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Piezoelectric energy harvesting from vibrations induced by jet-resonator system

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ABSTRACT

Inspired by musical instruments that create high amplitude tones corresponding to resonator acoustic modes when subjected to airflow, a new piezoelectric energy harvester for powering the electronic system of aircrafts is developed. It converts the incoming airflow energy into electricity via a piezoelectric transducer during the flight. With the airflow simulated by an air cylinder, prototypes of the developed energy harvester are fabricated and tested. Experimental results show that the curve of sound pressure, corresponding to the first resonator acoustic mode, is a regular sinusoidal pattern. Within the study range of airflow velocity, a linear relationship can be found not only between sound pressure and airflow velocity but also between open circuit voltage and airflow velocity. A power of above 85 mW is released on a passive electric load of 3 kΩ by using a single piezoelectric element of 10 mm diameter at relative airflow velocity of 159 m/s. And the maximum total energy conversion efficiency of the piezoelectric energy harvester is about 1.2‰. It has laid a solid foundation for powering sensors or other devices, thus eliminating a need for batteries.

1. Introduction

As the miniaturized development trend of aircrafts, electrical and intelligence degree become increasingly higher, small physical powers with good electromagnetic compatibility are desperately needed. All kinds of complicated application systems of electronic system (or microelectronics system) also need the power of self-sustaining supply or supplying other energy sources. In addition, the incoming airflow during the flight is a kind of mean flow with remarkable kinetic energy. Based on aero-acoustic principle, the incoming airflow can be used to induce an acoustic field with steady frequency and high power density. The acoustic energy generated aerodynamically can be harnessed and converted into electricity for powering sensors or other devices, thus eliminating the need for their battery replacement. The conversion of acoustic energy to electric power takes place in piezoelectric transducers.

Many scholars have studied fluid energy harvesting devices from the motion of fluid theoretically and experimentally. Allen and Smits placed a piezoelectric membrane or "eel" in the wake of a bluff body and used the von Karman vortex street forming behind the bluff body to induce oscillations in the membrane to generate electricity [1]. Taylor et al. developed an eel structure of piezoelectric polymer to convert mechanical flow energy to electric power [2]. They have focused on characterization and optimization of the individual subsystems of the eel system with a generation and storage units in a wave tank. Sanchez-Sanz et al. accessed the feasibility of using the unsteady forces generated by the Karman Street around a micro-prism in the laminar flow regime for energy harvesting [3]. They presented design guidelines for their energy harvesting devices. Shuguang, Jianping and Lipson have studied ambient wind energy harvesting by using cross-flow fluttering [4]. They proposed and tested a bio-inspired piezo-leaf architecture which converts wind energy into electrical energy by wind-induced fluttering motion. Hernandez, Jung and Matveev have studied acoustic energy harvesting from vortex induced tonal sound in a baffled pipe [5]. Generated sound energy was partially converted into electrical energy by a piezo element. Wang D-A and H-H Ko have developed a new piezoelectric and electromagnetic energy harvester for harnessing energy from flow-induced vibration [6–8]. It converts fluid energy into electric energy by piezoelectric conversion with oscillation of a piezoelectric film. Daming and Ya have developed a mean flow acoustic engine (MFAE) based on the mean flow induced acoustic oscillation effect [9,10]. It converts wind energy and fluid energy in pipeline into acoustic energy which can be used to drive generators without any mechanical moving parts.

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In this paper, a new piezoelectric energy harvester based on aero-acoustic principle and piezoelectric transducer mechanism is developed, which can convert the incoming airflow energy into electricity during the flight [11,12]. It is motivated by the phenomenon occurring in many practical musical instruments such as flutes, organs, and whistles [13]. When a jet is coupled with a resonator, it can lead to excitation of high amplitude tones corresponding to resonator acoustic modes. The cross section view of the piezoelectric energy harvester is shown in Fig. 1. As shown, the piezoelectric energy harvester mainly consists of an annular nozzle, which is comprised of the inlet and clog, an open-closed resonator and a piezoelectric transducer. During flight, when the relatively incoming airflow is guided into the inlet, annular jet stream is formed by the annular nozzle. The annular jet stream issuing from the orifice impinges on the leading edge of the resonator, and then produces a dipole sound source known as edge tone. The sound travels inside the resonator and reflects at the closed end, which finally leads to the formation of a stable standing wave resonance inside the resonator. And the maximum sound pressure is produced at the closed end of the resonator. As a result of the resonator feedback system, the vocal efficiency can be greatly improved. And it can produce stable sound mainly determined by the resonator. When the aforementioned sound pressure is applied to the surface of piezoelectric transducer installed at the closed end of resonator, the piezoelectric transducer can be driven into vibration. Strain can be produced in piezoelectric material. By normal strain, charges are accumulated on both sides of piezoelectric film. Finally, voltage is formed in thickness direction.

