A Vibration Energy Harvester with Internal Impact and Hybrid Transduction Mechanisms

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Abstract To increase the power harvesting capability of an internal impact type vibration energy harvester (VEH), the authors have developed a novel hybrid VEH integrating both piezoelectric and electromagnetic (EM) modules for energy conversion. The proposed VEH transforms a low frequency external base vibration into an internal impact vibration of the tip of a cantilever beam, which is used to cause energy conversion by the piezoelectric effect and electromagnetic induction. A prototype is designed, fabricated and tested; the optimum load resistances are determined experimentally, and the power output performance and the total power density of the proposed VEH have been experimentally characterized with respect to the excitation amplitude and frequency. The dependence of the optimum excitation frequency for maximum total power output on the excitation amplitude has also been experimentally investigated. The total output power and power density are 0.8 mW and 15 μW/cm^3, respectively, when the excitation amplitude and frequency are 1 mm (rms) and 15 Hz, respectively.

Keywords Vibration Energy Harvesting, Impact, Piezoelectric, Electromagnetic, Hybrid

1. Introduction

With the evolution of low power electronics, harvesting the structural vibration energy, which is clean, ubiquitous and renewable, has gained increasingly extensive attentions from worldwide researchers in the recent decade [1-4] for its great potentials for applications in areas of wireless sensor networks (WSNs), autonomous low power microsystems, distributed computing and portable alternative power sources, remote sensing and actuation, etc., to replenish or even replace traditional power supply such as battery. A number of vibration energy harvesters (or vibration-powered generators) using the piezoelectric effect [5-9] and electromagnetic induction [10, 11] have been proposed and developed.

Generally, a typical piezoelectric VEH employs a cantilever beam structure with a proof mass at its tip and excitation at its base [6]; thus only d_{31} mode is used. To increase the vibration energy harvesting capability of such mechanism, a piezoelectric VEH combining the d_{31} mode caused by flexural vibration and the d_{33} mode caused by direct impact was proposed [7]. It was found that piezoelectric components operating in the d_{33} mode can significantly increase the power generation of the conventional cantilevered piezoelectric VEH. Similar work using impact method has also been carried out by other researchers [12-15]. Nevertheless, to widen the application range of VEHs, the output power still needs to be increased.

To further enhance the energy harvesting capability and more efficiently utilize the space of VEH structure, the authors have developed an evolutionary version based on their previous work [7]. In the evolutionary version, the VEH converts low frequency external vibration into its internal impact vibration and uses the piezoelectric effect and electromagnetic induction to convert the internal vibration energy into electric energy. The VEH topologically consists of three modules. The first one is a piezoelectric module harvesting the energy of internal impact directly; the second one is another piezoelectric module harvesting the impact induced vibration energy in the frames of the VEH; the third one is an electromagnetic module comprised of one hand-wound enameled copper coil and two pairs of anti-symmetrically placed bulk NdFeB permanent magnets, using the magnetic flux change in the coil to generate AC voltage. A prototype has been designed, fabricated, tested and analyzed.

2. Structure and Principle

As shown in Fig. 1(a), the proposed VEH is generally comprised of three parts, i.e., the top and bottom frames, the middle cantilever beam, and the side frames. The frames are made of stainless steel, and the cantilever beam is made of phosphor bronze. Four piezoelectric modules (PZT-T-EX, PZT-T-IN, PZT-B-EX, and PZT-B-IN), each with five identical piezoelectric plates connected in parallel electrically, and two single piezoelectric plates (PZT-T-IMP and PZT-B-IMP) are bonded to the top and bottom frames. Two pairs of permanent magnets are anti-symmetrically bonded onto the side frames. A coil housing with a hand-wound enameled copper coil and impact body is attached to the tip of the middle cantilever beam, and acts as a proof mass. The coil housing is used to accommodate and fix the coil relative to the cantilever beam. The distance between the impact body and the impacted piezoelectric plates (PZT-T-IMP and PZT-B-IMP) is about 4.5 mm. The VEH could be mounted on a vibrating source for power generation. In our experiments, it is bolted on an electric shaker, as shown in Fig. 1(b).

