Acoustic Energy Harvester by Electromagnetic Mechanisms and Helmholtz Resonator

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Abstract. In order to harvest the acoustic energy in the environment, an electromagnetic acoustic energy harvest system is proposed based on Helmholtz resonator, coil, permanent magnet and interface circuit. When the sound wave is injected into the resonator, it causes the upper surface permanent magnet to vibrate and outputs electrical energy from the coil. The resonant frequency of the resonator is simulated and analysed by finite element method, the interface circuit is simulated and analysed, the acousto-electric conversion principle is analysed theoretically. The output characteristics of the system under different frequencies and sound pressure levels are studied by experiments, and the output characteristics of the system after using the interface circuit are studied. The experimental results show that the system can harvest the acoustic energy of different frequencies, and the power generation effect is better when the acoustic frequency is near 98Hz and 140Hz, which is close to the first two resonant frequencies of the system. The output voltage and power of the system increase with the increase of the sound pressure level. When the sound pressure level is lower than 105dB, the output voltage and power of the system under the acoustic frequency of 95Hz is higher, and when the sound pressure level is greater than 105dB, the output voltage and power of 140Hz acoustic frequency is higher. After using the interface circuit, the maximum open-circuit voltage is 13.65V when the sound pressure level is 110dB and the frequency is 98Hz, and the maximum output power of the system can reach 0.625mW when the sound pressure level is 110dB and the frequency is 140Hz.

1. Introduction
With the development of microelectronic and wireless transmission technology, wireless sensor networks node has become the feasible way for remote monitoring system. Due to the limitation of its capacity, batteries cannot power the wireless sensor networks for a long time, and needs to be replaced frequently. It leads difficulties to operate remote devices, and the used batteries causes environment pollution. To prolong the battery life without enlarge its size, acoustic energy harvester is a long-term power solution without battery replacement.

An acoustic energy harvester was designed with Helmholtz resonator, cantilever and acoustic waveguide [1]. Its maximum output power achieves 240μW, at SPL (Sound Pressure Level) of 94dB. The output power of disk-type piezoelectric energy harvester was researched in the sound field. The open-circuit voltage is 4.6V at frequency of 907Hz, and maximum output voltage achieves 6μW at SPL of 110 dB [2]. Wang [3] proposed an acoustic energy harvester with Helmholtz resonator and PVDF film, which can convert the acoustic energy from high-speed railway into electric energy. When the SPL
is 110dB, maximum output voltage is 74.6 mV. In Ref [4], a multi-function acoustic structure is designed for both sound isolation and acoustic energy harvest. Its output power is 0.21mW, when the SPL is 114dB and vibration frequency is 155 Hz. With Helmholtz resonator, piezoelectric composite plate and cantilever beam, Izhar [5] harvested the acoustic energy in three different frequencies. At the SPL of 130dB and frequency of 150 Hz, its maximum output power reaches 214.23μW. These current researches mainly focused on more output power with piezoelectric material, but acoustic energy harvesters by Electromagnetic Mechanisms are less reported. Because electromagnetic energy harvester can work independently or incorporated with piezoelectric energy harvester, it is an important complement in the field of acoustic energy harvest.

An acoustic energy harvester by Electromagnetic Mechanisms was designed with Helmholtz resonator, permanent magnet, coil and interface circuit. This proposed acoustic energy harvester can collect the energy from low frequency sound waves, and has not been reported yet. With the analysis of resonant frequency of Helmholtz resonator, the principle of acoustic-electric conversion is studied theoretically. After designed the interface circuit, its output characteristic is analysed by experiment.

