A Novel Hybrid Piezoelectric-Electromagnetic Micro-Power Generator by Harvesting Low Frequency Acoustic Energy

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Abstract. In order to harvest low frequency acoustic energy, a novel hybrid piezoelectric-electromagnetic micro-power generator was developed with Helmholtz resonator, piezoelectric patch, coil and permanent magnet. When the sound waves enter Helmholtz resonator, piezoelectric patch and coil will be vibrated then the electric energy are generated from them. With Multisim software, the circuit of proposed micro-power generator was simulated and its output performance was analysed. Results show that there is always an optimal resistance to maximize the output power of the novel hybrid piezoelectric-electromagnetic micro-power generator. Especially when the sound waves at 82Hz, the output power of proposed hybrid generator can more than the sum of independent piezoelectric and electromagnetic micro-generator. It indicates the power generation efficiency is significant significantly improved by the proposed hybrid method.

1. Introduction

In the recent years, to collect energy from environment is becoming an attractive method to power the micro electric devices. Comparing other types of energy, acoustic energy is more widely distributed, such as tunnels, railways, airports, malls and factories. Unlike the light and heat energy, acoustic energy is not limited by the natural conditions, and has more potential application in powering micro electric devices.

To harvest the low frequency noise energy from high-speed railways, Wang [1] designed a Helmholtz resonator with PVDF film. Its maximum voltage is 74.6 mV at the SPL (Sound Pressure Level) of 110dB. A multi-function acoustic system which can generate electricity and isolate the noise was proposed in Ref [2]. When the SPL is 114 dB and frequency is 155 Hz, its output power achieves 0.21mW. Izhar [3] designed a Helmholtz resonator with piezoelectric composite and cantilever, which can harvest acoustic energy in different resonant frequency. It gets the output power of 214.23μW at 130dB and 1501Hz. Qi [4] reported on an innovative and practical acoustic energy harvester based on a defected acoustic metamaterial (AMM) with piezoelectric material. The maximum power of 64.4μW can be harvested at 341 Hz. Although electromagnetic micro-power generator in is not as efficient as piezoelectric generator in acoustic energy harvesting, it is an important complement to improve the efficiency especially in hybrid micro-power generator.

Although piezoelectric-electromagnetic micro-power generator has been studied in vibration energy harvesting, but is less reported in acoustic energy harvest. In this paper, a novel hybrid piezoelectric-
emagnetic micro-power generator is proposed for low frequency acoustic energy. Its electrical output characteristics were analysed with simulation.

2. Circuit analysis

2.1. Experimental setup

As shown Fig. 1, the novel hybrid piezoelectric-electromagnetic micro-power generator is designed with Helmholtz resonator, piezoelectric patch, permanent magnet and coil. Helmholtz resonator is made of stainless steel, and its top surface is thinner than the other sides. The permanent magnet is fixed on piezoelectric patch that is glued on the top thin surface. Both piezoelectric patch and the coil above the Helmholtz resonator will generate electricity when the top thin surface vibrates.

![Diagram of novel hybrid piezoelectric-electromagnetic micro-power generator](image)

When the sound waves enter the Helmholtz resonator, it will vibrate the resonator. Due to different thickness, the vibration will be concentrated on the top thin surface. If frequency of sound wave is close to the resonant frequency of Helmholtz resonator, the SPL will be amplified in the cavity and excite the top thin surface. The vibration on the piezoelectric patch converts the mechanical energy into electric energy and the movement of permanent magnet cause the variation of magnetic flux through a coil. In this design, both piezoelectric patch and coil can output electric power, and they can work respectively or as an incorporated power supply.

2.2. Circuit Principle

In order to improve the efficiency, the equivalent circuits of proposed micro power generator were analyzed. The separated piezoelectric micro-power generator is shown in Fig. 2 (a), which is the parallel connection of current source and capacitor. The circuit shown in Fig. 2 (b) presents the separated electromagnetic micro-power generator, which is parallel connection of current source and inductor. The internal resistance of the piezoelectric generator can be ignored, but it cannot be ignored in coil, which represents $R_l$ in circuit. Fig. 2 (c) diagrams novel hybrid piezoelectric-electromagnetic micro-power generator and the three circuits will be discussed with the same load $R$.

