Harvesting acoustic energy by coherence resonance of a bi-stable piezoelectric harvester

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Abstract

In this work we proposed a bi-stable acoustic energy harvester (BAEH) to scavenge noise energy. The nonlinear BAEH is composed of a piezoelectric cantilever beam with a flat plate attaching at the free end, a curved plate, a movable magnet and a fixed magnet. The incident and reflecting sound waves will produce dynamic acting forces on the front and the back of the flat plate, thereby exciting the plate to oscillate and take snap-through between equilibrium positions, and thus give a large output. The experimental results prove that the BAEH can execute snap-through at a relatively low intensity of noise. It can reach coherence resonance and thus generate a large output voltage. It is found that the separation distance d is a key factor for occurrence of snap-through. Therefore, for a given sound pressure level (SPL), the BAEH can be optimized to reach coherence resonance and generates the maximum output power.

Keywords: acoustic energy harvesting, bi-stable acoustic energy harvester, snap-through, coherence resonance

1. Introduction

Power supplying techniques have captured enormous attention in the manufacture of wireless sensor and other micro-electromechanical devices over the past decades [1-3]. Many efforts on powering small-scale electronic equipment have

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been made based on different transformation mechanisms such as electrostatics [4, 5], electromagnetics [6, 7] and piezoelectricity [8-11]. Piezoelectric energy harvesters have received a great attention due to the advantages of easy establishments of energy resource, uncomplicated embodiment of the system and high efficiency of transduction. In addition, it can be realized in the environment such as vibrations, noises, winds, fluid flows etc. Acoustic noise as a clear, ubiquitous and renewable energy is prevalent abundantly both in domestic and industrial environments. Chang et al. [12] indicated that the sound pressure level (SPL) in the surroundings of household appliances (hair dryer, juicer, vacuum cleaner, and bean grinder) ranges from 67 dB to 78 dB, while the SPL of acoustic noise ranges from 87.7 dB to 136 dB in the environment of industries (print industry, textile manufacturing industry, fiber glass industry, etc.) [13, 14].

In recent years, much efforts have been made on developing acoustic energy harvesters (AEHs) by which electrical power for self-powered devices can be generated from acoustic energy sources. Horowitz et al. [15] first introduced an AEH with a PZT diaphragm bonded on the bottom of a Helmholtz resonator. A maximum output power density of $0.34 \mu\text{W}\cdot\text{cm}^{-2}$ was obtained at a SPL of 149 dB. Liu et al. [16, 17] developed an electromechanical Helmholtz resonator consisting of an orifice, a cavity and a piezoelectric diaphragm. Experimental results indicated that approximately 30 mW of output power was harvested for an incident SPL of 160 dB with a flyback converter. Kim et al. [18] also used the AEH to obtain an output voltage of 4 mV measured at 140 dB SPL and 1.4 kHz excitation frequency. Lallart et al. [19] proposed an enhancement of the energy harvesting process using a nonlinear processing of the output voltage of piezoelectric actuators and supporting experimental results exhibited a gain of up to 10 in power and a doubling of the bandwidth. The AEH with 70 k Ω internal impedance generated a peak power of 55 μW for a SPL of 100 dB. Li et al. [20, 21] introduced an AEH that used a quarter-wavelength straight tube acoustic resonator with polyvinylidene fluoride (PVDF) piezoelectric cantilever beams or PZT piezoelectric cantilever plates placed

inside the tube. The PVDF or PZT piezoelectric cantilever plates were designed to have the same resonant frequency with the quarter-wavelength resonator for improving output voltage. Yang et al. [22] proposed a high-efficiency broadband AEH consisting of a compliant-top-plate Helmholtz resonator and two piezoelectric cantilever beams. Experiment exhibited that the proposed AEH had 28–188 times higher efficiency than the conventional harvester with a piezoelectric composite diaphragm at 170–206 Hz excitation frequency and 140 dB. Khan and Izhar [23] developed an AEH consisting of a Helmholtz resonator, flexible membrane, moving magnets and a fixed wound coil. The maximum power 1503.4 μW was obtained at 144 Hz excitation frequency and 120 dB of SPL by experiment in open air with a large speaker as an acoustic source. Khan and Izhar [24] also reported a novel hybrid AEH utilizing both the electromagnetic and piezoelectric phenomena to convert the acoustic noise into electrical power. In experiments, an optimum power of 2.86 μW (at 114 Ω optimum load) and 50 μW (at 1000 Ω optimum load) were generated by the electromagnetic and piezoelectric harvester part. Moreover, in a practical domestic acoustic environment output voltages of 40 mV (25 mV DC) and 123 mV (202 mV DC) mV were produced by the electromagnetic and piezoelectric portions of the acoustic energy harvester.

