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Investigating the Optimum Efficiency of Acoustoelectric Conversion Plate Devices

Chien-Chih Chen[1], Wun-Yi Yan[2], Ying-Yan Wu[3] and Chen-Ching Ting[4, *]

[1] Graduate Institute of Mechatronic and Electrical Engineering

[2] Institute of Manufacturing Technology

[3] Institute of Mechatronic Engineering

[4] Institute of Mechanical and Electrical Engineering

National Taipei University of Technology, Taipei, Taiwan

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Abstract

This study aims to develop the acoustoelectric conversion plate in terms of electromagnetic induction law to convert sound energy to electricity, where the developed apparatus is made of three parts, the thin film coil, the spring, and the high-intensity magnetic framework. In process, the thin film coil receives the injecting sound vibration in connection with the spring to cause the reciprocating motion between the coil and the high-intensity magnet, which yields the electromotive force (EMF). In this study, a pearl plate of length 95 mm, width 95 mm, and thickness 1.5 mm adhered with a PET film of thickness 0.08mm is built as the substrate plate due to it has good properties of light and elasticity. In connection with the substrate plate and the electric coil is the thin film coil. Experiments used the speaker with output frequencies of 30~156 Hz and sound power of 0.5 W (sound intensity 0.32 W/m^2, sound pressure level 115 dB) as the sound source. The sound energy is captured by the acoustoelectric conversion plate for working efficiency and optimization parameters analysis. The studied parameters content of diameter, turns, and width of electric coil as well as distance between high intensity magnet and coil. The results show that diameter 0.11 mm, turns 220, and width 3 mm of the electric coil, in connection with steel spring of diameter 0.2 mm while input sound is 30 Hz, receives the average output voltage of 0.57 V, the average output current of 5.46 mA, the average output power of 3.13 mW, and the sound electric conversion efficiency of 0.63%. This innovation device could be used in highway, near waterfalls, and some high noise factories to capture energy for immediately charging cell-phone to save human life.

Keyword: electromagnetic induction, acoustoelectric conversion plate, spring, thin film coil, LabVIEW, sound power

1. Introduction

Noise is an annoying problem in today's civilized society, everywhere, especially in the workplace, labor, equipment room, runways and so on, and the strength is often large enough to cause injury to the point. Investigating the noise problem, the researchers often focus only on the issue of how to silence, but ignored the noise is actually hidden a lot of power energy.

* Corresponding author. E-mail address: chchting@ntut.edu.tw

Tel.: +886-2-27712171#2075; Fax: +886-2-27317191

For example, the 160 dB noise level of a jet aircraft content the sound power of about 10 kW; noise level of 140 dB heavy-duty truck engines contain the sound power of 100 W. In addition, the noise emitted by portable electric drill can also reach 120 dB, the sound power is nearly 1 W of power energy. In the 21st century, energy issues need to be resolved urgently moments, green technology is a major global technology.

The current discussing is divided into acoustic energy generation technology piezoelectric and electromagnetic acoustic energy generation technology in both directions. Piezoelectric generator uses piezoelectric material as transducer material. In recent years, researchers develop rapidly piezoelectric materials, but piezoelectric energy achieved primarily through the deformation of the piezoelectric material to convert mechanical energy into electrical energy. Strain or deformation of the piezoelectric material in the element causes charge separation and generates an electric field, and produce a voltage proportional to the applied pressure drop. The systems typically use cantilever structure and the end of the cantilever is placed on a separate mass. For a given input power, the structure can generate a greater deformation. The generating voltage influenced by time and its shape. Currently, the industry widely used lead-titanate piezoelectric ceramics - lead zirconate titanate ($PbTiO_3$-$PbZrO_3$) system, a PZT piezoelectric material, commonly known as energy conversion material having a high electromechanical coupling and good quality factor [1-2]. The composition contains a large number of lead elements, and lead toxic elements, but in a high temperature sintering process. The ceramic volatile contamination as environmental awareness, many substances harmful to the environment has gradually been disabled [3]. In addition, the piezoelectric vibrator in the AC-DC interface circuit and the load interaction mechanisms than pure communication interface circuit complexity of many [4-6].