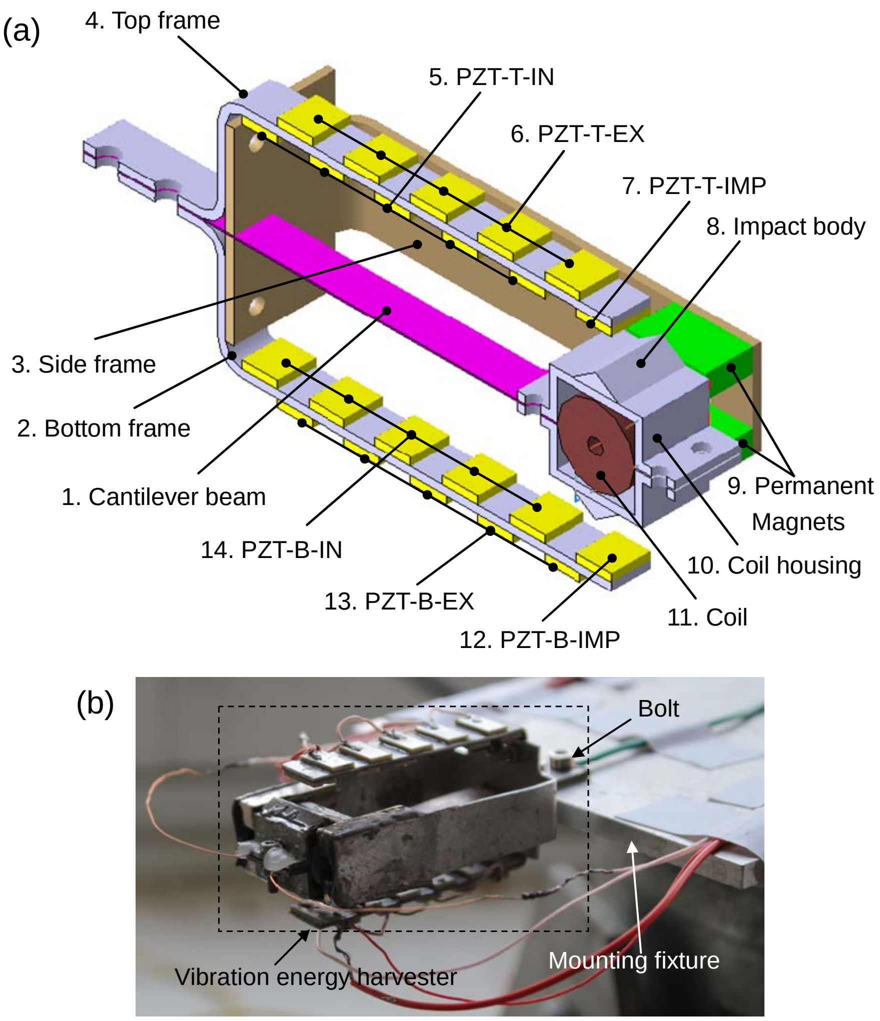


Figure 1. Harvester structure including (a) isometric section view of the proposed VEH structure and (b) photograph of the fabricated VEH prototype mounting on an electric shaker.

The detailed dimensions of structural components of the VEH prototype are listed in Table 1. The piezoelectric material adopted here is Lead Zirconate Titanate (PZT) ceramics (HAIYING P-51), the major material parameters is shown in Table 2. The enameled copper coil with main parameters shown in Table 3, is wound by using a 40-μm-diameter copper wire (DAYANG WIRE & CABLE) with polyurethane coating. The magnets used here is the sintered rare earth Neodymium Iron Boron (NdFeB) N33 permanent magnet. Its property is listed in Table 4.

