A ROTATION ENERGY HARVESTER USING CANTILEVER BEAM AND MAGNETOSTRICTIVE/PIEZOELECTRIC COMPOSITE TRANSDUCER

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Abstract: This paper presents an energy harvester to transform the rotation energy of a host structure into electrical power. The harvester is composed of a cantilever beam, a magnetostrictive/piezoelectric laminate magnetoelectric (ME) transducer and a magnetic circuit. The harvester is attached to a host structure rotating around a horizon axis, and the alternation of the gravity component while rotation causes the beam to vibrate along its transverse direction. The vibrating beam induces an alternating field applied on the ME transducer, which generates electrical power. A prototype is fabricated and tested and a power of 157.4μW is achieved at a rotating rate of 588rpm.

Keywords: rotation energy harvester, magnetoelectric transducer, cantilever beam

INTRODUCTION

The majority of wireless sensors are reliant on a variety of batteries for energy supply. However, these batteries impose a maintenance burden of recharging or replacement if a long sensor lifetime is required. For this reason, solutions that harvest energy from ambient environment are receiving a considerable mount of interest from many researchers as alternative energy sources [1, 2]. Light, heat and/or mechanical motion, are traditionally considered as potential energy sources. Of the various energy types, kinetic energy is particularly attractive for its abundance [3]. Kinetic energy is typically converted into electrical energy using electrostatic, electromagnetic or piezoelectric transduction mechanisms. Recently, a magnetoelectric (ME) transducer has been applied successfully in vibration energy harvesting [4]. The ME transducer employed in the proposed energy harvester is a magnetostrictive/piezoelectric laminate composite.

Energy harvesting from ambient mechanical motions especially linear vibration has been extensively and intensively studied, while only a few researches on energy-harvesting from rotation have been reported [5]. For many important applications, including tire pressure sensing and condition monitoring of machinery, host structures do undergo continuous rotation. In these cases, if the associate vibration acceleration is extremely low, a rotation energy harvester is more practical than a vibration one excited by ambient vibration.

This paper proposes a rotation energy harvester which can be used in either off-axis or on-axis cases. In previous reports, theoretical analyses of a cantilever beam undergoing rotation have been performed [6]. However, they focused on the controllability of the beam rather than using a cantilever beam to harvest energy from rotation for powering wireless sensors and low power electronic devices. In this paper, the influences of the rotation to the energy harvesting are investigated. A prototype employing a cantilever beam and a ME transducer is fabricated, and the dynamics characteristics and electrical output performance of the prototype are also tested. The prototype can produce a power of 157.4μW across a 3.3 MΩ resistor at a rotation rate of 588rpm.

ANALYTICAL MODEL

The schematic of the proposed rotation energy harvester is shown in Fig.1. The harvester is composed of a ME transducer, a cantilever beam, and a magnetic circuit. The transducer is a laminate structure made up of two Terfenol-D layers and one PZT layer. The piezoelectric layer is polarized in its thickness direction, and the magnetostrictive layers are magnetized along the longitudinal direction. The magnetic circuit is arranged on the free end of the beam and composed of two tungsten frames, two magnetic yokes and four pieces of rectangular NdFeB magnets. The magnets are aligned with their poles as shown in Fig.1. The magnetic circuit induces a concentrate magnetic field through the air gap between the magnets and also functions as tip mass of the cantilever beam. The ME transducer is placed in the air gap and fixed to the frame of the harvester. When the harvester is attached either off axis or on axis to a host rotating around a horizon axis, the tip mass causes the beam to vibrate along transverse direction due to the alternation of the gravity component while rotation. The vibrating beam induces an alternating magnetic field applied on the transducer, which causes the ME transducer to generate electrical power.

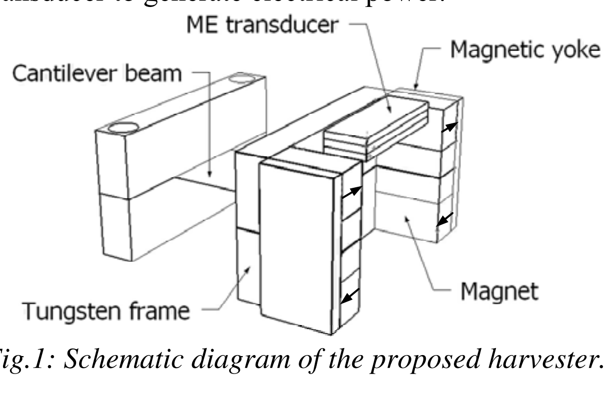

Fig.1: Schematic diagram of the proposed harvester.