![Equivalent circuits](image)
According to Kirchhoff’s law, the following equation can be derived from Fig. 2 (c),

$$
L \frac{dI_1(t)}{dt} + I_1(t) \cdot R_i + C \frac{d}{dt} \left( L \frac{dI_1(t)}{dt} + I_1(t) \cdot R_i \right) + I_1(t) = (I_e + I_p) \cdot \sin(\omega t)
$$

(1)

where $I_e$ and $I_p$ are the maximum output current of the sources respectively, $\omega$ is the angular frequency of vibration, $L$ and $C$ represent the inductor and capacitor respectively.

By solving equation (1), the current through inductor is

$$
I_1(t) = C_1 \cdot e^{-\frac{CRR+L+\sqrt{C^2R_i^2-4CLR^2+L^2}}{RLC} t} + C_2 \cdot e^{-\frac{CRR+L+\sqrt{C^2R_i^2-4CLR^2+L^2}}{RLC} t} \frac{\left[ (RLC\omega^2 - R - R_i) \sin(\omega t) + \omega(CRR_i + L) \cos(\omega t) \right] R}{\left( 1 + C^2\omega^2 + C(CR_i^2 - 2L)\omega^2 \right) R^2 + 2RR_i + L^2\omega^2 + R_i^2} (I_e + I_p)
$$

(2)

Ignoring the attenuation term, equation (2) can be simplified

$$
I_1(t) = \frac{\left[ (RLC\omega^2 - R - R_i) \sin(\omega t) + \omega(CRR_i + L) \cos(\omega t) \right] R}{\left( 1 + C^2\omega^2 + C(CR_i^2 - 2L)\omega^2 \right) R^2 + 2RR_i + L^2\omega^2 + R_i^2} (I_e + I_p)
$$

(3)

Then the voltage across the load is

$$
U(t) = L \frac{d}{dt} \left( I_1(t) \right) + I_1(t) \cdot R_i = \frac{R \omega(CLR^2 - CR_i^2) \cos(\omega t) - \sin(\omega t) \left( L^2\omega^2 + 2RR_i + R_i^2 \right) \omega^2}{\left( 1 + C^2\omega^2 + C(CR_i^2 - 2L)\omega^2 \right) R^2 + 2RR_i + L^2\omega^2 + R_i^2} (I_e + I_p)
$$

(4)

and the average power consumed by the load is

$$
P = \frac{1}{T} \int_0^{2\pi} \frac{U(t)^2}{R} dt = \frac{R \left( L^2\omega^2 + R_i^2 \right) (I_e + I_p)^2}{2 \left( R^2L^2C^2 + C^2\omega^2R_i^2 - 2R^2LC\omega^2 + \omega^2L^2 + R_i^2 + 2R_i^2 + 2RR_i \right)}
$$

(5)

When $\frac{dP}{dR} = 0$, there is an optimal resistance value to maximum the output power,

$$
R_{opt} = \frac{\omega^2L^2 + R_i^2}{\omega^2L^2C^2 + \omega^2C^2R_i^2 - 2\omega^2LC + 1}
$$

(6)

$$
P_{max} = \frac{I_e^2 \left( \omega L + R_i \right) \left( \omega^4L^2C^4 + 1 + \omega^2C(CR_i^2 - 2L) \left( \omega^2L^2 + R_i^2 \right) \right) + 4 \left( \omega^4L^2C^4 + 1 + \omega^2C(CR_i^2 - 2L) \left( \omega^2L^2 + R_i^2 \right) \right) \left( \omega^2L^2 + R_i^2 \right) + 4 \left( \omega^4L^2C^4 + 1 + \omega^2C(CR_i^2 - 2L) \left( \omega^2L^2 + R_i^2 \right) \right) \left( \omega^2L^2 + R_i^2 \right)}{4R_i \sqrt{\omega^4L^2C^4 + 1 + \omega^2C(CR_i^2 - 2L) \left( \omega^2L^2 + R_i^2 \right) + 4 \left( \omega^4L^2C^4 + 1 + \omega^2C(CR_i^2 - 2L) \left( \omega^2L^2 + R_i^2 \right) \right)}}
$$

