A Vibration Energy Harvester Using Magnetostrictive/Piezoelectric Composite Transducer

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Abstract—An energy harvester is presented to convert ambient mechanical vibration into electrical energy. The harvester consists of a cantilever beam, a magnetic circuit and a magnetostrictive/piezoelectric laminate magnetoelastic (ME) transducer. The magnetic circuit is arranged on the free end of the beam and produces a concentrated flux gradient. When the harvester is excited, the magnetic circuit moves relative to the ME transducer. The ME transducer undergoes magnetic field variations and produces a power output. The nonlinear vibration performances of the harvester are studied using the Lindstedt-Poincaré method, and the electrical-output performances of the harvester at resonance are analyzed. A prototype has been fabricated and tested. The experimental results are in agreement with the analytical results. The prototype produces a power of 2.11 mW for an acceleration of 1 g at frequency of 51 Hz.

I. INTRODUCTION

With the advancement in low power very large scale integration design and CMOS fabrication, the power consumption of wireless sensors has reduced to the order of μW to mW level [1]. Energy harvesting is receiving a considerable amount of interest as a means for powering wireless sensors. Researchers are working on alternative energy sources like solar, thermal, acoustics, and vibration [2, 3]. Among these alternative sources, ambient vibration is particularly attractive because of its abundance. Ambient vibrations is typically converted into electrical energy using electromagnetic, piezoelectric, electrostatic, and ME transducers [4]. Magnetostrictive materials have high energy density and high magneto-mechanical coupling factor. It is reported that the energy harvested per unit volume in the device of the magnetostrictive/piezoelectric-based harvester exceeds those using other energy conversions at the same low frequency and vibration acceleration [5]. This paper presents a vibration energy harvester with a cantilever and a Terfenol-D/PZT/Terfenol-D laminate composite. The nonlinear vibration and electrical output performances of the harvester are analyzed in this paper. A prototype is fabricated which can produce a load power of 1.055 mW across 564.7 kΩ under a resonant vibration of about 51 Hz with 1 g (1 g = 9.8 ms⁻²) acceleration.

II. HARVESTER STRUCTURE AND MODELLING

The schematic diagram of the proposed energy harvester is illustrated in Fig. 1. The harvester consists of a cantilever beam, a magnetic circuit, and a ME transducer. The magnetic circuit is made up of four rectangular NdFeB magnets and three magnetic yokes. The ME transducer is a sandwich of one PZT layer bonded between two Terfenol-D layers and is fixed on the housing of the harvester. The Terfenol-D layers are magnetized along the longitudinal direction, and the piezoelectric layer is polarized in its thickness direction. Due to the flux gradient produced by the magnets, the ME transducer undergoes magnetic field variations under the excitation of a vibration acceleration. Therefore, the ME output is induced in the ME transducer.

The harvester can be described as a mass-spring-damper system, as shown in Fig. 2, where m is the mass of the magnetic circuit; k is the equivalent stiffness of the cantilever; b is the mechanical damping coefficient; \( F_m(z) \) is the magnetic force of the magnetic circuit; \( z_f \) is the vertical displacement of the frame; \( z \) is the vertical displacement of the mass relative to the frame, and the origin of the z-coordinate is established at the center point of the mass when the structure is situated at the static equilibrium position.

The magnetic force of the magnetic circuit, \( F_m(z) \), is...
nonlinear, thus the vibration of the structure is nonlinear. $F_m(z)$ can be expressed by the power series for the convenience of a nonlinear vibration analysis:

$$F_m(z) = \sum_{n=0}^{N} a_n z^n.$$  \hspace{1cm} (1)

where $a_n$ is constant. For a sinusoidal excitation $\ddot{z}(t) = -A \cos(\alpha t + \theta)$, where $\ddot{z}$ is the input acceleration; $A$ is the input acceleration amplitude; and $\omega$ and $\theta$ are the angular frequency and the phase angle, respectively, the governing dynamic equation of motion for this system can be determined from Newton’s Second Law as

$$m \ddot{z} + b_m \dot{z} + k z + \sum_{n=1}^{N} a_n z^n = m A \cos(\alpha t + \theta).$$  \hspace{1cm} (2)