2. Principal of the acoustic energy harvester

As shown in Fig. 1, the acoustic-electric conversion modular consists of Helmholtz resonator, permanent magnet and coil. Helmholtz resonator was made of stainless steel, with a light sheet covered its top. The permanent magnet was fixed on the light sheet, and the coil was clipped above the Helmholtz resonator, which is 0.5cm from the light sheet. The centre of coil was aligned with permanent magnet, so that the magnetic flux in the coil will change periodically if the light sheet vibrates. The cavity of Helmholtz resonator with volume V was connected with short tube which section area is S₀ and length is l, as shown in Fig. 1(a). When wave length of sound is much larger than length l and volume of short tube is much less than V, the motion characteristics of the gas in the resonator are similar to the mass-spring-damping system shown in Fig. 1(b). In this case, the resonant frequency is [6]

\[ f_0 = \frac{c}{2\pi} \sqrt{\frac{S_0}{l_0 V}} \]  

(1)

\[ l_0 = l_n + \Delta l \]  

(2)

where c is the average speed of sound in the resonator, \( l_0 \) is the effective length of inlet tube, \( \Delta l = 1.7a \) is the length correction that take into account the flow effect of gas near the short tube, and a is radius of the short tube.

In case of resonating, the sound pressure amplification factor of proposed Helmholtz resonator can be expressed as

\[ A = \frac{P_0}{P_{in}} = 2\pi \sqrt{\frac{l_0^2 V}{S_0^3}} \]  

(3)

where \( P_{in} \) is the sound pressure at the inlet, \( P_0 \) is the sound pressure inside the cavity.

According to equation (1) to (3), the resonant frequency and sound pressure amplification factor of proposed Helmholtz resonator is related with length l, section area is S₀, volume V. The sound pressure amplification factor and resonant frequency will affect each other.

Fig. 1 (a)Principle of acoustic energy recovery system (b) Lumped parameter model
When the sound pressure enters the Helmholtz resonator, it vibrates the resonator. Because the stainless-steel plates of resonator are relatively thick except the light sheet covered the top, the vibration will be concentrated on the light sheet. This vibration will drive the permanent magnet, and cause the relative motion between magnet and coil. Then the electric energy was generated from the coil, which converts the acoustic energy into electric energy.

In circuit analysis, the proposed acoustic energy harvester can be equivalent to the parallel connection of current source branch and coil branch. As shown in Fig. 2, the coil branch includes its inductance and internal resistance. A differential equation can be established according to Kirchhoff’s theorem,

\[
\frac{L \cdot dI_i(t)}{dt} + I_i(t) \cdot R_i + I_i(t) = I_m \cdot \sin(\omega t)
\]

(4)

Solute equation (4) and ignore the oscillatory attenuation term, the current through the inductor is

\[
I_i(t) = \frac{R \left(-R - R_i\right) \cdot \sin(\omega t) + \omega L \cos(\omega t)\right)}{\omega^2 L^2 + R^2 + 2RR_i + R_i^2}
\]

(5)

and the voltage on load is

\[
U(t) = \frac{I_m R \left(\omega^2 L^2 + RR_i + R_i^2\right) \cdot \sin(\omega t) + \omega RL \cdot \cos(\omega t)}{\omega^2 L^2 + R^2 + 2RR_i + R_i^2}
\]

(6)

Then the average power consumed by a load in a period can be obtained

\[
P = \frac{I_m^2 R \pi \left(\omega^2 L^2 + R_i^2\right)}{2\pi \left(\omega^2 L^2 + R^2 + 2RR_i + R_i^2\right)}
\]

(7)

In case of \( \frac{dP}{dR} = 0 \), there is an optimal resistance \( R_{opt} \) to maximize output power. They can be calculated by

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

(8)

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

(9)

Fig. 2 Equivalent circuit diagram
To transform the alternating current from the coil into direct current that is suitable to power the electric devices, an interface circuit was designed with voltage double circuit. Due to the rectification and current guidance of the diodes, the voltage was transferred to the two capacitors respectively. The series connection of the two capacitors will double the input voltage, as shown in Fig. 3. In the positive half cycle, current source charges the capacitor $C_2$ through diode $D_1$, until the voltage on $C_2$ reaches its maximum $U_m$. In the negative half cycle, current source charges the capacitor $C_1$ through $D_2$, until the voltage on $C_1$ reaches its maximum $U_m$. After several cycles, the voltage on series connected $C_1$ and $C_2$ will stabilize at $2U_m$.