The rotation energy harvester can be modeled as a hub-beam system that an elastic cantilever beam built in a rigid hub as shown in Fig.2.

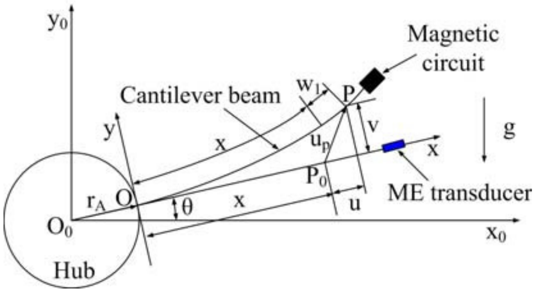

Fig.2: Structural model of the hub-beam system

The coordinates systems O_0 - X_0Y_0 and O - XY in Fig.2 are defined as the inertial frame and the reference frame, respectively. The hub rotates around a horizontal axis and the beam rotates along with the hub. The parameter θ is the angular rotation of the hub and m_t is the tip mass at the end of the beam. The center point of the tip mass is assumed to be superposed with the end of the beam. P_0 is an arbitrary point of the beam, and x is the location of P_0 when not deformed. After deformation, the point P_0 moves to point P, and u_P is denoted as the flexible deformation vector at point P with respect to the O - XY system. The location vector of P in the O_0 - X_0Y_0 system is presented by r_P.

The kinetic energy of the harvester with the cantilever beam and the tip mass can be written as

$$T=\frac{1}{2}\int_0^L \rho_l \dot{r}_P^T \dot{r}_P dx \quad (1)$$

where $\dot{r}_P$ represents the first-order partial derivative with respect to t, L is the length of the beam and ρ_l is defined as

$$\rho_l=\left[\rho A+m_t\delta_0\left(x-L\right)\right] \quad (2)$$

where ρ is the density of the beam, A is the cross section, and $\delta_0\left(x\right)$ is the Dirac function. From Eq.1, the kinetic energy variation δT can be computed.

By using Euler–Bernoulli theory, the elastic potential energy of the beam can be expressed as

$$\Pi_E=\frac{1}{2}\int_0^l EAw_1'^2 dx+\frac{1}{2}\int_0^l EIw_2''^2\ dx \quad (3)$$

where I is the beam area moment of inertia, E is the Young's modulus, w_1 is the axial extension quantity and w_2 is the transverse deformation, w_1' and w_2'' represent the first- and second- order partial derivative with respect to x, respectively. From Eq.3, the elastic potential energy variation $\delta\Pi_E$ can be computed.

The virtual work of the magnetic force of the magnetic circuit is given by

$$\delta W_m=\left(\Theta F_m\right)^T \delta r_t \quad (4)$$

where F_m is the magnetic force vector defined in the reference frame, r_t is the location vector of the tip mass in the O_0 - X_0Y_0 system, and Θ is the direction cosine matrix that is the O - XY system with respect to the O_0 - X_0Y_0 system.

The variation of the potential energy of the harvester in the reference frame can be given as

$$\delta\Pi=\delta\Pi_E+\delta W_m \quad (5)$$

The virtual work of the gravity and the traditional damping force are given by

$$\delta W_g=\left(\Theta F_g\right)^T \delta r_p \quad (6)$$

and

$$\delta W_c=\left(\Theta F_c\right)^T \delta r_p \quad (7)$$

where the parameter F_g and F_c are the gravity vector and damping force vector defined in the O - XY system, respectively. The virtual work of these nonconservative forces can then be given as

$$\delta W_F=\delta W_g+\delta W_c \quad (8)$$

The governing equations of motion can now be obtained through application of the Hamilton principle

$$\int_{t_1}^{t_2}\left(-\delta T+\delta\Pi-\delta W_F\right)dt=0 \quad (9)$$

By substituting δT, $\delta\Pi$ and δW_F into Eq.9, the equations of motion of the beam can be written as

$$\mathbf{M}\ddot{\mathbf{q}}+\mathbf{G}\dot{\mathbf{q}}+\left(\mathbf{K_0}+\mathbf{K_d}\right)\mathbf{q}=\mathbf{Q} \quad (10)$$

where $\mathbf{q}$ is the generalized co-ordinate of the elastic beam, $\mathbf{M}$ and $\mathbf{Q}$ are the generalized mass and force matrices, $\mathbf{K_0}$ and $\mathbf{K_d}$ are the conventional stiffness and dynamic stiffness matrices, respectively.