In addition, there is a sound generator called thermal (thermoacoustric power generator) [7-8], it is an innovation technologies. In 1999, Symko et al. published a convert waste heat such as heat waves, which can then be converted into electricity concepts. In 2006, the development of this technology for the hot sound generator, which is characterized by the heat into sound waves, is formed by the heat exchanger back to back, the multi-chip thin metal plate overlap, and the cooler and a heater sandwiched thermoacoustic generating element constituting both ends [8]. Wherein the dielectric material to form a single-frequency acoustic resonance frequency (resonant acoustric frequency). When the thermal energy is formed into the tube when the acoustic resonance, and then the coupled to the piezoelectric transducer, finally the sound into electricity. The use of a portion of dielectric material called PVDF (polyvinylidene fluoride) of piezoelectric polymer, the Chinese name of polyvinylidene fluoride material, the material characteristics can be transferred directly to the mechanical energy into electrical energy. However, there are many problems of this material exist, such as limited operating temperature conditions, subject to a thermal transfer mechanical energy driving force, excessive transmission mechanism to increase the energy loss, and the energy capture is not efficient than conventional power plant [9].

Lai et al. [10] designed and produced sound waves drive a high voltage output characteristics micro-generators, and the performance of the generator carried simulation analysis and experimental. The generator was made by a planar coil, supporting beam suspension plate and a permanent body composition. The experimental results show human or speaker sound waves role in this micro-generators, by the electromagnetic induction manner, can generate electric power. Its micro-generator size with 3 mm × 3 mm, driving frequency sound waves at 470 Hz obtained 0.24 mW.

According to the literature, in present study against the sound energy transfer into electrical energy by using the traditional electromagnetic induction developed induction vibrating membranes, which can directly capture the energy of sound noise. The reciprocating motion through spring to make mechanical energy into kinetic energy, thereby bringing thin film coil and with the magnet generate a magnetic field cutting, induced electromotive force generated, reached sound energy capture and electric energy conversion of purpose. Figure 1 shows a thin film coil induction generate electricity, which is totally different between piezoelectric material. Figure 2 illustrates a piezoelectric induction generate electricity, its development value lies simple process technology, the material is not restricted, low cost, environmentally friendly, long life. In order to improve the smooth and accurate implementation, a home-made automatic winding machine and the I-V curve efficiency measurement system are be made. Electromagnetic induction influenced by magnetic flux intensity, namely, present study focus on optimizing the quality and elasticity of thin film coil induction vibrating membranes, coil diameter, diameter, number of turns, number of layers, spring material and elastic modulus, collocation suitable the resonant frequency of the thin film coil induction generator.

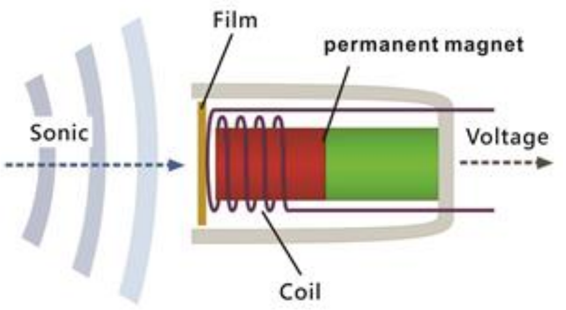

Fig. 1 The thin film coil induction generator schematic [Citing from Wikipedia]

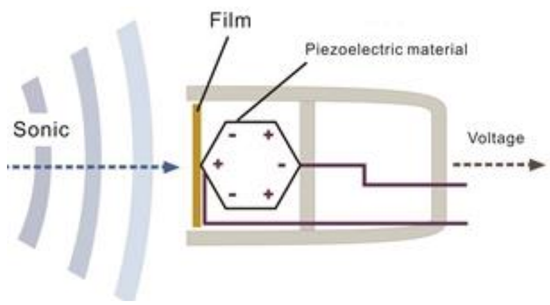

Fig. 2 Piezoelectric induction generator schematic [Citing from Wikipedia]

2. Basic Theory

The theory of acoustic energy generating device is content five major parts: sound pressure, sound Intensity, plane wave sound source, sound field characteristics, and acoustoelectric conversion efficiency. The details describe as shown in below.