Recently some researchers found that the triboelectric nanogenerator could be used to harvest acoustic energy [25-27]; the maximal current density and power output of the device reached 1.6 mA/m² and 60.2 mW/m², respectively. Cui et al. [27] fabricated a new mesh-membrane based triboelectric nanogenerator that could have a good performance of harvesting acoustic energy in a wide frequency bandwidth and it reached a short-circuit current density as high as 45 mA/m² and peak power density of 202 mW/m². Recent work proposed that piezoelectric materials could be used in a novel way to harvest wind energy in a mean flow acoustic engine based on flow induced acoustic oscillation. Based on the mean flow induced acoustic oscillation effect, piezoelectric materials could be used in a novel way to harvest the kinetic energy of natural wind in a mean flow acoustic engine [28-30]. Moreover,

piezoelectric materials may be used in traveling-wave thermoacoustic electric generator [31, 32].

The piezoelectric energy harvesters for scavenging base vibration energy adopted linear scenarios in the beginning, but they showed insufficient for applications in realistic environment. To date, a number of other types of energy harvesting methods have been proposed. Xu et al.[33] proposed a bi-stable energy harvester based on a simply supported piezoelectric buckled beam, its open-circuit RMS voltage could be increased by approximately 300% compared to the traditional one. Arrieta et al. [34] investigated a bistable piezoelectric composite plate that owned a wide frequency range and could harvest broadband nonlinear vibration energy. Pan et al. [35] presented a novel piezoelectric harvester based on bi-stable hybrid symmetric laminates. It was studied experimentally and the results demonstrated that it had the better performance at low frequencies compared to the traditional resonance one. Zhao [36] designed a convection-driven Rijke–Zhao thermo-acoustic-piezo system for sound energy harvesting. When the sound pressure level reaches about 139 dB, the energy conversion efficiency is increased by 105% compared to the conduction-driven thermo-acoustic-piezo system. Zhao and Ega [37] investigated a piezoelectric generator with three different aspect-ratio rectangular wings. The wing with a surface area of 0.025 m^2 could produce a power output of 55 mW. Scarselli et al. [38] presented a novel power harvesting concept that used bistable composite with a 'lever effect' and developed a more efficiently bistable energy harvester. Zhao et al. [39] considers a thermo- and piezo-electric energy harvester based on bifurcating tubes and carried out thermodynamic analysis on heat-driven oscillations. The harvester generated approximately a total electrical power of 5.71 mW, of which the piezoelectric module produces about 0.21 mW. Zhao et al. [40] designed and tested the performance of three different-diameter energy harvesters driven by flowing water and air and produced approximately a power of 0.3 W.

To the authors' best knowledge, few works have been explored on AEHs with multi-stable characteristics, since generally the noise excitation is not able to drive

multi-stable structures to undergo snap-through as the base excitation does. Thus for sound energy harvesting, most of the AEHs were based on the Helmholtz resonator, in which elastic piezoelectric plates or beams were placed. The corresponding studies showed that they exhibited good performances while working near the resonance frequency of the system. However, acoustic noise existing in environments includes many frequency components, or even is distributed over a wide range of frequency. It have been found that the sound energy in high frequency can't be harvested effectively by conventional scenarios, since the high frequency part of sound can't excite the beam or plate to reach a vibration with relatively large amplitude. From the perspective of vibration, to harvest broadband noise energy, the best harvester should have the ability to transfer the high frequency excitation to the low frequency response, by which the harvester can create a fairly large amplitude's response and give a high output voltage and power. In view of this, a bi-stable acoustic energy harvester (BAEH) configuration was presented here. The BAEH is composed of a piezoelectric cantilever beam with a flat plate, a curved plate, a movable magnet and a fixed magnet. Its harvesting ability was analyzed theoretically and studied experimentally. The results showed that its coherence resonance could maintain a nearly regularly jumping under broadband noise excitations and thus generated a high output power.