After being discretized by the assumed method, Eq.10 can be solved by Linstedt-Poincaré method [4], and it can be predicted that due to the rotation the equivalent fundamental frequency of the beam increases and is always beyond the rotation frequency, and the maximum amplitude is achieved at the second-order super-harmonic resonance. Prediction of the transverse displacement of the magnetic circuit, y_t, at the second-order super-harmonic resonance is shown in Fig.3

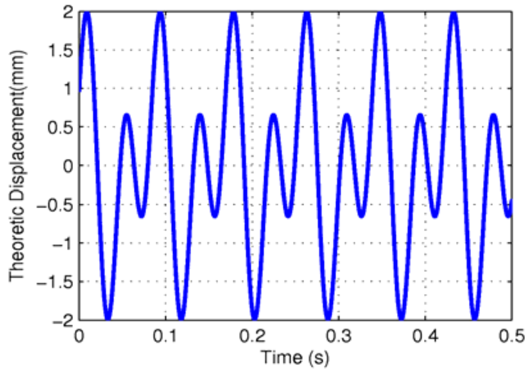

Fig.3: Prediction of the transverse displacement of the magnetic circuit versus time at the second-order super-harmonic resonance

As the magnetic circuit moves relative to the ME transducer, the transducer undergoes magnetic field variations, and the changing magnetic field causes the magnetostrictive layers to generate stress. The stress is then transmitted to the piezoelectric layer, which generates electrical power. The induced magnetic field on the ME transducer, $B(y_t)$, can be solved by the Finite Element Analysis (FEA) simulation.

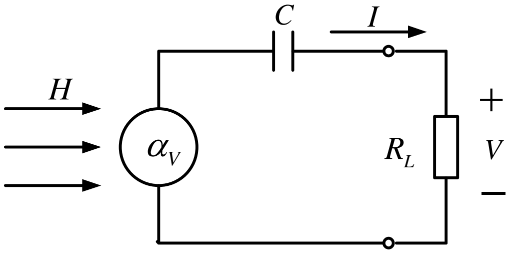

Fig.4: ME transducer equivalent circuit

The equivalent circuit of the transducer is as shown in Fig.4, H is the external magnetic field including bias magnetic field and alternative magnetic field; α_V is the ME coefficient, and $\alpha_V = \partial V_{ME} / \partial H$ with V_{ME} the induced ME voltage; I is the electric current; R_L is the resistance of the external load, C is the equivalent capacitance of the ME transducer. The induced ME voltage of the ME transducer is

$$V_{ME}(t) = \alpha_V H(t) = \alpha_V B(y_t(t)) / \mu_0 \qquad (11)$$

where μ_0 is the permeability of vacuum.

FRABRICATION

Fig.5 shows the photograph of the proposed energy harvester. The ME transducer is a sandwich of one PZT layer ($12 \times 6 \times 0.8\, mm^3$) bonded between two Terfenol-D layers ($12 \times 6 \times 1\, mm^3$).The cantilever beam ($12 \times 14 \times 0.25\, mm^3$) is made up of beryllium bronze. The remnant flux density of the magnets ($5 \times 6 \times 10\, mm^3$) is 1.2T, being poled in the $5\, mm$ direction. The total weight of the magnetic circuit is $77.4\, g$. The width of the air gap between the magnets is $14.2\, mm$. The measured ME voltage coefficient is $102.4\, mV / Oe$.

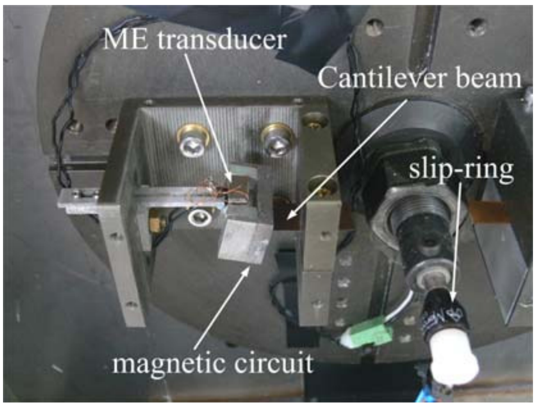

Fig. 5: Photograph of the proposed energy harvester.