![Diagram of interface circuit](image)

**Fig. 3 Interface circuit diagram**

### 3. Experiments
The size of Helmholtz resonator in this experiment is $20 \times 20 \times 15$cm, and its side short tube is 5cm in length with diameter of 6cm. The thick of its shell is 4mm and the light sheet on top only 0.5mm in thick. The height of permanent magnet is 1.5cm with basal diameter of 1cm. The total turns of the coil shown in Fig. 4(b) is 25000, and its skeleton 1.5 cm high with 1.3cm in diameter. The speaker is 10cm distance from the inlet of short tube, and it is the sound source that generate sound wave of different intensity and frequency. As illustrated in Fig. 4, the oscilloscope monitors the output voltage of the proposed acoustic energy harvester, and decibel meter detect the SPL.

![Experimental platform, coil, permanent magnet, and coil and permanent magnet](image)

**Fig. 4** (a) Experimental platform (b) Coil (c) Permanent magnet (d) Coil and permanent magnet
If the SPL keeps a constant, the output voltage of the coil changes with the frequency of sound wave as shown in Fig. 5, the two local maximums appear at the frequencies of 98Hz and 140Hz that correspond to the first and second resonant frequencies. The output performance of the coil is much better when the frequency of sound waves near the two resonant frequencies. The open circuit voltage is 0.68V at 98Hz, and obtains 0.43V at 140Hz.

If the frequency of sound wave is 98Hz or 140Hz, the output voltage increases with SPL ranging from 80dB to 110dB. When SPL is less than 105dB, the output performance at first resonant frequency is better. The output voltage at second resonant frequency increases faster, and it is higher than the output voltage at the first resonant frequency, when the SPL is larger than 105dB. In case of 110dB, output voltages are 6.35V and 7.2V respectively at frequency of 98Hz and 140Hz, as shown in the Fig. 6.

To power the micro electric devices, it is necessary to transform the alternating current from the coil into direct current. An interface circuit was designed and connected to coil, which consists of two Schottky diode and two capacitors of 10μF. At the frequency of 98Hz, the output voltages with and without the interface circuit was compared in Fig. 7. Obviously, the output voltage with interface circuit is double of the voltage from the coil.

After connected the interface circuit, the output power of the proposed acoustic energy harvester was recorded with a resistor as a load. When the SPL is 110dB, frequencies of sound waves are 98Hz and
140Hz, the output power of proposed harvester is changing with the load. As shown in Fig. (a), the two curves rise first and then decreases with the load. It should be noted that there is always an optimal resistance which can maximize the output power. The maximum output power achieves 0.5mW at 98Hz and 52kΩ load, while it obtains 0.625mW at 140Hz, 160kΩ. With the similar methods, the maximum output power in different SPL and different frequency of sound waves as shown in Fig. (b).

![Fig. 8 (a) Output power varies with load (b) Output power at different sound pressure levels](image)

4. Conclusion
An acoustic energy harvester by electromagnetic mechanisms and Helmholtz resonator is developed with permanent magnet, coil and interface circuit. After theoretical analysis of the acoustic-electric conversion modular, experiments were performed to study the output voltage and power of the proposed harvester in different frequency and SPL. Results shows that the proposed harvester can collect more power when frequency of sound wave is close to the resonant frequencies 98Hz and 140Hz. Its output voltage and power increases with the SPL. The coil more power at 98Hz when SPL is less than 105dB, but it outputs more power at 140Hz when SPL larger than 105dB. With the interface circuit, the open circuit voltage of proposed harvester is 13.65V at 110dB, 98Hz, while its output power is 0.625mW at 110dB, 140Hz. It indicates that the proposed acoustic energy harvester has the potential application to power the micro electric devices without battery replacement.

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