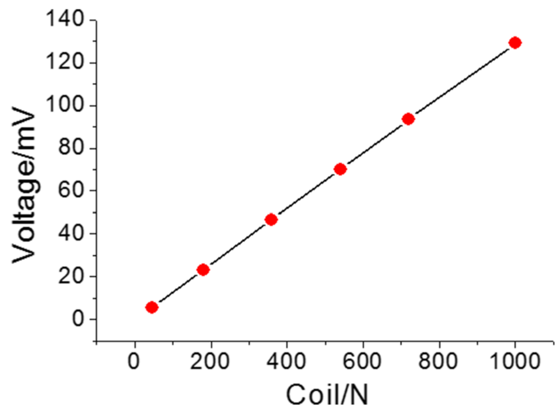


FIG. 7. EM output voltage for different coil turns at fixed coil volume.

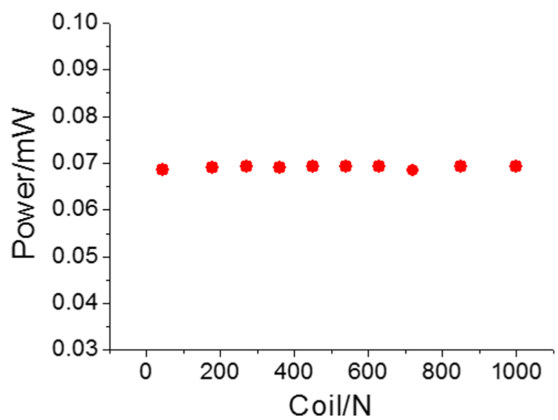


FIG. 8. EM output power for different coil turns at fixed coil volume.

Besides, when the volume of coil is fixed, the coil turns vary with diameter. In this case, output voltage and power of EM element are shown in Figures 7 and 8 at different coil diameters. It can be obtained that EM output voltage linearly increases with coil turns increasing while the power does not change, which may be caused by the internal resistance of coil increasing. Therefore, the output power of EM element and hybrid energy harvester keeps invariant at this case.

### C. Effect of coil height on performances

When the inner diameter and coil turns are 16.5mm and 360 respectively, the effect of coil height on EM output power is illustrated in Figure 9. From the results, EM power increases firstly and then decreases with the coil height increasing; moreover, it reaches the maximum 0.069mW when the coil height is 7mm.

Accordingly, when the coil height is 3mm, 7mm and 12mm, electromagnetic damping and PE power are illustrated in Table IV and Figure 10 respectively. By the simulation results, PE output power does not change with coil height. Therefore, in order to output the maximal power, the optimal coil height needs to be optimized for hybrid energy harvester.

### D. Effect of resonant frequency on performances

For vibration energy harvester, the resonant frequency varies with the structural parameters. In this part, effect of resonant frequency on output power of harvester is simulated when the amplitude keeps invariant, and the result is illustrated in Figure 11. When the resonant frequency is 60Hz, 83Hz and 100Hz, output power of EM element are 0.031mW, 0.054mW and 0.105mW respectively.

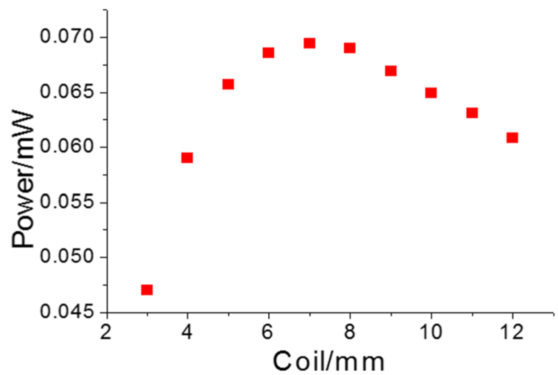


FIG. 9. EM output power for different coil height.

TABLE IV. EM damping for different coil height.

| Coil height | 3mm | 7mm | 12mm |
|---|---|---|---|
| EM damping | 0.0347 | 0.0513 | 0.045 |

From the results, it can be concluded that EM output power increases with resonant frequency increasing.