2.1. The basic theory of sound

2.1.1. Sound pressure

Sound pressure, a physical energy, commonly use Pascal or mbar (Microbar) units, which is approximately equal to 10^{-6} mbar atmospheric pressure. Sound pressure P generally used as a symbolic representation, which is called sound pressure or sound pressure level P_S (sound pressure level, SPL). Sound pressure level (L_P) expressed in decibels is defined as equation (1):

$$L_P = 20 \log \frac{P_S}{P_0} \tag{1}$$

where P_S is the sound pressure, P_0 is the reference sound pressure, the smallest sound pressure could be heard by human ear, which is defined as 0 dB (equal to 20 × 10^{-6} Pa). By the above formula (1), assuming a known sound pressure level (L_P) sound pressure can be rewritten as the following formula (2):

$$P_S = P_0 \times 10^{\frac{L_P}{20}} = 10^{(\frac{L_P}{20} + \log P_0)} \tag{2}$$

2.1.2. Sound intensity

Sound intensity is defined as limited time through limited area of energy, in units of W/m^2. Present study generally used as a sound intensity, called sound intensity value, or sound intensity level (sound intensity level, SIL). In this paper, I_S is defined as following formula (3):

$$L_I = 10 \log(\frac{I_S}{I_0}) \tag{3}$$

where I_S is per limited time through limited area of energy, measured in W/m^2, I_0 is the smallest sound pressure could be heard by human ear, its value is equal to 10^{-12} W/m^2.

2.2. Plane wave sound source and sound field characteristics

In this study, in order to provide stable and energy parameters of the sound source, a rectangular planar waveguide to form a uniform plane wave was be built. Due to the sound wave propagation a same area and the sound energy is limited by a rectangular planar waveguide, the sound intensity (I_S) does not decreasing by increasing the distance from the sound source. The sound pressure level (L_P) is equal to the value of the sound intensity (L_I), when a plane sound wave propagation. The relationship between sound intensity (I_S) and sound pressure (P_S) as shown in equation (4):

$$I_S = \frac{{P_S}^2}{\rho c} = \frac{{P_{rms}}^2}{\rho c} \tag{4}$$

where P_{rms} means rms value of sound pressure (Pa); ρ is the mass density (kg/m^3); c is the speed of sound (m/s), within air as the medium is generally at ambient temperature. The acoustic impedance of the sound velocity values, the value of ρc = 400 kg/m^2 s.

In addition, according to the 2006 by the Han Guohua [11] proposed theoretical derivation of a rectangular plane sound source propagation the sound power. Therefore, perpendicular to the waveguide plane rectangular faces the sound source and the ground along a direction parallel to the total sound intensity measurement points can be expressed the following formula (5) and (6):

$$I_S = \int \frac{2\pi}{2\pi r^2} \cdot cos\alpha = \frac{W}{2\pi}\varphi \tag{5}$$

$$\varphi = \int \frac{d_s}{r^2} \cdot cos\alpha \tag{6}$$

where, ψ consists of six rectangular faces of sound intensity relative to measurement point level vector addition to posed. The r is rectangle surface, an infinitesimal element to measurement point sound waves propagation path length. The W is sound power per unit area, d_s for each rectangular surface area of infinitesimal element, α is r path length and the measuring point path forming an angle, and $W = \frac{2\pi}{\varphi} \cdot I_S$, which can be obtained as following equation:

$$W_S = I_S \cdot \left(\frac{2\pi}{\varphi} S_r\right) = I_S (C_e S_r) \tag{7}$$

which W_S is the actual sound source power; $C_e = C_e = \frac{2\pi}{\varphi}$, C_e is the measured surface area equivalent coefficient; S_r is the sound source rectangle area of a radiating; $C_e S_r$ is effective sound source rectangle area of a radiating. In this study, the radiation of source rectangle area is 0.01 m^2 and the distance between measuring points and the sound source is 0.5 m.