Table 1. Dimensions of structural components of the proposed vibration energy harvester

Component	Length (mm)	Width (mm)	Height (mm)	Thickness (mm)
1	60	10	-	0.2
2,4	65	10	14.9	1
3	52	30	24	1
5,6,7,12,13,14	10	5	1	-
8	17	6	2	-
9	10	6	3	-
10	20	17	6	1
11	-	-	15	-

Table 2. Material property parameters of the employed piezoelectric material

Electromechanical coupling factor	k_{31}	0.36
	k_{33}	0.70
Piezoelectric charge constant (10^{-12} C/N)	d_{31}	-185
	d_{33}	400
Relative dielectric constant	$\varepsilon_{11}^{T}/\varepsilon_0$	2400
	$\varepsilon_{33}^{T}/\varepsilon_0$	2100
Mechanical quality factor	Q_m	100
Dielectric dissipation factor (%)	$\tan\delta$	2.0

Table 3. Parameters of the wound copper coil

Number of turns	Internal resistance (R_o) (kΩ)	Inductance (L_o) (H)
~11000	~3.9	~0.3

Table 4. Properties of NdFeB permanent magnet

Residual Induction B_r (mT)	Maximum energy product $(BH)_{max}$ (KJ/m^3)	Coercive force H_{cb} (KA/m)
1.13~1.17	247~263	~836

The resonance frequency of the middle cantilever beam of our VEH prototype is $f_{cr} = \sqrt{k/m}/2\pi$ ≈ 11.0 Hz, where *m* and *k,* the effective mass and spring constant, are 1.04E-3 kg and 51.7 N/m, respectively. When subjected to external vibration excitation, bending vibration of the middle cantilever beam would be excited. As seen in Fig. 2(a), while the beam vibrates, the impact body may hit PZT-T-IMP and PZT-B-IMP and induce resonant vibration mode in the top and bottom frames. Due to the piezoelectric effect, AC voltage is generated across all piezoelectric components. At the same time, the copper coil vibrates relatively to the permanent magnets, as shown in Fig. 2(b), causing a variation of magnetic flux through the coil. According to the Faraday's law, AC voltage will be generated in the coil. To generate voltage in the electromagnetic module efficiently, it is so designed that the net magnetic flux through the coil is zero when the middle cantilever remains static.

For low frequency (several to tens of Hertz) excitation, we only take into consideration the fundamental vibration mode of the middle cantilever beam, which can be simplified into an equivalent single-DOF spring-mass-damping system. As indicated in Fig. 2(a), the displacement of the vibration energy harvester and the tip of the cantilever beam are denoted by x_s and x, respectively, with respect to the inertial reference frame of the earth. Setting the relative displacement between the cantilever tip and VEH frame be $y = x - x_s$, and the source excitation of the shaker be harmonic, i.e. $x_s = A_s \sin\omega_s t$, the steady-state solution of the differential vibration equation of the cantilever beam is [16]

$$y = Y \sin(\omega_s t - \psi), \tag{1}$$

$$Y = \frac{A_s \left(\frac{\omega_s}{\omega_{cn}} \right)^2}{\sqrt{\left[1 - \left(\frac{\omega_s}{\omega_{cn}} \right)^2 \right]^2 + \left(2\zeta \,g \frac{\omega_s}{\omega_{cn}} \right)^2}}, \tag{2}$$

$$\psi = \tan^{-1} \left[\frac{2\zeta \,g \frac{\omega_s}{\omega_{cn}}}{1 - \left(\frac{\omega_s}{\omega_{cn}} \right)^2} \right]. \tag{3}$$

where ω_{cn} is the natural angular frequency of the cantilever beam, m, ζ and k are the equivalent mass, damping ratio and spring constant, respectively. Hence, the condition for impact is

$$Y \geq D. \tag{4}$$

For a given low excitation amplitude ($A_s < D$), there exists an excitation frequency range beyond which the impact cannot happen. Denoting ω_{sl} and ω_{su} as the lower and upper limits of the excitation frequency range, it is derived that

$$\omega_{sl} = \omega_s \sqrt{\frac{\left(1 - 2\zeta^2\right) - \sqrt{\left(1 - 2\zeta^2\right)^2 - \left(1 - \frac{A_s^2}{D^2}\right)}}{1 - \frac{A_s^2}{D^2}}}, \tag{5}$$