In addition, when the resonant frequency of harvester are 60Hz,83Hz and 110Hz respectively, EM damping of harvester is illustrated in Table V, which indicates that EM damping is the maximum at 100Hz. From Figure 12, it shows that although PE power decreases with resonant frequency increasing, the total power of hybrid energy harvester improves 0.061mW when the resonant frequency varies from 60Hz to 110Hz.

## E. Output power comparison

When the acceleration is 0.6g, the power of hybrid energy harvester at different excitation frequencies is shown in Figure 13, and it improves 26% and 122% respectively compared with piezoelectric-only and electromagnetic-only energy harvester. From Figure 13, the resonant frequency and maximal power of piezoelectric-only, electromagnetic-only and hybrid energy harvester are 83Hz, 72Hz, 83Hz and 0.126, 0.072, 0.16 respectively. Therefore, it is indicated that combining the piezoelectric and electromagnetic harvesting mechanism can enhance the output power and harvesting efficiency, which means that hybrid energy harvester is much better choice in the vibration environment.

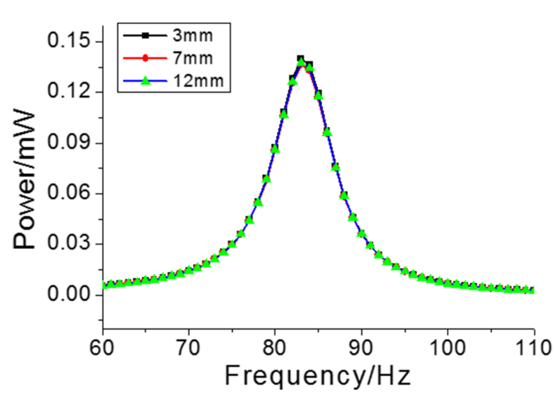


FIG. 10. PE output power for different coil height.

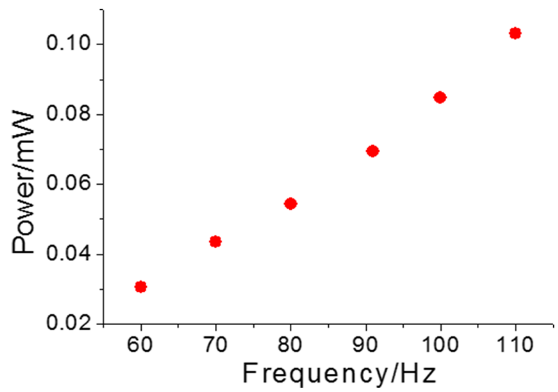


FIG. 11. EM output power for different resonant frequency.

TABLE V. EM damping for resonant frequency.

| Resonant frequency | 60Hz | 83Hz | 110Hz |
|---|---|---|---|
| EM damping | 0.0226 | 0.0512 | 0.0763 |

Therefore, in order to improve the performances of hybrid energy harvester, it is necessary to comprehensively consider the effect of EM and PE parameters based on the application environment and size limitation of energy harvester.

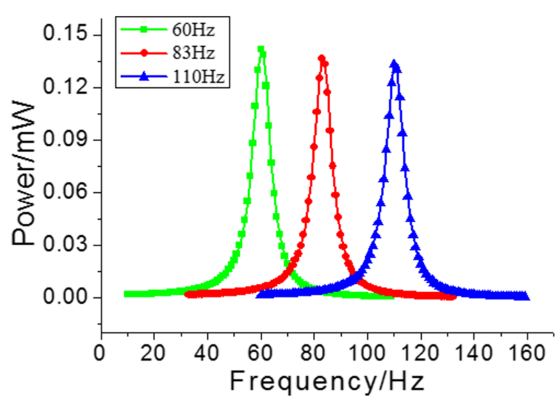


FIG. 12. PE output power for different resonant frequency.