2.3. Acoustoelectric conversion efficiency

Present study uses acoustoelectric conversion plate conducted sound energy capture, conversion into electrical energy output, and find the maximum output power. In addition, employs a noise meter to measure sound pressure level (L_P), which can convert into sound pressure (P_S). According to formula (7) derived sound power (W_S) and thus obtain acoustoelectric conversion efficiency formula (8):

$$\begin{aligned}\eta &= \frac{P_{out}}{P_{in}} \times 100\% \\ &= \frac{P_{av}}{W_S} \times 100\% \\ &= \frac{I_{av} \times V_{av}}{I_S \cdot (\frac{2\pi}{\varphi} S_r)} \times 100\% \\ &= \frac{I_{av} \times V_{av}}{\frac{P_S{}^2}{\rho c} \cdot (\frac{2\pi}{\varphi} S_r)} \times 100\% \\ &= \frac{I_{av} \times V_{av}}{\frac{(10^{(\frac{L_P}{20} + \log P_0)})^2}{\rho c} \cdot (\frac{2\pi}{\varphi} S_r)} \times 100\%\end{aligned} \quad (8)$$

where P_{out} is captured sound energy into electrical energy to the average output power. Formula (10), the average output power within the measurement time by maximum amplitude of the positive half cycle whichever is the average voltage and current values obtained by the product of the unit is Watt. P_{in} is the actual source of sound power, the sound source measurement device the measured sound pressure level (L_P) through formula (2) converted into the corresponding sound pressure (P_S). Substituting into formula (4) obtained by the area of a rectangle waveguide sound intensity, measured in W/m^2. Finally, substituted into (7) formula derived rectangular planar waveguide actual audio sound power.

3. Experimental Setup

This work mainly captures sound energy and translates into electrical energy. Developing "acoustoelectric conversion plate" to capture the sound energy, the acoustoelectric conversion plate bodies including waveguide, thin-film coil springs and powerful magnets four parts. The sound energy propagated through a rectangular planar waveguide to the thin film coil causing vibration motion. The vibration coil and powerful magnets generate induced electromotive force. In addition, research process simultaneous efficiency measurement and analysis. Therefore, combined with LabVIEW erection "I-V curve measurement device", fast Fourier transform (FFT) instant analysis audio and sound intensity "sound source analysis measuring devices". All measurement equipment are followed ISO 1996 standardize.