(7)
When the piezoelectric micro-power generator work separately as shown in Fig. 2 (a), the average power consumed by the load, maximum optimal resistance value and maximum the output power can be derived in the same method.

\[
P_p = \frac{1}{T} \int_{0}^{2\pi} \frac{U(t)^2}{R} dt = \frac{R_t^2 I_p}{2(\omega^2 R_t^2 C + 1)} \tag{8}
\]

\[
R_{opt} = \frac{1}{\omega C} \tag{9}
\]

and

\[
P_{max} = \frac{I_m^2}{4\omega C}. \tag{10}
\]

If only work with electromagnetic micro-power generator shown in Fig. 2 (b), the average power consumed by the load, maximum optimal resistance value and maximum the output power are

\[
P_e = \frac{I_e^2 R_t \pi (\omega^2 L^2 + R_i^2)}{2\pi(\omega^2 L^2 + R_2^2 + 2R_i R_2 + R_i^2)} \tag{11}
\]

\[
R_{opt} = \sqrt{\omega^2 L^2 + R_i^2} \tag{12}
\]

\[
P_{max} = \frac{\omega(\omega^2 L^2 + R_i^2)^{3/2} I_m^2}{2\left(2\omega^2 L^2 + 2R_i^2 + 2\omega R_i \sqrt{\omega^2 L^2 + R_i^2}\right)} \tag{13}
\]

The sum of the piezoelectric and electromagnetic micro-power generator is the sum of equation (8) and (11)

\[
P_0 = \frac{R_t^2 I_p}{2(\omega^2 R_t^2 C + 1)} + \frac{I_e^2 R_t \pi (\omega^2 L^2 + R_i^2)}{2\pi(\omega^2 L^2 + R_2^2 + 2R_i R_2 + R_i^2)} \tag{14}
\]

Comparing equation (5) and (14), the output novel hybrid generator is not the simple add of the two separately generator. To improve the efficiency of hybrid generator, further researches was performed in the next section.

2.3. Circuit Simulation

Because the output power of the generator is increasing with the SPL as presented in equation (5)-(7), the intensity of sound field kept an constant for simplifying the analyze. In the circuit simulation, the amplitude of current source which corresponds SPL was set to be constant. Three types of micro-power generators shown in Fig. 2 were simulated in Multisim software. As shown in Fig. 3, the amplitudes of current sources were chosen to be 5mA and 0.8mA respectively for piezoelectric and electromagnetic modular. The inductor of coil is 16H and its internal resistance is 9kΩ. The equivalent capacitance of piezoelectric patch is 200nF, and the simulation was performed in the frequency range of 0-200Hz.

![Simulation of separated piezoelectric micro-power generator](image1)

![Simulation of separated electromagnetic micro-power generator](image2)
5

When the frequency of sound waves changes, the frequency of corresponding current source varies in the Multisim. The output power of the three types of micro-power generators can be computed in different frequency, and their result curves are shown in Fig. 4. When the frequency of sound waves increases from 20 to 200 Hz, the output power of piezoelectric micro-power generator constantly decreases and the output power of electromagnetic micro-power continuously increased, and the novel hybrid piezoelectric-electromagnetic micro-power generator increases then decreases. Their output power is 60.425mW, 1.126mW and 61.261mW. At 82Hz, the output power of proposed hybrid generator almost equal to the sum of piezoelectric and electromagnetic generator. In the frequency less than 82 Hz, the output power of proposed hybrid generator is less than the sum of other two. The maximum output power of proposed hybrid generator achieves 62.367mW at 95Hz. The other types output 52.138mW and 1.2mW in the same frequency.

Fig. 4 Simulation results
3. Conclusion
A novel hybrid piezoelectric-electromagnetic micro-power generator was proposed for low frequency acoustic energy. Simulation results show that the output power of the proposed hybrid power increases then decreases. In the frequency less than 82 Hz, the output power of hybrid power generator is higher than the sum of piezoelectric and electromagnetic power generator. But the proposed hybrid generator outputs more than the other two at the frequency higher than 82 Hz. In this case, the proposed hybrid piezoelectric-electromagnetic micro-power generator is more efficient and can output more power in low frequency acoustic energy.

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