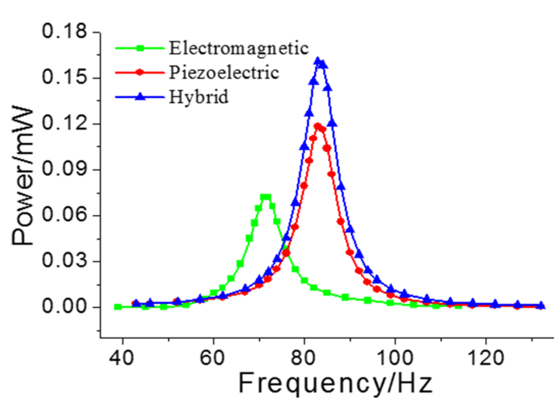


FIG. 13. Power of piezoelectric, electromagnetic and hybrid energy harvester.

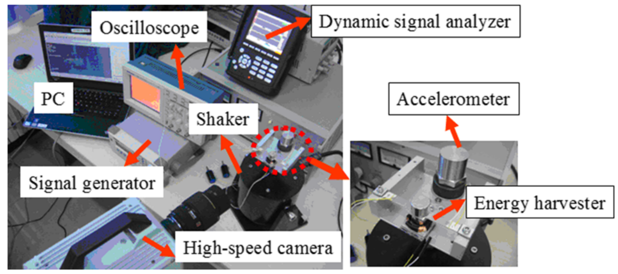


FIG. 14. Experimental setup.

## IV. EXPERIMENTAL TEST

In this section, performances of the designed hybrid energy harvester are tested, and the structural parameters are the same as those used in the simulation. The whole setup of the device in Figure 14 is mounted on the vibrating shaker, and signal generator output excitation signal to vibration shaker through power amplifier. The vibration signal is tested by acceleration sensor (PCB Inc, Model 393B04), and output voltage of energy harvester is recorded by dynamic signal analyzer (Crystal Instrument corporation, COCO-80), and the displacement of harvester is tested by high-speed camera (Photron SA4). Meanwhile, lead wires from the piezoelectric cantilever beam and coils are connected across a variable resistor to maximize the power output.

### A. Effect of load resistance on performances

From equation (11), the output power is associated with load resistance. At the resonant frequency 74.4Hz, the power of PE, EM and hybrid energy harvester are shown in Figure 15 when they connect with different load resistances. From the test results, there are optimal load to make three harvesters output the maximal power, and at the corresponding load resistance, the power of hybrid energy harvester is bigger than that of PE and EM energy harvesters. In addition, because PE and EM harvesting elements can output maximal power at the thousands of ohm and several ohm respectively, the hybrid energy harvester can be used at the much more wide load application range.

According to test results, compared with PE and EM energy harvester, the hybrid energy harvester not only can improve the output power, but also broaden the 3dB bandwidth and load application range.

### B. Effect of excitation frequency on performances

When the excitation acceleration is 0.6g, the output power of hybrid energy harvester at different excitation frequencies are illustrated in Figure 16, and the results are compared with piezoelectric-only and electromagnetic-only energy harvester.

According to the results shown in Figure 16, the resonant frequency of three harvester are 72.5Hz, 65.5Hz, 74.4Hz respectively; the optimal load resistance of PE and EM energy harvester are 279kΩ

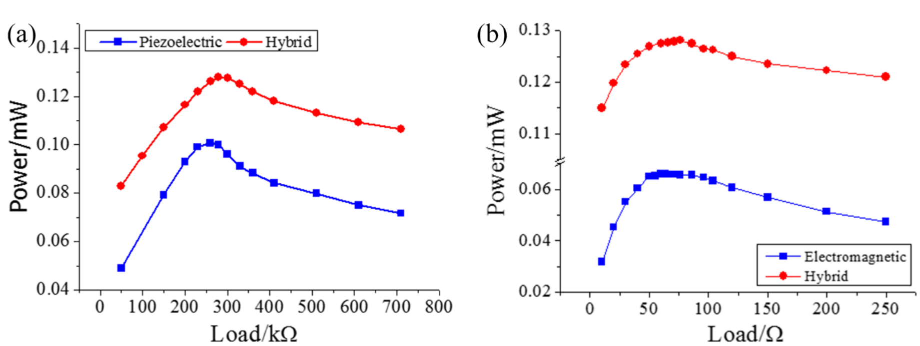


FIG. 15. The output power varied with the load resistance: (a) PE power; (b) EM power.