3.1. Acoustoelectric conversion plate

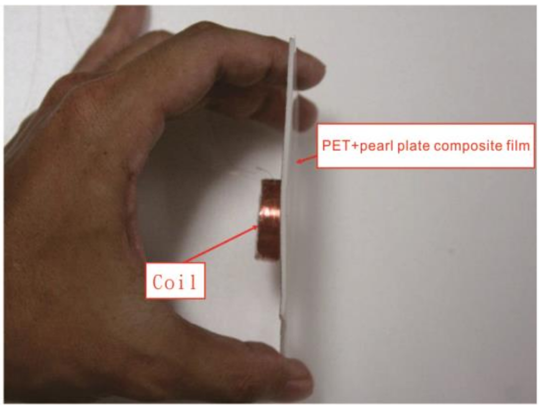

Fig. 3 The thin film coil

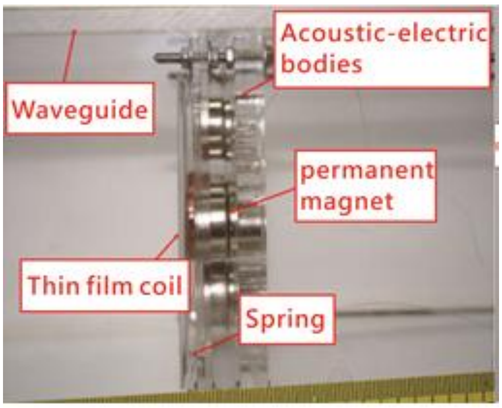

Fig. 4 The acoustoelectric conversion plate

This study designed acoustoelectric conversion plates to capture sound vibration energy. Electromagnetic induction power was generated by a square planar waveguide running through the acoustoelectric conversion plate. Acoustoelectric conversion plate constituent elements introduction: the thin film materials with thick 0.08mm made by PET film and the thick of 1.5 mm pearl plate, and the coil affixed to thin film. Figure 3 shows a thin film coil transferring energy through the spring, the powerful magnets for magnetic field cutting induced electromotive force. Fig. 4 exhibits an acoustoelectric conversion plate.

3.2. Acoustoelectric conversion efficiency measuring of erecting

This work employs commercial ALTEC Model VS4121 speakers as sound source. Using LabVIEW to design the sound source analysis measurement system, through laptop provides signals to the speaker with analog sound source output. Figure 5 is the measurement software system; figure 6 shows its photo. A microphone is used to receive the sound wave signal and translates to voltage signals for LabVIEW software. The software uses fast fourier transform (FFT) for A/D, D/A data processing and graphic display which can available for immediate analysis of the frequency distribution. Using LabVIEW software measured the I-V curve by provide maximum output power for calculation. Figure 7 is an acoustoelectric conversion efficiency measurement photo.