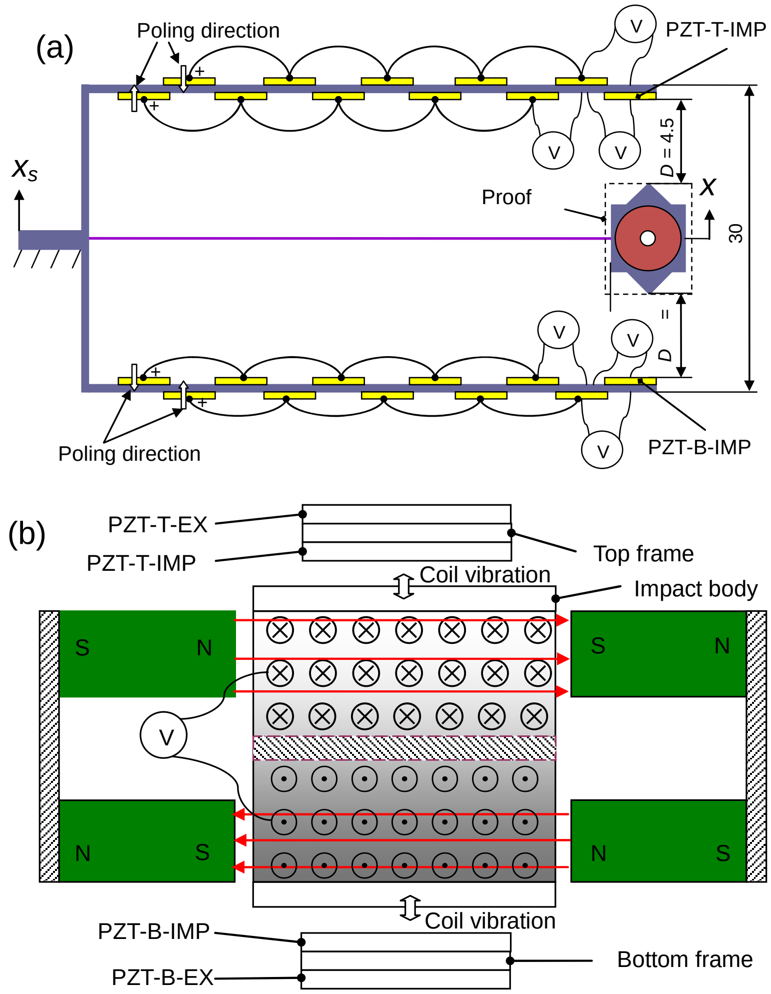
$$\omega_{su} = \omega_s \sqrt{\frac{\left(1-2\zeta^2\right)+\sqrt{\left(1-2\zeta^2\right)^2-\left(1-\frac{A_s^2}{D^2}\right)}}{1-\frac{A_s^2}{D^2}}}. \tag{6}$$

Since $\zeta = 1$, $\omega_{sl} = \omega_s\sqrt{1/\left(1+A_s/D\right)}$, $\omega_{su} = \omega_s\sqrt{1/\left(1-A_s/D\right)}$. Therefore,

$$f_{sl} = \frac{\omega_{sl}}{2\pi} = f_s\sqrt{\frac{1}{1+\frac{A_s}{D}}}, \tag{7}$$

$$f_{su} = \frac{\omega_{su}}{2\pi} = f_s\sqrt{\frac{1}{1-\frac{A_s}{D}}}. \tag{8}$$

When f_s = 11 Hz, A_s = 1.4 mm (0-peak) and D = 4.5 mm, f_{sl} and f_{su} are calculated to be about 9.6 Hz and 13.3 Hz, respectively.



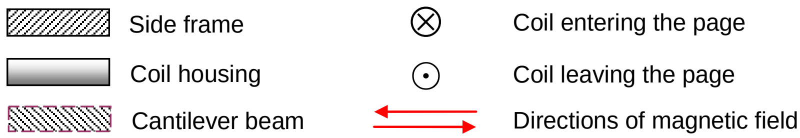


Figure 2 Schematics of (a) the piezoelectric energy harvesting modules and (b) the electromagnetic energy harvesting module.