2. Theoretical modeling

Fig. 1 illustrates the structure of the proposed BAEH. It is composed of a cantilever bimorph piezoelectric beam with a flat plate attaching to the free end, a curved plate at whose focus the flat plate locates, two permanent magnets (one is attached to the free edge of the flat plate, while another is fixed on the base, and their distance is denoted by d (as shown in Fig. 2)). When the incident sound wave reaches the BAEH, it will exert an acting force on the front of flat plate, while the reflecting wave reflected by the curved plate exerts an acting force on the back. The two dynamic forces will drive the plate to oscillate. Due to the existence of the two magnets and their repulsive effect, the BAEH can execute consecutively jumping

between the two equilibrium positions, which will produce a large deflection for the piezoelectric beam and thus generate a large output voltage.

The piezoelectric constitutive equations in terms of mechanical stress and electric field can be written as [41]:

$$\begin{cases} T_x = c_{xx}^E S_x - e_{zx}^T E_z \\ D_z = e_{zx} S_x + \epsilon_{zz}^S E_z \end{cases} \quad (1)$$

where T_x and S_x denote the mechanical stress and strain respectively; E_z and D_z denote the electric field and the displacement respectively; e_{zx} is the piezoelectric coupling coefficient; $()^T$ means transposed matrix; c_{xx}^E denotes the Young's modulus of piezoelectric material in a constant electric field; ϵ_{zz}^S is the permittivity constant for a constant stress.

In magnetic force modeling, the magnets can be regarded as point dipoles. The magnetic moment vector $\mathbf{m}$ is dependent on the magnet's volume V , and its magnetization $\mathbf{M}$ is related to the magnet's residual flux density $\mathbf{B}_r$, $\mathbf{M} = \mathbf{B}_r/\mu_0$, where $\mu_0 = 4\pi \times 10^{-7} \text{ Hm}^{-1}$ is magnetic permeability constant [41-43]. Let $\mathbf{m}_A$ represent the magnetic moment vector of magnet A. Then the potential energy of magnetic field generated by magnet B upon magnet A can be given by [42]

$$U_m = -\mathbf{B}_{BA} \cdot \mathbf{m}_A \quad (2)$$

where $\mathbf{B}_{BA}$ is the flux density generated by magnet B upon magnet A. $\mathbf{B}_{BA}$ can be calculated by [42]

$$\mathbf{B}_{BA} = -\frac{\mu_0}{4\pi} \nabla \frac{\mathbf{m}_B \cdot \mathbf{r}_{BA}}{\|\mathbf{r}_{BA}\|_2^3} \quad (3)$$

where $\mathbf{r}_{BA}$ is the vector directed from the magnetic moment source of magnet B to that of magnet A; $\|\mathbf{r}_{BA}\|_2$ and ∇ denote the Euclidean norm and the vector gradient operator respectively.

The geometric relative positions of magnet A and magnet B are plotted in Fig. 2. To calculate the interaction force between them, we need to give the transverse and longitudinal displacements of magnet A. Let us denote by $w(x, t)$ the transverse

displacement of the beam at distance x and instant t . To provide insight into the locations, a dashed-line box is plotted to represent the neutral position of the tip magnet while the beam is not deflected. When the beam begin to oscillate, the tip magnet A will traverse a distance of $w(L_s, t)$ along with a small rotation angle given by $\alpha = \arctan [w'(L_s, t)]$. Considering the magnet's size, its transverse displacement should be $w(L_s, t) + \frac{a \sin \alpha}{2}$, where a is the side length of magnet A; and the longitudinal displacement of magnet A is $\Delta x = \frac{a}{2}(1 - \cos \alpha)$. Since $\alpha \approx 0$, $\Delta x \approx 0$. Vector $\mathbf{r}_{BA}$ finally becomes

