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Modeling of Piezoelectric Acoustic Energy Harvester

SIDIK Susilo[1, a], AZMA Putra[b], and KOK Swee Leong[c]

[1]Centre for Advanced Research on Energy, Universiti Teknikal Malaysia Melaka,
Hang Tuah Jaya 76100, Durian Tunggal, Melaka, Malaysia

[a]sidiksoesilo@student.utem.edu.my, [b]azma.putra@utem.edu.my, [c]sweeleong@utem.edu.my

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Abstract. Harvesting ambient acoustics for conversion into usable electricity provides a potential power source for emerging technologies including wireless sensor networks. Acoustic energy harvesters convert energy from acoustic waves to electrical energy. Here acoustic energy harvesting from ambient noise utilizing flexural vibration of a flexible panel is investigated. A flexural vibration from the panel is use to extract more energy from the ambient acoustics where piezoelectric materials of PVDF films are attached around the plate edges. This study found that the energy harvesting can be obtained with a maximum output power of 480 pW at 400 kΩ load resistance.

Introduction

Energy harvesting technology as self-powering sources has been studied theoritically and experimentally [1,2]. In particular, the applications of piezoelectric materials to harvest ambient energies, such as wind flow, water current, and raindrops, have become increasingly interesting [3-5].

Most previous systems harverst acoustic energy at high frequency and/or their harvesting power densities are low [6]. Therefore, it is necessary to investigate a highly efficient acoustic energy harvesting mechanism which can convert a low audible sound energy to electricity.

In this study, a flexible panel with polyvinylidene flouride (PVDF) piezoelectric films has been used to harvest acoustic energy from sound energy. We have previously demonstrated the potential energy could harvested with this metdhology [7]. When the flexible panel is excited by an external sound wave at its eigenfrequency, a resonant standing wave is developed. When PVDF films are attached to the flexible panel, the resonant standing wave excites the vibration motion of the PVDF films, resulting in the generation of electricity.

Methodology

The 31-mode of the piezoelectric materials is adopted to harvest the electric energy. A 31-mode power generator is a beam type piezoelectric energy harvester To simplify the analysis, the generator is considered as a laminated cantilever beam with uniform thickness and width in our model. Fig. 1 shows the laminated piezoelectric material, in which PVDF film is attached to a flexible panel. When the flexible panel is vibrating under external acoustic wave excitation, a corresponding deformation is induced in the PVDF films.

The electrical displacement in the radial direction within the PVDF layer is a function of the stress in the circumferential direction and electric field within the piezoelectric layer. The piezoelectric constitutive relation is expressed as [8]:

$$D = d_{31}T + \varepsilon_{33}E \tag{1}$$

where d_{31} is the piezoelectric constant in the 31 coupling direction z, T is stress in x direction, ε_{33} the electric constant, and E_r is the electric field. The charge collected on the electrode surface can be expressed as the electrical displacement integral in the area of the surface given by

$$Q = b\int_0^{L_b} \left(d_{31}T + \varepsilon_{33}E\right)dx \tag{2}$$

The voltage potential difference between the upper surface and lower surface of the piezoelectric layer is denoted as v. Based on the uniform electrical field assumption, the electric field can be expressed as [9]

$$E = -\frac{V}{t_p} \tag{3}$$

where t_p is the thickness of piezoelectric layer. Substitution of the Eq. 3 into Eq. 2 gives

$$Q = \frac{bt_s d_{31}}{2}[\varphi(0) - \varphi(L_b)] - bL_p\varepsilon_{33}\frac{V}{t_p} \tag{4}$$

where φ is the slope of deflection of the beam and t_s is the thickness of the substrate.

The current, charge, and voltage are all functions of time. The frequency of these period functions depends on the mechanical vibration. The amplitude of the current is that of the charge times the frequency was

$$I = \omega Q \tag{5}$$

The relation between voltage and current for external load, *R*, as an electrical circuit is

$$I = \frac{V}{R} \tag{6}$$

Combining the Eq. 4, Eq. 5, and Eq. 6 the amplitude of the current can be obtained as

$$I = \frac{\omega bt_s d_{31}[\varphi(0) - \varphi(L_b)]}{2\left(1 + bL_p\varepsilon_{33}\dfrac{\omega R}{t_p}\right)} \tag{7}$$

The amount of power harvested by vibrating piezoelectric material depends on the external electrical loading. The harvested power can be maximized when external load resistance is optimized as [10]

$$R_{opt} = \frac{1}{\omega_n C_p}\frac{2\zeta}{\sqrt{4\zeta + k^4}} \tag{9}$$

where k is the piezoelectric coupling coefficient, ζ is the damping ratio, and C_p is the capacitance piezoelectric material. Thus the harvested power can be obtained as

$$P_{opt} = IV = \left(\frac{\omega bt_s d_{31}[\varphi(0) - \varphi(L_b)]}{2\left(1 + bL_p\varepsilon_{33}\dfrac{\omega R_{opt}}{t_p}\right)}\right)^2 R_{opt} \tag{10}$$

Result and Discussion

In this investigation, the piezoelectric material, PVDF, was attached to flexible panel to harvest energy from the acoustic energy. A 125 µm polyester layer was laminated to a 28 µm piezoelectric material. Fig. 1 shows the laminated PVDF film and diagram of acoustic energy harvester. There are three layers with the center layer is the piezoelectric material. The slope diference used was 2 x 10^{-9} m.