According to Hayt et al.[17] and Fu et al.[9], the theoretical optimum load resistances of the electromagnetic and piezoelectric modules for maximum power output are

$$R_{LEO} = \sqrt{R_o^2 + (2\pi f_c L_o)^2}\ , \tag{9}$$

$$R_{LPO} = \frac{1}{10\pi f_{rf} C_p}\ . \tag{10}$$

where R_o and L_o are the internal resistance and inductance of the coil, respectively, f_c is the angular frequency of vibration of the cantilever beam, f_{rf} is the resonant frequency of the top or bottom frames, and C_p is the clamped capacitance of a piezoelectric plate.

3. Experimental Method

During the experiments, the VEH was firmly fixed on an electric shaker (HSB-01, HUASHEN) by bolting connection, as shown in Fig. 3. A function generator (AFG 3022B, TEKTRONIX) was used to supply sinusoidal excitation signal to a power amplifier, through which the signal was power amplified and transferred to the shaker to generate harmonic excitation for the test. Excitation frequency and amplitude can be controlled by adjusting the function generator and the power amplifier. The input signal to the shaker was monitored by digital oscilloscope (TDS 2014, TEKTRONIX). To measure the power generation capability, a resistive load R_L was directly connected to the VEH prototype; the root mean square (rms) voltage V_{rms} across the load was measured; the average power by R_L was calculated by $P_a = V_{rms}^2 / R_L$. In addition, the excitation acceleration of the electric shaker was measured by a strain gauge accelerometer (LC0801, LANCE) and the resonant frequency of first bending mode was measured by Polytec Scanning Vibrometer PSV-300.

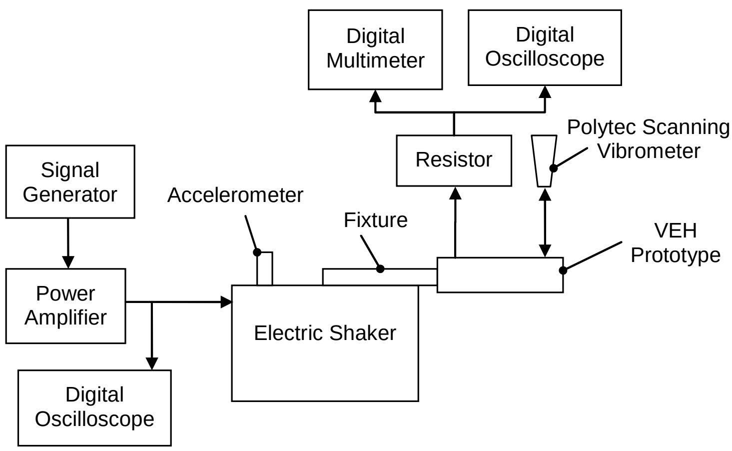


Figure 3 Schematic diagram of the experimental setup.

In our experiments, at first, the relationship between the cantilever vibration frequency and excitation frequency was investigated. Then different load resistances were connected to the prototype to determine the optimum load resistances for the electromagnetic and piezoelectric modules. After that, the experimentally determined optimum load resistances were used to obtain the quantitative effects of the excitation amplitude and frequency on the power output and the total power density. Finally, the optimum excitation frequency for maximum power output and the total output power at the optimum excitation frequency vs. the excitation amplitude were measured.

Since it was found that the power generation of the directly impacted piezoelectric plates (PZT-T-IMP and PZT-B-IMP) was much lower than that of the other four piezoelectric modules under the same excitation condition, this part of power extraction is neglected in the following study. All the following experiments were conducted only for the electromagnetic and piezoelectric modules at the excitation frequency around the resonance frequency of the middle cantilever beam ($f_{rc} \approx 11$ Hz).

4 Results and Discussion

Applying an excitation to the prototype and making the cantilever tip impact with the frames, the relationship between the vibration frequency of the cantilever beam f_c and the excitation frequency f_s has been measured firstly, and the result is shown in Fig. 4. It is manifested that either the cantilever tip vibrates freely or there is impact between the cantilever tip and frames, the cantilever vibration still has the same frequency as the external excitation.