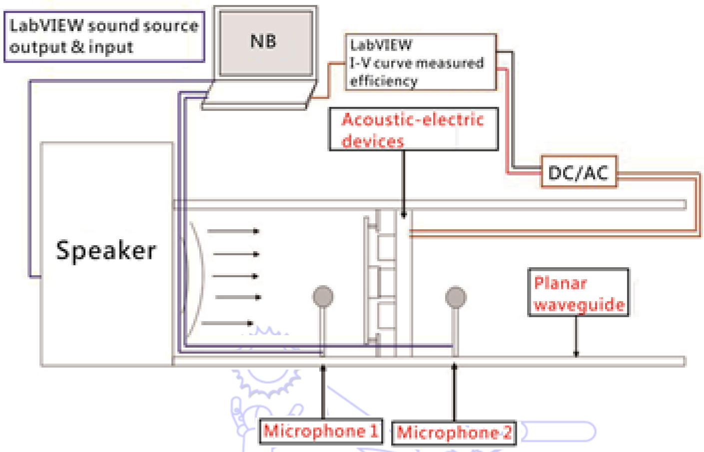

Fig. 5 Schematic experimental measurement erection

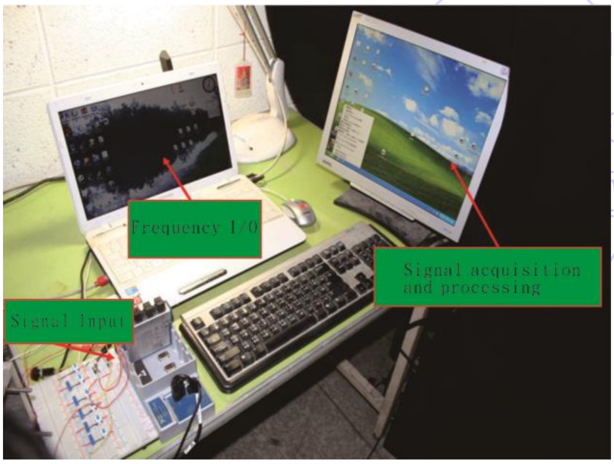

Fig. 6 Analysis of the measurement device sound source

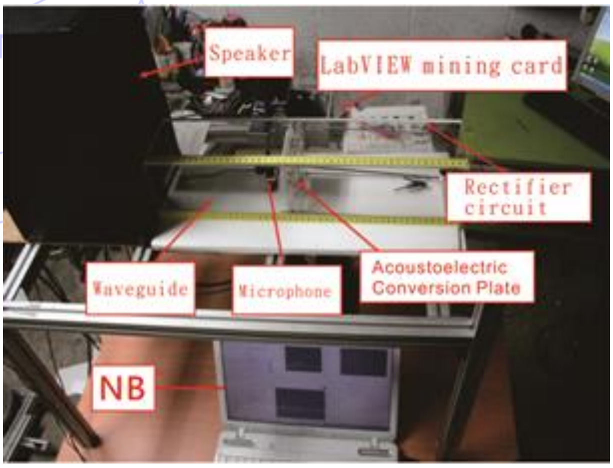

Fig. 7 The soundelectric conversion efficiency measure setup photo

4. Results and Discussion

This study is focused on capturing environment of sound vibration energy by acoustoelectric conversion plate. The sound energy runs through the rectangular plane waveguide transfer to the acoustoelectric conversion plate. A rectangular waveguide plane within sound field is a uniform plane wave, the sound intensity will not attenuation with increasing of the distance. In addition, the coil of thin film material with thickness is 0.08 mm and PET film thickness is 1.5 mm, within flexible, thin, long service life benefits. More suitable for acoustoelectric conversion of film material, with the diameter 0.2 mm and 0.4 mm of the stainless steel springs resonant frequency explore. The applied audio frequency between 30 Hz~ 156 Hz with 115 dB sound pressure level as input source. The coil diameter is 0.11 mm with 220 and 940 cycles with width 3 mm.

4.1. Explore of resonant frequency

Present study made an acoustoelectric conversion plate to investigate the best frequency. Adjusting the elastic coefficient of spring and quality of thin film coil, we build the acoustoelectric conversion plate and the output sound source to achieve the best conditions. The $f = \frac{1}{2\pi}\sqrt{\frac{k_s}{m}}$ was calculated the resonant frequency (f) and the applied mass (m) in different elastic coefficient (k_s) of the spring relationship. Figure 8 show diameter with 0.2 mm and 0.4 mm of the film quality stainless steel spring of different resonant frequency. Figure 8 shows that the resonant frequency of spring elasticity is relatively low, and vice versa is higher, due to the smaller elasticity of the spring restoring force by the spring is smaller. The applied mass increasing, the resonant frequency is smaller. The greater spring rate provides a strong spring restoring force, but larger the mass will get the smaller resonance frequency. Present discussed the diameter with 0.2 mm and 0.4 mm of springs and show that the diameter with 0.2 mm of spring obtained the lower of resonance frequency.

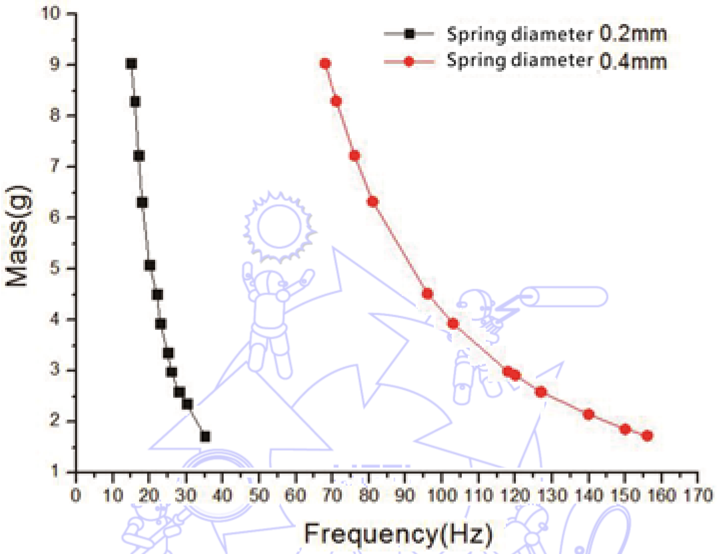

Fig. 8 The relationship between spring diameter and resonant frequency

4.2. Optimization and efficiency analysis for the acoustoelectric conversion plate

This work calculated the coefficient of elasticity of the spring with the optimal thin film coil to achieve quality of the resonant frequency of vibration system curve. Analyzing different diameter and turns of the coil, power generation efficiency, and the resonant effect obtained the low-frequency acoustic energy transfer efficiency.