$$\mathbf{r}_{BA} = [w(L_s, t) \quad 0 \quad d] \quad (4)$$

and $\mathbf{m}_A$ and $\mathbf{m}_B$ are

$$\mathbf{m}_A = [M_A V_A \sin \alpha \quad 0 \quad -M_A V_A \cos \alpha] \quad (5)$$

$$\mathbf{m}_B = [0 \quad 0 \quad M_B V_B] \quad (6)$$

where M_i and V_i represent the magnetization intensity and the volume of magnet i ($i=A$ or B). Therefore, the magnetic potential energy U_m generated by magnets A and B can be derived to give

$$U_m = \frac{\mu_0 M_A V_A M_B V_B (-w(L_s, t)^2 + 2d^2 - 3dw(L_s, t)w'(L_s, t))}{4\pi \sqrt{((w'(L_s, t))^2 + 1)(w(L_s, t)^2 + d^2)^{5/2}}} \quad (7)$$

The elastic potential is

$$U_e = \frac{1}{2} E_s I_s \int_0^{L_s} [w''(x, t)]^2 dx + \frac{1}{2} E_p I_p \int_0^{L_p} [w''(x, t)]^2 dx + \frac{1}{2} E_{Fp} I_{Fp} \int_{L_s - L_{Fp}}^{L_s} [w''(x, t)]^2 dx \quad (8)$$

where $E_s I_s$, $E_p I_p$ and $E_{Fp} I_{Fp}$ are the bending stiffness of the substrate layer, the piezoelectric layer and the flat plate, respectively; L_s , L_p and L_{Fp} refer to the lengths of the substrate layer, the piezoelectric layer and the flat plate, respectively; and the prime notation $()''$ represents $\partial^2 / \partial x^2$.

The parameters used for numerical and experimental studies are listed in Table 1.

The total potential energy of the BAEH consists of two components: the elastic potential energy and the magnetic potential energy. From Eq. (2) the magnetic potential energy can be calculated. Since the characteristics of the BAEH can be inferred from its potential energy shape basically, we plot the total potential energy of the BAEH versus d in Fig. 3(a). As we can see, for d large (e.g. $d=45$ mm), the system degenerates to a linear or mono-stable one, which has only a unique stable equilibrium position at the origin; then as d decreases, two symmetric wells of potential energy will emerge gradually, which results in three equilibrium positions in total (an unstable and two stable ones). Fig. 3(b) shows the bifurcation of the equilibrium positions versus d . It can be seen that there occurs a pitchfork bifurcation at the point PF. It should be noted that with decreasing the separation distance d , as shown in Fig. 3(b), the distance between the two potential wells increases reversely, and the barrier between the wells rises (Fig. 3(a)). It is known that the increase in well distance will lead to a large amplitude of snap-through, but the increase in barrier height implies there needs more excitation energy for realizing the snap-through. Therefore, the separation distance d play a key role for the snap-through and its amplitude.

3. Validation experiments

To demonstrate the advantage of the nonlinear BAEH in harvesting acoustic energy, corresponding validation experiments were carried out. Fig. 4 shows the experimental setups. A DIKASEN KD-721 (RATED POWER: 30 W, SENSITIVITY: 91 dB) loudspeaker and a YAMAHA RX-V375 (RATED POWER: 135 W per Channel) power amplifier were used to generate incident acoustic wave. The noise signal was played in a computer and exported to the amplifier. In experiments the SPL is set to range from 80 dB to 130 dB. The BAEH prototype was composed of a bimorph piezoelectric beam with a tip magnet, a flat plate, a curved plate, a fixture with a fixed magnet (Fig. 4(a)). The tip magnet has the same polarity opposed to that of the fixed magnet. The two stable equilibrium positions are shown in Fig. 4(c). If

the two magnets are removed, the structure becomes a classical AEH, which has a unique stable equilibrium position and is a nearly linear system for small deflection.