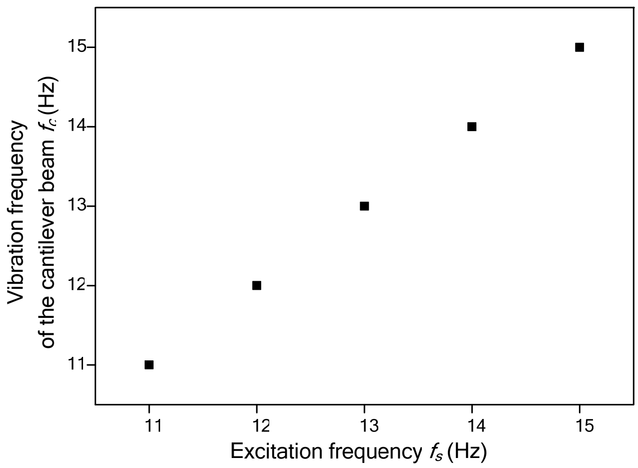


Figure 4. The vibration frequency of the cantilever beam f_c vs. the excitation frequency f_s.

According to Eqs. (9) and (10), the theoretical optimum load resistances can be obtained. In our VEH prototype, R_o =3.9 kΩ, L_o = 0.3 H, $C_p = \varepsilon_{33}^T \varepsilon_0 L_p W_p / H_p$ = 0.92925 nF, f_c=11 Hz and f_{rf} is measured to be 169.5 Hz using Polytec Scanning Vibrometer PSV-300, such that R_{LEO} and R_{LPO} are calculated to be 3.9 kΩ and 202 kΩ approximately. To acquire these values experimentally, the output power P_o vs. load resistance R_L was measured for the electromagnetic and piezoelectric modules under the excitation amplitude of 2 mm (rms) and excitation frequency of 11 Hz. As shown in Fig. 5(a), the optimum resistance for electromagnetic module R_{LEO} is found to be about 4 kΩ; from Fig. 5(b), it is found that the optimum resistance for each piezoelectric module R_{LPO} is almost the same and equals 200 kΩ approximately, which well agree with the theoretical values.

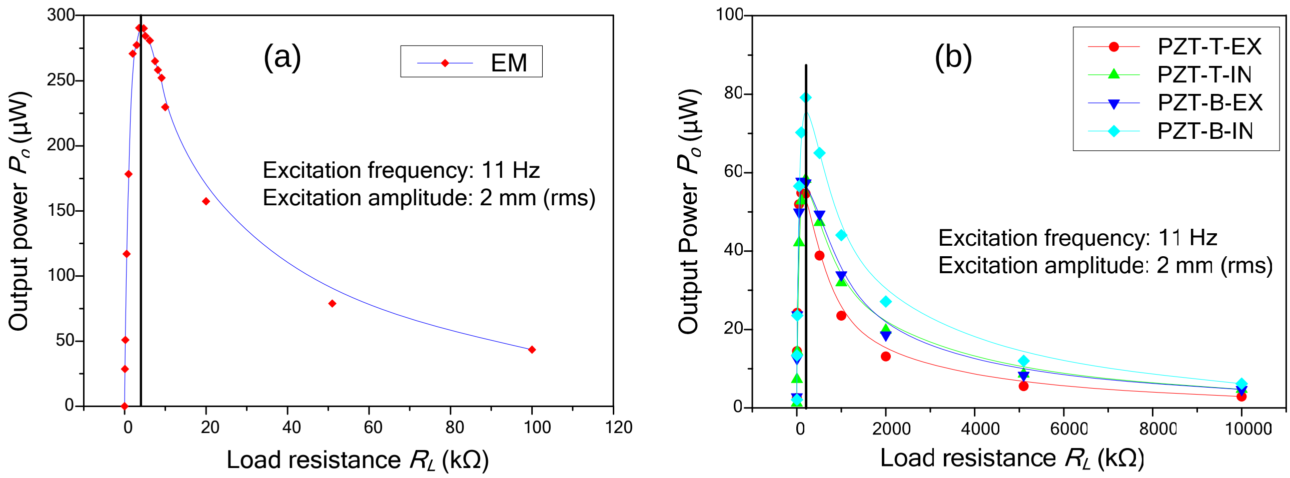


Figure 5. Output power P_o as a function of the load resistance R_L for (a) the electromagnetic module and (b) the piezoelectric modules when the excitation amplitude and frequency are 2 mm (rms) and 11 Hz, respectively.