EXPERIMENT

The experiment setup is shown in Fig.6. The prototype is screw-mounted on a wheel with a radial distance of 50mm from the axis. The wheel is driven by an AC servo-actuator, and the rotation velocity can be set by a human machine interface system from Delta, Inc. The wiring to the rotary assemble on the wheel is achieved using a slip-ring from Mercotac, Inc. The two lead wires from the prototype are connected to the “rotor” of the slip-ring. There is an internal mechanism to electrically connect the terminals on the “rotor” to the “stator”. Then the signals from the “stator” are wired out. The output voltage is measured and stored by a Tektronix TDS2022B digital storage oscilloscope.

Fig.6: Experiment set-up

The peak output voltages without load versus rotation frequency are shown in Fig.7. The maximum open-circuit peak-to-peak voltage achieves 126V at the second-order super-harmonic resonance, when the rotation frequency is 9.8Hz (588rpm). The prediction of the second-order super-harmonic resonance frequency is 11.8Hz which is 2Hz higher than the actual value. There are several possible reasons for this discrepancy. First, the actual vibration mode of the cantilever beam undergoing rotation is different from the assumed mode, which leads to inevitable deviation in the equivalent stiffness and the resonance frequency as well. Second, the mean length of the beam is longer than that taken in the analytical modal since the tip mass is actually also subject to deformation which is ignored in this paper.

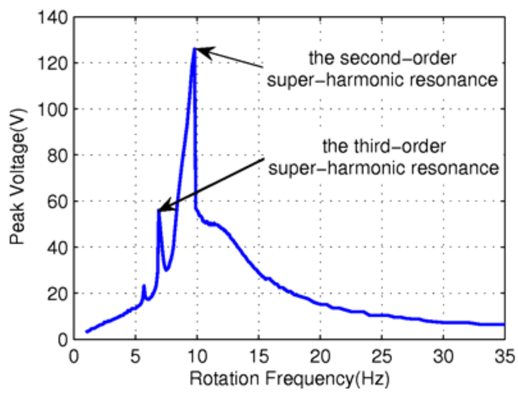

Fig.7: Measured peak voltage free of load versus rotation frequency

Fig.8 illustrates the measured open-circuit voltage versus time, and the maximum peak voltage is 126V.

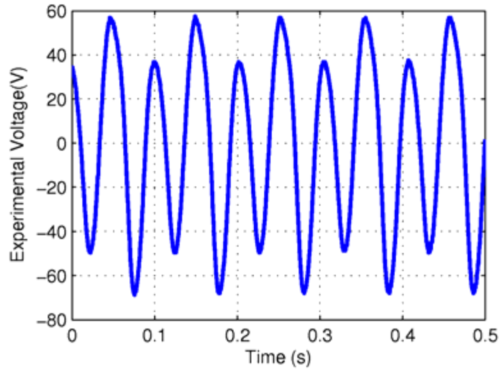

Fig.8: Measured peak voltage free of load

Because the output voltage waveform of the load is not a pure sine wave, the formula

$$P = (1/T)\int_0^T \left(v(t)^2/R\right)dt \qquad (12)$$

is involved to calculate the load power, where $v(t)$ is the voltage of the load resistance, R is the load resistance and T is the period of $v(t)$. The voltage and power across resistive loads are shown in Fig.9, and the maximum output power reaches 157.4μW across a 3.3MΩ resistor.

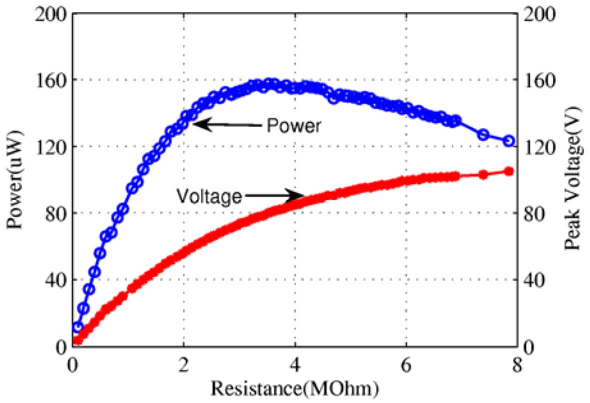

Fig.9: Experimental power and voltage versus load resistance.

CONCLUSION

This paper presents a rotation energy harvester to scavenge energy from continuous rotation of the host using a cantilever beam and a ME transducer. The governing equations are driven by Hamilton principle to investigate the influences of the rotation to the energy harvesting. A prototype has been fabricated and tested, and the experimental results are approximately in agreement with the analytical results. The prototype produced a power of 157.4μW across a 3.3 MΩ resistance at a rotation frequency of 9.8Hz (588rpm).

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