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Design and analysis of a piezoelectric energy harvester for rotational motion system

Mingjie Guan [a], Wei-Hsin Liao [b,*]

[a] Department of Mechanical and Electrical Engineering, Xiamen University, Xiamen, Fujian, China
[b] Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China

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ABSTRACT

This paper presents a piezoelectric energy harvester for rotational motion applications. The piezoelectric energy harvester is mounted on a rotating system in which the axis of rotation is more or less parallel to the Earth's surface. As the harvester rotates, the piezoelectric elements in the energy harvester are repeatedly deformed to generate electrical power. A novel design of the harvesting structure is proposed in this paper and analyzed theoretically. Experiments were conducted to validate the concept and analysis. Power output of 83.5–825 μW is achieved at the rotating frequencies of 7–13.5 Hz with a prototype of rotational energy harvester. Results show that the harvester can offer sufficient power for low-power wireless transmitters.

1. Introduction

In recent years, with the development of the low-power wireless sensor network, to supply power for these low-power electronic devices is drawing more and more attentions. Knight et al. [1] reviewed the state-of-the-art technology in the field of both energy storage and energy harvesting for sensor nodes. In order to overcome the drawbacks of chemical batteries with their limited lifespan, maintenance difficulties and pollution problems, harvesting the energy from the ambient environment has been of great concern. Various kinds of energy sources have been considered for energy harvesting, including thermoelectric energy [2], photovoltaic energy [3], and kinetic energy [4]. Mitcheson et al. [4] reviewed the principles and related work in kinetic energy harvesters and discussed trends, suitable applications, and future developments. Considering the kinetic energy, piezoelectric energy harvesting schemes have attracted lots of concerns due to their relatively high power densities and compact structures. Lee and Choi [5] designed and investigated a piezoelectric stain energy harvester, which could be mounted inside a rotating tire. Yang and Zu [6] studied an energy harvester, named high-efficiency compressive-mode piezoelectric energy harvester. It was shown in the paper that the compressive mode is preferred than the commonly-used bending mode and tensile mode due to the superior compressive strength of piezoceramics. Fan et al. [7] designed and verified a beam-roller piezoelectric energy harvester that can scavenge energy from both sway and bi-directional vibrations. Saadon and Sidek [8] reviewed researches on vibration-based piezoelectric energy harvesters and it was stated piezoelectric harvesters had good potentials to power small-scale electronic devices in the near future.

Harvesting energy from rotational motion (i.e., rotating machinery, wheels, shafts, *etc.*) is one of kinetic energy harvesting technologies, but has special characteristics that need to be considered [9]. Some researches have been done to harvest the rotational energy with piezoelectric materials. Roundy and Tola [9] examined harvesting devices that rotate through the Earth's gravitational field and the axis of rotation is parallel to the Earth's surface. Their simulations predicted power of approximate 100 μW at 60 mph. Manla et al. [10] developed a non-contact piezoelectric energy harvester to generate power from magnetic forces due to the effect of the centripetal force. However, their output power ranging from 0.2 μW to 3.5 μW is quite low. Gu and Livermore [11] developed passively self-tuning piezoelectric rotational harvesters using resonant method. In their designs, the resonant frequency of the harvester well matched the rotating frequency ranged from 4 Hz to 16.2 Hz. Their output power was 60 μW at 6.2 Hz and 123 μW at 15.2 Hz. However, one problem with the harvester is that the mounting radius of the harvester was determined experimentally, so that it is difficult to implement the harvester in real applications. Moreover, the piezoelectric element is easy to break due to the frequent impact during operation. Hsu et al. [12] developed a computational code based on finite element method to analyze

* Corresponding author.
E-mail address: whliao@cuhk.edu.hk (W.-H. Liao).

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the self-frequency-tuning piezoelectric energy harvester proposed by Gu and Livermore [11]. However, in their study the problems with the structure proposed by Gu and Livermore [11] remain unsolved. Khameneifar et al. [13] presented design and experiments of a piezoelectric mounted rotary flexible beam that could be used as an energy harvester for rotational motion applications. However, their prototype can generate an output voltage higher than 5 V only at a high rotating speed above 18.3 Hz. Yang et al. [14] demonstrated a means to utilize ball-impact-induced resonance to harvest energy from available wind on a small scale. However, the experimental results of their prototype were shown only under one particular frequency, 200 r/min or 0.5305 Hz. More experimental results should be shown to convince people that their design could work under other rotation frequencies. Janphuang et al. [15] explored an approach for evaluating the efficiency of impact harvesters by implementing a rotational flywheel to quantify the mechanical input energy. However, no theoretical analysis of the structure was performed. This paper is aimed at introducing an innovative design of piezoelectric rotational energy harvester which can generate a high output voltage at low rotating speed with high output power in a wide rotating speed range.