As for the piezoelectric beam, its substrate layer is made of stainless steel with a dimension of $175 \times 10 \times 0.12 \text{ mm}^3$. Two piezoelectric patches are bonded on the substrate, which have the same dimension of $5 \times 5 \times 0.15 \text{ mm}^3$. The flat plate made of aluminum alloy with a dimension of $70 \times 70 \times 0.05 \text{ mm}^3$ is attached to the plate's end. As for the magnets, the two neodymium magnets have the same dimension of $12 \times 4 \times 2 \text{ mm}^3$. A data acquisition device (DH5922, DONGHUA) is employed to record output voltage and strain. The sampling rate of responses is $f=2000 \text{ Hz}$. For measurement of SPL, a sound level meter (HT-825, HCJYET) is used.

For the experimental results, the variance of dynamic strain of the beam (σ_ε) and the open-circuit RMS voltage of the piezoelectric patches (V_{rms}) are chosen as the significant quantities. The results of σ_ε and V_{rms} for different SPLs are shown in Fig. 5. It can be found that for the BAEH there appears a sharp increase in σ_ε at SPL=90 dB (Fig. 5(a)), which implies the occurrence of snap-through, or the jumping between the stable equilibrium positions; correspondingly in Fig. 5(b), the V_{rms} has a large increase at the same SPL; thus this SPL is termed as the threshold for occurrence of snap-through (SPL_t), below which the snap-through can't happen, and the BAEH's voltage is at the same level as the linear AEH (Fig. 6). To show the advantage of snap-through, let us increase the SPL a little higher than 90 dB, e.g., SPL=95 dB, then we found that the times of snap-through increased accordingly and several peaks of high voltage appeared in the BAEH (Fig. 7). This relationship suggests that the rise in output voltage mainly is attributed to the increase in occurring times of snap-through. Comparing their RMS voltages, as a whole, we could conclude that the BAEH is preferred to the linear AEH in scavenging acoustic energy for $SPL > SPL_t$.

In order to further study the performances of the BAEH and the linear AEH, their time histories in terms of strain, open-circuit voltage, spectrum of strain and spectrum of voltage are given in Figs. 6-9, where the red line and blue line represent the results of the BAEH and the AEH respectively. At a relatively low SPL (SPL=80 dB), it can

be seen that both harvesters generate a low output voltage, since they are trapped in one of their potential wells (Fig. 6). Then when SPL increases to 95 dB (Fig. 7), it can be observed that in the dynamic voltage of the BAEH there appear some sharp peaks (Fig. 7(b)), which correspond to the jumping between the stable equilibrium positions (Fig. 7(a)). As for spectrum, Figs. 7(c) and (d) show the spectra of the strain response and the output voltage for the BAEH and the AEH, from which we know that the BAEH can transfer the noise energy to a low frequency response by snap-through.

Then for a suitably high sound pressure (SPL=125 dB), the corresponding experimental results are illustrated in Fig. 8. Now the response of the AEH still maintains a fairly low amplitude, whereas that of the BAEH has arrived at a state of coherence resonance, or regularly jumping between potential wells (Fig. 8(a)). From Fig. 8(b) we can see that now there appear dense peaks of voltage in the output of the BAEH, and its maximum voltage can reach 1.8 V, nearly 4 times that of the linear AEH. From their spectra (Figs. 8(c) and (d)), it is evident that the BAEH has a dominantly nearly periodic component in the low frequency region.

In order to show the effect of jumping on the output voltage clearly, we magnify a portion of Fig. 8 and show it in Fig. 9. From the time history of strain (Fig. 9(a)) and the corresponding output voltage (Fig. 9(b)), we find that the jumping in strain can lead to a large increase in the output voltage. Fig. 9(c) shows the corresponding spectra, from which we know that in the BAEH the components of low frequency play a dominant role, owing to the occurrence of coherence resonance.

It should be noted that the separation distance d has an important influence on the stability and performance of the BAEH. Therefore, we performed corresponding experiments. Fig. 10 shows the variations of σ_ε and V_{rms} with d for three SPLs (95 dB, 105 dB and 125 dB). As shown in Fig. 10(a), there appears a large increase of σ_ε for all three SPLs, which implies the occurrence of snap-through; the higher SPL can lead to the larger σ_ε and the higher V_{rms} (Fig. 10(b)). Furthermore, the peaks in Fig. 10(a) suggest that for a given intensity of noise, we can adjust the separation distance d to enable the BAEH to reach coherence resonance and thus generate the

largest output.