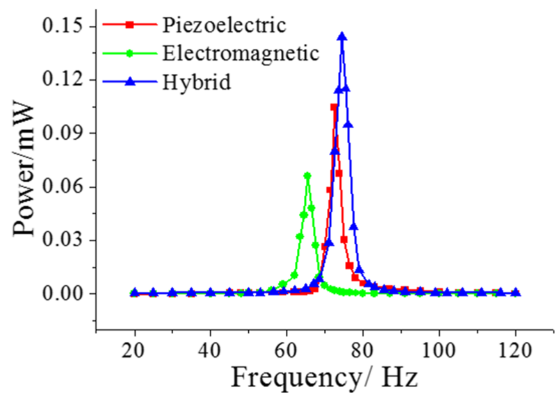


FIG. 16. Power test results of piezoelectric, electromagnetic and hybrid energy harvester.

and 63.2Ω, while optimal load resistance of PE and EM element for hybrid energy harvester are 320kΩ and 70Ω. In addition, 3dB bandwidth and output maximal power of PE, EM and hybrid energy harvester are 1.5Hz, 2Hz, 2.5Hz and 0.104mW, 0.66mW, 0.144mW respectively. Compared with PE and EM energy harvester, 3dB bandwidth and output power of hybrid energy harvester increases 67%, 25% and 38%, 118% respectively. Therefore, the designed hybrid energy harvester can improve the output power and harvesting efficiency, which is in accord with the results of the simulation results.

### C. Effect of excitation acceleration on performances

By Equation (12), output power of harvester is related with excitation amplitude. Therefore, when the harvester is connected with optimal load resistance and excited at the resonant frequency, the output power varied with the excitation acceleration is illustrated in Figure 17. According to test results, output power linearly increases with the acceleration increasing; furthermore, the power of hybrid energy harvester is bigger than that of PE and EM energy harvester at the same excitation.

### D. Effect of coupling strength on performances

Based on results in the former study for hybrid energy harvester,[24] PE and EM coupling coefficient are respectively

$$\eta_p = \frac{\theta^2}{KC_p} \tag{13}$$

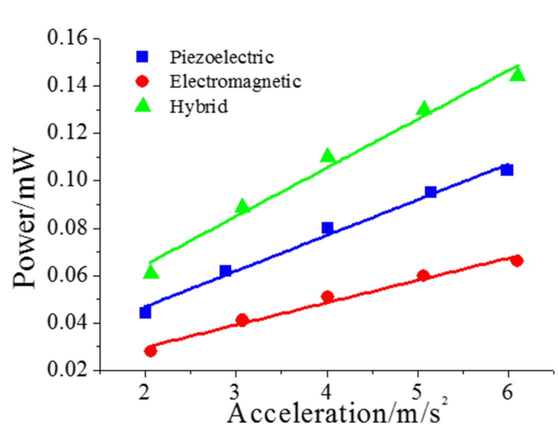


FIG. 17. The output power varied with the excitation acceleration.

TABLE VI. Coupling coefficient for different coupling strength.

| | PE element | EM element | Hybrid system |
|---|---|---|---|
| harvester1 (the length of the beam is 2mm) | 0.0124 | 0.007 | 0.0194 |
| harvester2 (the length of the beam is 2.8mm) | 0.029 | 0.01 | 0.039 |

$$\eta_{em} = \frac{\omega_n k_{em}^2}{KR_{coil}} \tag{14}$$

According to Equations (13) and (14), the coupling coefficient varies with the stiffness of beam. Therefore, two type harvesters with different beam length were designed in the experiment, and the coupling coefficient is illustrated in Table VI when the length of beam is 2.8mm and 2mm respectively, which indicates the coupling strength of harvester 1# is smaller than that of harvester 2#.

For designed harvesters 1# and 2# shown in Table VI, the output power at 0.6g is illustrated in Figure 18 when they connect with optimal resistance. By the test, for harvesters 1# and 2#, the resonant frequency is 76Hz and 48.8Hz respectively and the maximal output power is 0.013mW and 0.03mW respectively; moreover, it outputs the maximal power at the resonant frequency. Therefore, it can be concluded that the output power increases with coupling strength increasing, which is consistent with theoretical analysis results.