The organization of this paper is as follows. In Section 2, the system design of the piezoelectric energy harvester is presented. In Section 3, the dynamic equations describing the motion of the structure are obtained. Expressions describing the voltage and the power output of the piezoelectric energy harvesting system are presented. In Section 4, experiments are conducted to demonstrate the performances of the energy harvester and compared with the theoretical results. The conclusions and discussions are finally made in Section 5.

2. System design

For a given load profile, a cantilever beam can be used to increase the strain delivered to a piezoelectric element on the surface of the cantilever [16]. High robustness can be reached by means of a metal substrate as auxiliary structure to attach the seismic mass and to realize the clamping. Utilizing the cantilever beam structure, a conventional rotational energy harvester in which the axis of rotation is more or less parallel to the Earth's surface is shown in Fig. 1 [9,11,12].

Although a rotating system offers a large amount of mechanical energy, extreme centrifugal forces and accelerations at high speed complicate a reliable design. When the object rotates at a constant speed ω_0, the centrifugal force F_{cent} of the rotating object is given by

$$F_{cent} = m_0 \omega_0^2 r_0 \tag{1}$$

where m_0 is the mass of the rotating object and r_0 is the radius of the rotation. The centrifugal force is oriented away from the axis of the rotation.

As the axis of rotation is more or less parallel to the Earth's surface, when the structure rotates, the rotating beam and mass will be subjected to a ±1g excitation from the Earth. In a conventional rotating cantilever beam, the radius of the rotation is equal to or larger than the beam length. When the beam structure rotates at a normal frequency (e.g., 7 Hz for a rolling vehicle wheel), the amplitude of the centrifugal force will be much larger than that of the gravitational force. Thus, only small transverse vibration of the beam could be generated.

In order to increase the beam vibration amplitude, our design is to reduce the amplitude of centrifugal force to be comparable with the amplitude of the gravitational force by decreasing the radius of the rotation r_0. The schematic of our design is shown in Fig. 2. In principle, the mass center of the rotating beam structure coincides with the center of rotation in zero gravity. There is a constrained frame adjacent to the seismic mass to constrain the vibration amplitude of the structure. The gaps between the constrained frame and seismic mass are symmetric with the radiating center line. With the constraint of the rotation radius, the amplitude of the centrifugal force will be decreased to be comparable with the gravitational force and will be much smaller than that in a conventional structure as shown in Fig. 1.

Fig. 3 shows four beam positions during rotation. From Fig. 3 it can be seen that the gravitational force on the seismic mass causes sustained oscillation in the beam when the beam is rotating. At position 1, the piezoelectric element "Piezo A" is compressed and at position 3 is stretched.

3. Modeling and analysis

Under the assumption that the rotating beam vibrates in small amplitude, the mass of the beam can be approximately treated as an object moving back and forth in a linear motion. The restoring force of a bended cantilever beam acted on the seismic mass can be regarded as a spring force in the transverse direction. Therefore, the structure can be represented as a schematic shown in Fig. 4.

An imaginary massless rigid rod is pivoted about point O. The equivalent mass m slides along the rod and is connected to end point B of the rod by an equivalent spring of stiffness k and an equivalent damper of damping coefficient c. When the equivalent mass m is at the point O, the spring will be at its original length. In Fig. 4, the spring is stretched by length u. A torque $\tau(t)$ is applied to the end point B of the rod to make the structure rotate.

The position vector of the mass m in the XY inertial coordinates can be written as

$$\underline{r} = u \sin\theta \cdot \hat{i} - u \cos\theta \cdot \hat{j} \tag{2}$$

where $\hat{i}$, $\hat{j}$ are the unit vector co-directional with the x, y axes. To obtain the kinetic energy expression, the velocity vector can be represented as follows:

$$\dot{\underline{r}} = (\dot{u} \sin\theta + \dot{\theta} u \cos\theta) \cdot \hat{i} - (\dot{u} \cos\theta - \dot{\theta} u \sin\theta) \cdot \hat{j} \tag{3}$$

The kinetic energy of the system can be expressed as

$$T = \frac{1}{2} m \dot{r}^2 = \frac{1}{2} m (\dot{u}^2 + \dot{\theta}^2 u^2) \tag{4}$$

The potential energy is given by

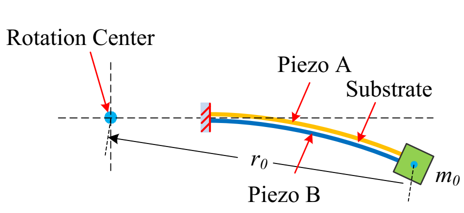

Fig. 1. Schematic of a conventional rotating cantilever beam.

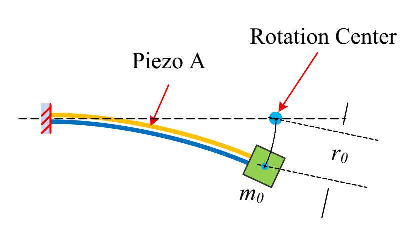

Fig. 2. Schematic of our designed rotating cantilever beam.