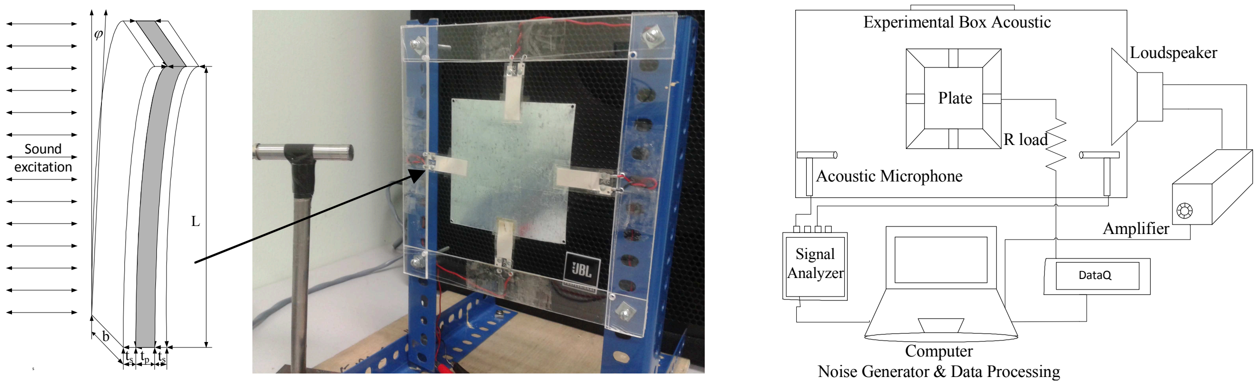

Fig. 1 Diagram of acoustic energy harvester system and experimental setup.

The host panel is a square aluminum panel having dimensions of 10 x 10 cm^2. The speaker (JRX200) was used as the sound source and connected to an amplifier (XLS1000). In this study, the panel was excited with white noise. The output voltage from PVDF was measured using a data acquisition DataQ Instruments. The PVDF film was connected with load resistance and therefore the output power can be obtained.

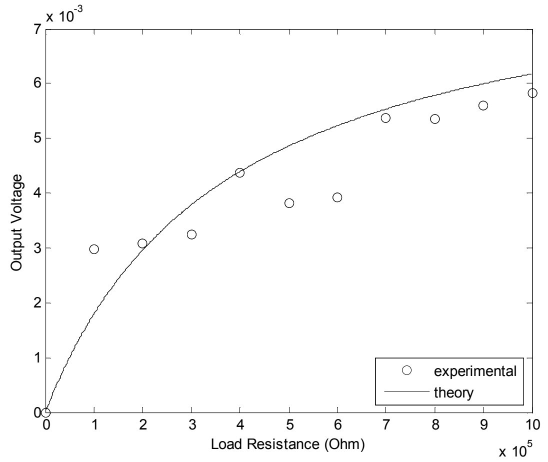

Fig. 2 Measured output voltage delivered to the load resistance.

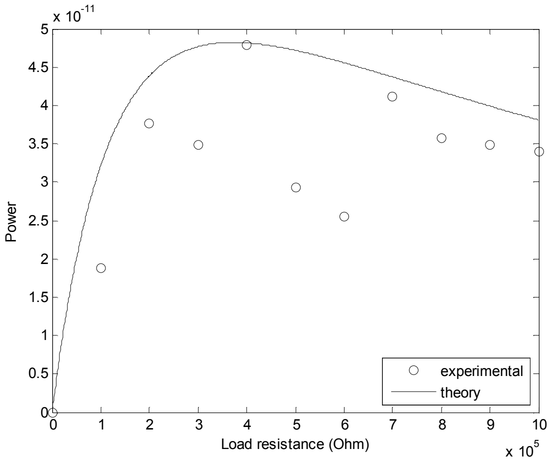

Fig. 3 Measured output power delivered to the load resistance.

Fig. 2 and Fig. 3 show the output voltage and power generated by a single PVDF film delivered to load resistance compared to theory. Acording to Eq. 10 it can be seen that the maximum output voltage of 5.8 mV and the maximum power of 48 pW were obtained. The output voltage and power can be obtained by using Eq. 7 and Eq. 9 and are subtituted to Eq. 6. When the load resistance was increased to reach 400 kΩ, the output voltage increases slowly with an increasing load resistance. The power increases with an increasing load resistance until a critical point and then decreases. This trend was generally followed by the experimental result, although discrepancy occurs at 500 and 600 kΩ. The maximum power is experimentally observed corresponding to a load resistance of 400 kΩ. The value is close to the 380 kΩ which is calculated by Eq. 10. In general, the experimental output voltage and power are in agreement with the calculated ones.

Conclusions

An acoustic energy conversion using piezoelectric film and flexible panel has been discused where the piezoelectric are attached at the plate edges. A model for energy harvesting of the piezoelectric is also presented here to predict the output voltage and the output power of the energy conversion. A maximum output voltage of 5.8 mV and output power of 48 pW were obtained with load resistance of 400 kΩ. The experimental results are in reasonably good agreement with the theory.

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