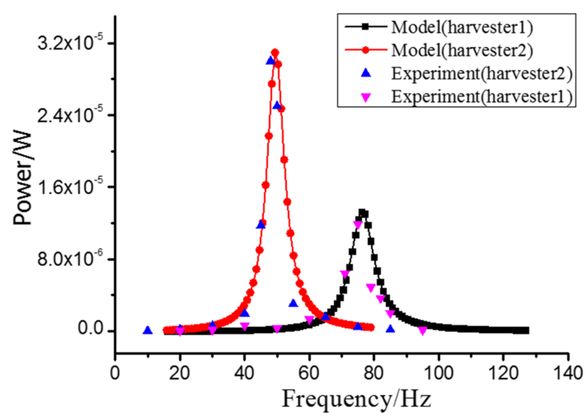


FIG. 18. Power of hybrid energy harvesters for different coupling effect.

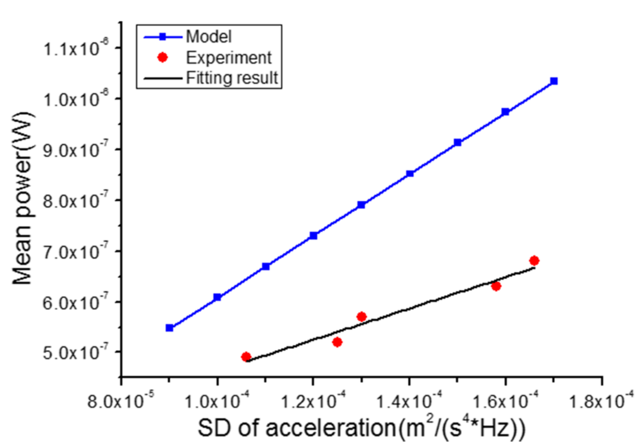


FIG. 19. Mean power at the different spectral density of acceleration.

## E. Output power under random excitation

In the experiment, when the excitation is random acceleration and the harvester connects with the optimal load resistance, mean power of hybrid energy harvester at the different spectral density of acceleration is shown in Figure 19. It illustrates that output power is linearly proportional to the acceleration spectral density, which is consistent with theoretical analysis results.

## F. Energy storage test

As the vibration energy harvester outputs AC signal, the output power needs to be transformed to DC signal before supplying the power for low power devices. Therefore, the energy storage circuit including the rectification, filtering and voltage regulation is designed for hybrid energy harvester, and the flow chart of energy acquisition and storage is shown in Figure 20.

The designed PE energy storage circuit in Figure 21(a) adopts the LTC3588 chip(Linear Technology Corporation), which is connected with PE element directly (PZ1 and PZ2 ports). In addition, EM energy storage circuit based LTC3108 chip (Linear Technology Corporation) is shown in Figure 21(b). Because output voltage of EM element is usually hundreds of mV, EM signals need to be boosted through transformer after connecting at V1 port.

After being connected to output end of the harvester, the energy circuit board with LTC3588 and LTC3108 chip can be used to charge the rechargeable battery, which is shown in Figure 22. In the experiment, the voltage of the rechargeable battery ML621 (5.8mAh) is recorded by signal analyzer when the harvester supplies the power for it, as illustrated in Figure 23.

When the harvester is excited at 0.75g, the charging result of PE element is illustrated in Figure 23. It shows that the battery takes about 200min to rise from 2.5V to 3.48V. For EM element, with the energy storage circuit, it takes about 150min to charge the battery voltage from 2.3V to 2.65V when the acceleration is 1.5g.

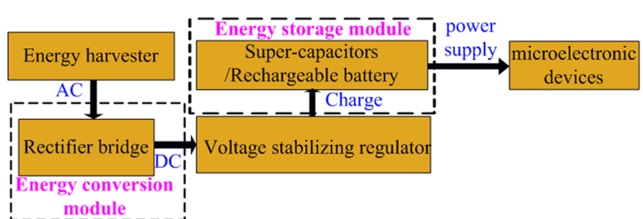


FIG. 20. Function diagram of energy acquisition and storage circuit.