This paper focuses on the investigation of energy extraction from the developed piezoelectric energy harvester. The experimental setup used to measure the sound pressure at the closed end of the resonator, open circuit output voltage, output power and energy conversion efficiency of the piezoelectric energy harvester is reported. The results can provide reference for future studies.

2. A model of mechanical and electrical conversion

The model of piezoelectric transducer, shown schematically in Fig. 2, is fabricated from a brass disk bonded with one PZT-5H disk. The piezoelectric ceramic disk, poled along the z-direction, has a radius of r_p, a thickness of h_p. The brass disk has a radius of r_m, a thickness of h_m. The diameter of piezoelectric ceramic disk and brass disk are much larger than their thickness. The piezoelectric transducer is simply supported at $r = r_m$ by a fixture, which vibrates along the z-direction harmonically driven by sound pressure p at a given frequency ω. If the device is vibrated harmonically, there is harmonic output voltage across the two electrodes, which is placed upon the upper and lower surfaces of the transducer.

Considering the axially symmetric flexural motions of the transducer in the z-direction, and the deflection is much smaller than the thickness of the transducer. Consequently, the strain components can be expressed in terms of deflection u_z as follows:

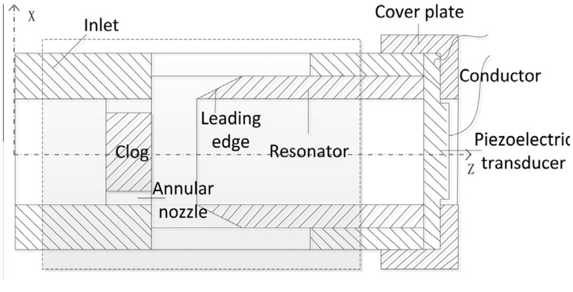

Fig. 1. Cross section view of the piezoelectric energy harvester.

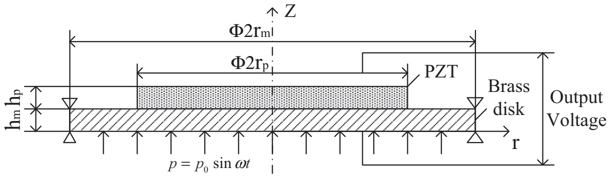

Fig. 2. Schematic diagram of a piezoelectric transducer.

$$S_r = -z\frac{\partial^2 u_z}{\partial r^2}, \quad S_\theta = -\frac{z}{r}\frac{\partial u_z}{\partial r}, \quad S_z = S_{rz} = S_{\theta z} = S_{r\theta} = 0 \tag{1}$$

The convention that a comma followed by an index denotes partial differentiation with respect to the coordinate associated with the index is used. The electric field in the piezoelectric layer corresponding to the electrode configurations, shown in Fig. 2, is of the following components:

$$E_r = 0, \quad E_\theta = 0, \quad E_z = -V/h \tag{2}$$

where V denotes the voltage across the piezoelectric layer.