(1) Spring diameter, output sound pressure level, resonant frequency, and incident frequency are 0.2 mm, 115 dB, 29.7 Hz, and 30 Hz, individually.

Figures 9 and 10 show the I-V and P-V curve of acoustoelectric conversion plate with spring diameter 0.2 mm, sound source under 115 dB, and 29.7 Hz of the resonant frequency. Increasing the turns of coil will increase the thin film quality, but the resonant frequency down to 30 Hz. Figures 9 and 10 show the 220 turns of coil with the incident frequency is 30 Hz, the average output voltage of 0.57 V, the average output current of 5.46 mA, the average output power of 3.13 mW, and the sound electric conversion efficiency of 0.63%.

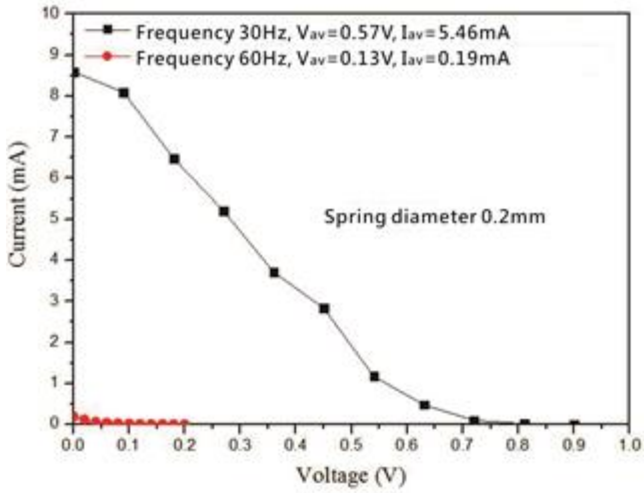

Fig. 9 The I-V curve with diameter 0.2 mm and 220 turns of the electric coil

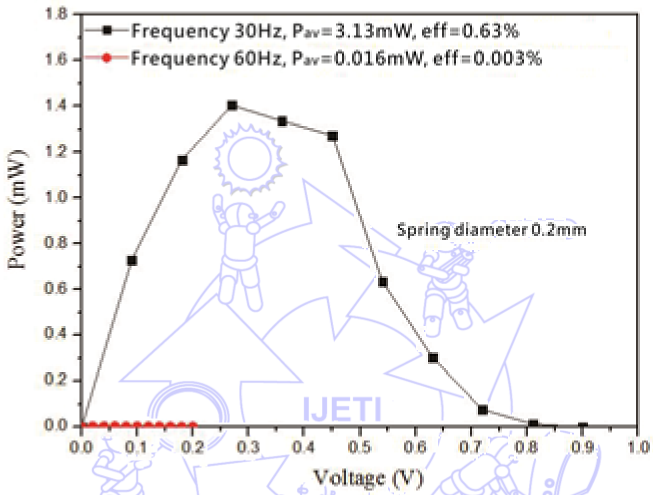

Fig. 10 The P-V curve with diameter 0.2 mm and 220 turns of the electric coil

(2) Spring diameter, output sound pressure level, resonant frequency, and incident frequency are 0.4 mm, 115dB, 71 Hz, and 35 Hz, individually.

Figures 11 and 12 show the I-V and P-V curve of acoustoelectric conversion plate with spring diameter 0.4 mm, output sound pressure 115 dB sound source, and 71 Hz of the resonant frequency. Although the resonant frequency is 71 Hz, the springs are used in the operating frequency range. The 940 turns of the coil induced great electromotive force, but according to the Lenz's Law, the more coil it is, the higher resistance between thin film coil and the magnet will get. The higher resistance caused anon-harmonious vibration different between incident frequency and the resonance frequency. Namely, a harmonious vibrations generated a greater absorption of sound energy when the frequency is about half of the resonant frequency in 35 Hz.