4. Conclusions

We proposed a bi-stable acoustic energy harvester for scavenging broadband noise energy. Corresponding theoretical and experimental studies were carried out. From simulations we found that by adjusting the separation distance between the tip and the fixed magnets, the system owned two stable equilibrium positions in the static state and could execute jumping between them under noise environment. The experimental results showed that the BAEH could realize snap-through and reach coherence resonance under sound excitations, which could generate large output voltages. Moreover, according to a given SPL, the separation distance d can be optimized such as to elicit coherence resonance and produce the largest output power.

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Fig. 1. Schematic presentation of the BAEH.

Fig. 2. Geometric configuration of the tip magnet A and the fixed magnet B.

Fig. 3. (a) Potential energy (b) equilibrium positions of the BAEH with versus the tip position for different separation distances.

Fig. 4. Experimental setups: (a) the profile of BAEH (b) the front of BAEH (c) stable positions of BAEH (d) positions of the magnets.

Fig. 5. (a) Variance of strain (σ_ε) (b) open-circuit RMS voltage versus SPL (BAEH and linear AEH).

Fig. 6. (a) Strain (b) voltage (c) strain FFT (d) voltage FFT (SPL=80 dB, BAEH and linear AEH).

Fig. 7. (a) Strain (b) voltage (c) strain FFT (d) voltage FFT (SPL=95 dB, BAEH and linear AEH).

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427 **Fig. 8.** (a) Strain (b) voltage (c) strain FFT (d) voltage FFT (SPL=125 dB, BAEH and linear
428 AEH).

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Fig. 9. (a) Strain (b) voltage (c) strain FFT (SPL=125 dB, BAEH and linear AEH).

Fig. 10. (a) Variance of strain (σ_ϵ) (b) open-circuit RMS voltage versus d (BAEH).

Nomenclature

B_{BA}	flux density generated by magnet B upon magnet A
d	distance between the tip magnet and fixed manget
D_z	electric displacement
e_{zx}	piezoelectric coupling coefficient
E_z	electric field component
EI	bending stiffness
$\mathbf{m}$	magnetic moment vector
$\mathbf{M}$	magnetization intensity
$\mathbf{r}_{BA}$	direction vector
S_x	mechanical strain
T_x	mechanical stress
V	volume of magnet
$w(x, t)$	the transverse displacement of the beam at distance x and instant t

x	distance x from clamp
α	rotation angle of tip magnet
ϵ_{zz}^S	permittivity constant for a stress
μ_0	magnetic permeability constant

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440 **Table 1**

441 Model parameters used for numerical and experimental studies.

Symbol	Parameter	Value
<i>Substrate properties</i>		
L_s	Length	175 mm
b_s	Width	10 mm
h_s	Thickness	0.12 mm
ρ_s	Density	7800 kg/m ³
E_s	Young's modulus	205 Gpa
<i>Flat plate</i>		
L_{Fp}	Length	70 mm
b_{Fp}	Width	70 mm
h_{Fp}	Thickness	0.1 mm
ρ_{Fp}	Density	2400 kg/m ³
E_{Fp}	Young's modulus	72 Gpa
<i>Curved plate</i>		
L_{CP}	Length	300 mm
b_{CP}	Width	250 mm
h_{CP}	Thickness	0.3 mm
ρ_{CP}	Density	2400 kg/m ³
E_{CP}	Young's modulus	2 Gpa

<i>Piezoelectric laminate properties</i>		
L_p	Length	5 mm
b_p	Width	5 mm
h_p	Thickness	0.15 mm
ρ_p	Density	1785 kg/m ³
$E_p(c_{xx}^E)$	Young's modulus	2 Gpa
e_{zx}	Piezoelectric coupling coefficient	23×10 ⁻¹⁰ C/N
ϵ_{zz}^S	Permittivity constant	1.06×10 ⁻¹⁰ F/m
<i>Magnet properties</i>		
m	Mass	1.49 g
A_r	Area	12×4 mm ²
$a(b)$	Thickness	2 mm
B_r	Residual flux density of magnet	1.48 T