The relevant constitutive relations for the piezoelectric layer can be written as

$$\begin{cases} S_r = s_{11}^D T_r + s_{12}^D T_\theta + g_{31} D_z \\ S_\theta = s_{12}^D T_r + s_{11}^D T_\theta + g_{31} D_z \\ E_z = -g_{31} T_r - g_{31} T_\theta + \beta_{33} D_z \end{cases} \tag{3}$$

where s_{11} and s_{12} denote the elastic compliances under the constant electric displacement, g_{31} denotes the piezoelectric voltage constant, β_{33} denotes the dielectric impermeability under the constant stress. From (3) we solve for the radial stress T_r, the circumferential stress T_θ, and the transverse electric field E_z:

$$\begin{cases} T_r = \frac{1}{s_{11}^D(1-\sigma_p^2)} S_r + \frac{\sigma_p}{s_{11}^D(1-\sigma_p^2)} S_\theta - \frac{g_{31}}{s_{11}^D(1-\sigma_p)} D_z \\ T_\theta = \frac{\sigma_p}{s_{11}^D(1-\sigma_p^2)} S_r + \frac{1}{s_{11}^D(1-\sigma_p^2)} S_\theta - \frac{g_{31}}{s_{11}^D(1-\sigma_p)} D_z \\ E_z = -\frac{g_{31}}{s_{11}^D(1-\sigma_p)} S_r - -\frac{g_{31}}{s_{11}^D(1-\sigma_p)} S_\theta + \overline{\beta_{33}} D_z \end{cases} \tag{4}$$

where k_p is the electromechanical coupling coefficient, σ_p is Poisson's ratio of piezoelectric element.

$$\sigma_p = -\frac{s_{12}}{s_{11}}, \quad \overline{\beta_{33}} = \beta_{33}(1 + k_p^2), \quad k_p^2 = \frac{2g_{31}^2}{\beta_{33}(s_{11} + s_{12})} \tag{5}$$

By substitution of (1) into (3), we have:

$$\begin{cases} T_r = \frac{-z}{s_{11}^D(1-\sigma_p^2)} \left(\frac{\partial^2 u_z}{\partial r^2} + \frac{\sigma_p}{r}\frac{\partial u_z}{\partial r}\right) - \frac{g_{31}}{s_{11}^D(1-\sigma_p)} D_z \\ T_\theta = \frac{-z}{s_{11}^D(1-\sigma_p^2)} \left(\sigma_p \frac{\partial^2 u_z}{\partial r^2} + \frac{1}{r}\frac{\partial u_z}{\partial r}\right) - \frac{g_{31}}{s_{11}^D(1-\sigma_p)} D_z \\ E_z = \frac{z g_{31}}{s_{11}^D(1-\sigma_p)} \left(\frac{\partial^2 u_z}{\partial r^2} + \frac{1}{r}\frac{\partial u_z}{\partial r}\right) + \overline{\beta_{33}} D_z \end{cases} \tag{6}$$

For the brass layer element, its constitutive relation is given by:

$$\begin{cases} T_r = -\frac{zE}{1-\sigma_m^2} \left(\frac{\partial^2 u_z}{\partial r^2} + \frac{\sigma_m}{r}\frac{\partial u_z}{\partial r}\right) \\ T_\theta = -\frac{zE}{1-\sigma_m^2} \left(\sigma_m \frac{\partial^2 u_z}{\partial r^2} + \frac{1}{r}\frac{\partial u_z}{\partial r}\right) \end{cases} \tag{7}$$

where E and σ_p are the Young's modulus and Poisson's ratio of the metal layer, respectively.

The bending moments per unit length can be written by integrating stress over the dimension z of the layers. From (6) and (7), we get:

$$\begin{aligned} M_r &= \int_0^{h_m+h_p} T_r \cdot z\,dz \\ &= -T_1\left(\frac{\partial^2 u_z}{\partial r^2} + \frac{\sigma_m}{r}\frac{\partial u_z}{\partial r}\right) - T_2\left(\frac{\partial^2 u_z}{\partial r^2} + \frac{\sigma_p}{r}\frac{\partial u_z}{\partial r}\right) - T_3 D_z \end{aligned} \tag{8}$$

$$\begin{aligned} M_\theta &= \int_0^{h_m+h_p} T_\theta \cdot z\,dz \\ &= -T_1\left(\sigma_m \frac{\partial^2 u_z}{\partial r^2} + \frac{1}{r}\frac{\partial u_z}{\partial r}\right) - T_2\left(\sigma_p \frac{\partial^2 u_z}{\partial r^2} + \frac{1}{r}\frac{\partial u_z}{\partial r}\right) - T_3 D_z \end{aligned} \tag{9}$$

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