Figures 11 and 12 show the I-V and P-V curve of acoustoelectric conversion plate under 940 turns of the coil with the incident frequency about half of the resonant frequency. The average output voltage, the average output power, and the average output current with the frequency 35 Hz are 1.13 V, 1.44 mA, and 1.63 mW, individually. The sound electric conversion efficiency is 0.325%.

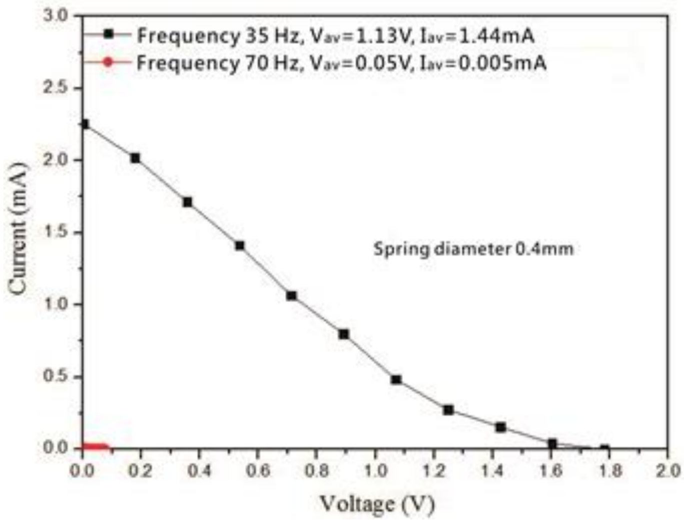

Fig. 11 The I-V curve with diameter 0.4 mm and 940 turns of the electric coil

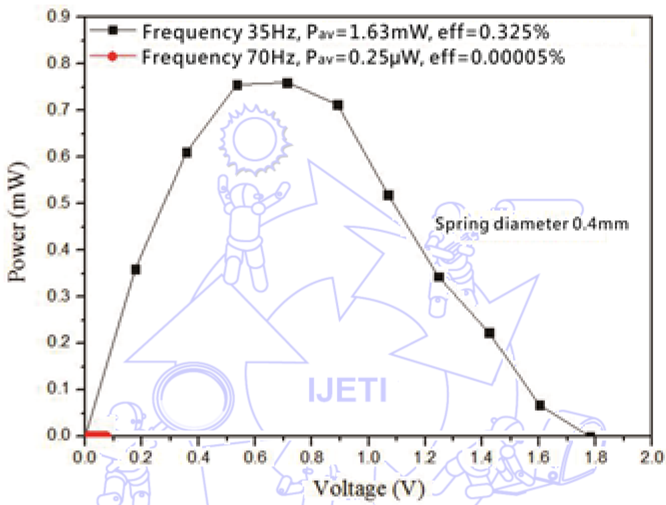

Fig. 12 The P-V curve with diameter 0.4 mm and 940 turns of the electric coil

5. Conclusions

This study developed a low-frequency acoustoelectric conversion plate module, associated measurement, process equipment production, conducted a series of the measurements of efficiency, and those important results are shown as follows:

(a) The smaller elasticity of spring modulus it is, the lower resonant frequency it will. The best power conversed efficiency under 0.2 mm diameter of stainless steel spring with input resonance frequency of 30 Hz.

(b) The input sources frequency in 30 Hz, sound power 0.5 W (sound pressure level 115 dB), diameter 0.11 mm with 220 turns of thin film coil, diameter 0.2 mm of stainless steel springs is obtained the average output voltage of 0.57 V, the average output current 5.46 mA, the average output power of 3.13 mW and best acoustic-electric conversion efficiency of 0.63%.

Summary, electromagnetic induction produced by sound electric conversion power generation device is only suitable for below 70 Hz acoustic energy frequencies. Using smaller elastic coefficient of springs will reach larger power energy with the incident acoustic of resonant frequency. In other words, the power generation unit generates resonance effect. Further, uses lager elastic coefficient springs of generating device will not instant reaction too high vibration frequency, but it can capture double of the resonant frequency by the incident sound energy. Finally, electromagnetic acoustic energy generating device can apply for low frequency acoustic energy fields with a smaller elastic coefficient spring.

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