Connecting resistors with the above experimentally determined optimum resistances to the VEH prototype individually, power consumed by the loads has been measured as a function of the excitation amplitude at the excitation frequency of 11 Hz. As shown in Fig. 6(a), the output power of the electromagnetic module and the total output power of the piezoelectric modules are at the same order. It is also seen that as the excitation amplitude increases, the change of the output power of electromagnetic and piezoelectric modules manifests in a similar way. At first, the output power of each energy harvesting module increases quickly as the excitation amplitude increases; with further increase of the excitation amplitude, the increasing speed of the output power slows down. With the increase of the excitation amplitude, the impact speed increases, resulting in the increase of harvested energy. However, when the excitation amplitude is larger than 1 mm (rms), the cantilever tip impacts the top and bottom frames, which limits the further increase of vibration velocity of the cantilever tip and the further increase of the output power. The total power density is calculated by the ratio of the total output power to the volume of VEH. As shown in Fig. 6(b), for the proposed VEH at the excitation frequency of 11 Hz, the total power density increases with the increase of the excitation amplitude.

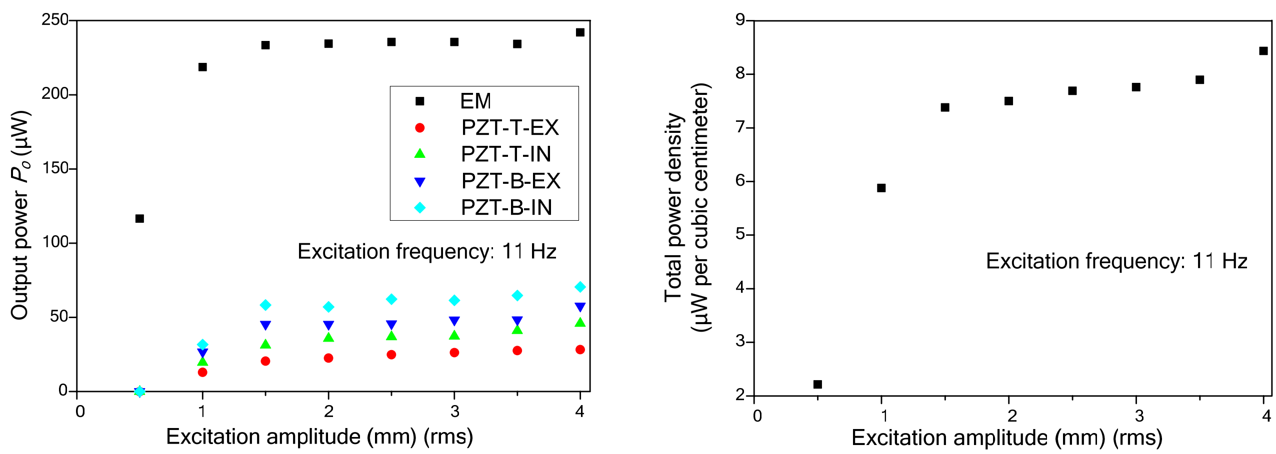


Figure 6. (a) Output power and (b) the total power density vs. the excitation amplitude at the excitation frequency of 11Hz.