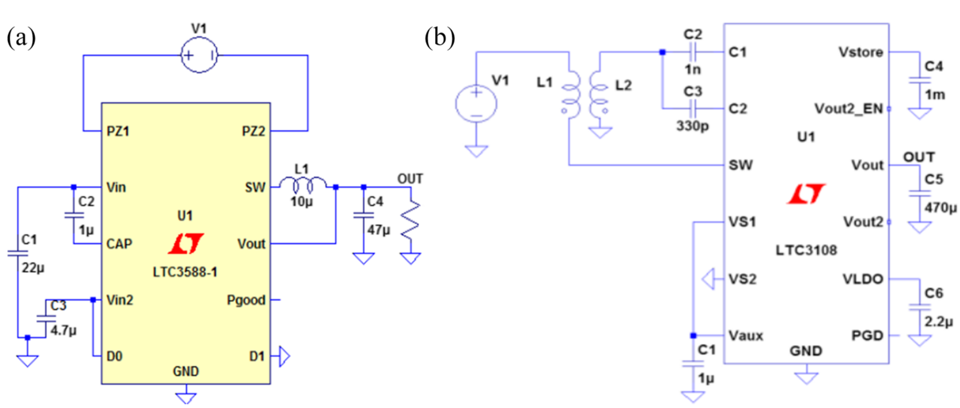


FIG. 21. Energy acquisition and storage circuit: (a) PE element; (b) EM element.


FIG. 22. Energy storage test setup.

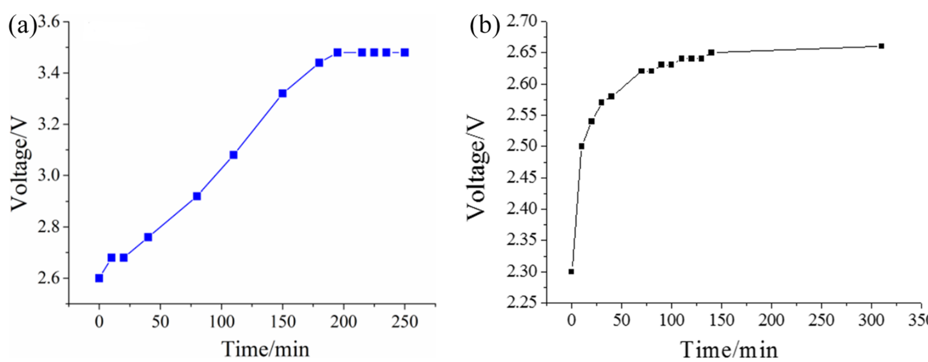


FIG. 23. Energy storage test results: (a) PE element; (b) EM element.

## V. CONCLUSIONS

In this paper, a hybrid piezoelectric and electromagnetic energy harvester is designed, and electromechanical coupling state is established. Then, expressions of amplitude, output power, voltage and current of harvester are derived. By theoretical analysis, simulation and experimental test, effects of characteristic parameters of harvester, coupling strength, excitation acceleration and excitation frequency on performances of hybrid energy harvester are studied. From the results, it can be concluded that,

(1) Compared with piezoelectric-only and electromagnetic-only energy harvester, 3dB bandwidth and output power of designed hybrid energy harvester increases 67%, 25% and 38%, 118% respectively. Therefore, the designed hybrid energy harvester can improve the output power and harvesting efficiency, which is in accord with the simulation results.
(2) Output power of harvester linearly increases with acceleration amplitude increasing at the harmonic excitation and acceleration spectral density increasing at the random excitation respectively.
(3) The bigger coupling strength, the bigger output power is, and there is the optimal load resistance to make the harvester output the maximal power.
(4) The total power of hybrid energy harvester increases with resonant frequency increasing.

(5) The energy storage circuit is designed for hybrid energy harvester, and the power charging the rechargeable battery is realized through experiment test.


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