The output power P_o vs. the excitation frequency f_s at the excitation amplitude of 1 mm (rms) has also been measured, and the result is shown in Fig. 7. For the electromagnetic module, with the increase of f_s, P_o first increases and then reaches a summit at 15 Hz, passing which it begins to decrease. For the piezoelectric module, P_o is almost zero when f_s is less than 9 Hz; it increases as f_s increases from 9 Hz to 15 Hz; it reaches the maximum at 15 Hz and decreases as f_s increases further. From equations (7) and (8), the impact frequency range at the excitation amplitude of 1 mm (rms) is calculated to be from 9.6 to 13.3 Hz, which means a too small or too large excitation frequency may decrease the vibration of the cantilever tip and suppress the impact from happening, which qualitatively explains the phenomenon shown in Fig. 7. The maximum total output power and optimum excitation frequency f_s for the excitation amplitude of 1 mm (rms) are 0.8 mW and 15 Hz, respectively. In addition, comparing Figs. 6(a) and 7, it can be found that the energy harvesting of the proposed VEH is more sensitive to the excitation frequency than the excitation amplitude.

To further understand the energy harvesting characteristics of the VEH prototype, the optimum excitation frequency f_{so} for maximum total output power and the total output power at f_{so} (= the maximum total output power P_m) under different excitation amplitude have been measured, and the results are shown in Fig. 8. It is found that the maximum total output power P_m and optimum excitation frequency f_{so} increase with the increase of the excitation amplitude. From equation (8), it is seen that the upper limit of the impact frequency range increases as the excitation amplitude increases. It seems that the impact frequency range may increase the optimum excitation frequency.

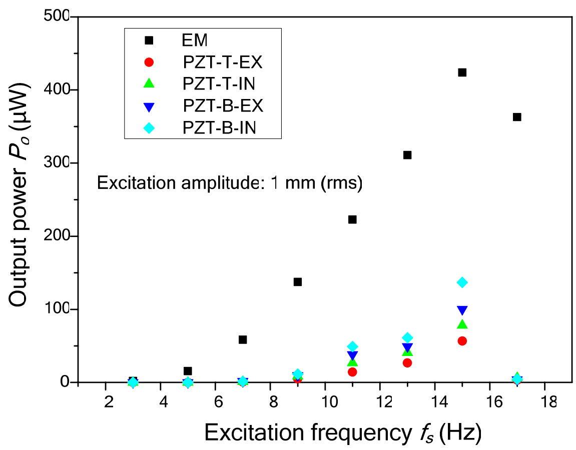


Figure 7. Output power P_o vs. the excitation frequency f_s at the excitation amplitude of 1 mm (rms).

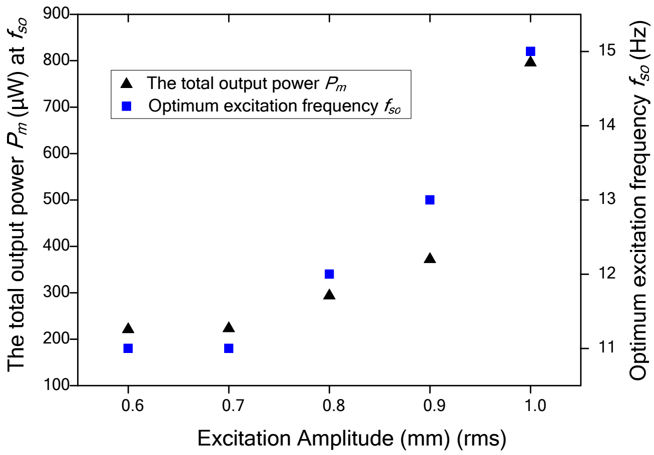


Figure 8. The optimum operating frequency f_{so} and the total output power at f_{so} vs. the excitation amplitude.

5. Conclusions

In this paper, a hybrid internal impact type vibration energy harvester that uses the piezoelectric effect and electromagnetic induction both has been investigated experimentally. It is found that, for a given excitation frequency, when the excitation amplitude increases, the total output power increases fast first and the increasing speed slows down when the excitation amplitude increases further; for a given excitation amplitude, there is a frequency range in which the total output power increases with the increase of the excitation frequency; the optimum excitation frequency and its corresponding total output power increases with the increase of the excitation amplitude. The total output power and power density are found to be 0.8 mW and 15 μW/cm^3, respectively, when the excitation amplitude and frequency are 1 mm (rms) and 15 Hz, respectively. The proposed vibration energy harvester may be used to harvest the vibration energy of low frequency vibration sources, which exist universally in nature, artificial structures, machines, vehicles, etc.

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