Because $N$ is not greater than 5 in many nonlinear systems, the dynamic equation can be approximated as

$$m \ddot{z} + b_m \dot{z} + (k + a_1) z + \sum_{n=2}^{5} a_n z^n = m A \cos(\alpha t + \theta).$$  \hspace{1cm} (3)

Equation (3) can be rewritten as

$$\ddot{z} + 2 \xi \omega_0 \dot{z} + \omega_0^2 z + \frac{\xi}{m} \sum_{n=2}^{5} a_n z^n = \varepsilon A \omega_0^2 \cos(\alpha t + \theta),$$  \hspace{1cm} (4)

where $\omega_0 = \sqrt{(k + a_1)/m}$ is the primary natural frequency of the system; $\xi = \frac{b_m}{2 \sqrt{(k + a_1)m}}$ is the damping ratio; $\varepsilon = 1/\omega^2_0$ is a small positive parameter.

Equation (4) can be solved by the Lindstedt-Poincaré method at the primary resonance [6, 7]. The first-order approximate solution to (4) is

$$z(t) = \beta \cos \omega_0 t + \frac{a_1 \beta^3}{6 m \omega_0^5} \cos 2 \omega_0 t + \frac{4 a_1 \beta^3}{128 m \omega_0^5} \cos 3 \omega_0 t + \frac{a_1 \beta^4}{120 m \omega_0^7} \cos 4 \omega_0 t + \frac{a_1 \beta^5}{384 m \omega_0^9} \cos 5 \omega_0 t,$$  \hspace{1cm} (5)

where $\beta$ is solved by

$$(2 \xi \beta)^2 + \left( \frac{6 a_1 \beta^3 + 5 a_1 \beta^5}{8 m} \right)^2 = A^2.$$  \hspace{1cm} (6)

When the harvester is excited, the ME transducer undergoes magnetic field variations. The induced magnetic field on the ME transducer, $B(z)$, can be solved by the Finite Element Analysis (FEA) simulation. Assuming the expression of $B(z)$ is

$$B(z) = f(z).$$  \hspace{1cm} (7)

From (5), the relation between $B$ and $t$ at resonance, $B(t)$, can be obtained as

$$B(t) = f(z(t)).$$  \hspace{1cm} (8)

When the ME transducer vibrates under free-free boundary conditions at low frequency, the ME voltage coefficient, $a_i$, is an approximate constant [8]. The open-circuit voltage of the ME transducer is

$$v(t) = a_i B(t)/\mu_0,$$  \hspace{1cm} (9)

where $\mu_0$ is the permeability of vacuum.

III. FABRICATION AND SIMULATION

A. Prototype Fabrication

Fig. 3 shows the photograph of the prototype. The schematic diagram of the cantilever beam and magnetic circuit is shown in Fig. 4. The cantilever beam is made up of 10×10×0.5 mm³ beryllium bronze. The aluminum fixing plate is designed in a U-shape and attached to the free end of the beam. The thickness of the fixing plate is 1 mm, and the other dimensions are illustrated in Fig. 4. The remnant flux density and the relative permeability of the NdFeB magnets (10×6×5 mm³) are 1.2 T and 1.05, respectively. The magnet distance between the upper side and the lower side is 2.5 mm and that between the left side and the right side is 14 mm. The material of the magnetic yoke 1 (14.5×10×1.5 mm³) and the magnetic yoke 2 (14×10×2 mm³) are mild steel. The ME transducer is a sandwich of one PZT layer (12×10×1 mm³) bonded between two Terfenol-D layers (12×10×1 mm³).

B. Simulation

Based on the theoretical analysis in Section II, the
expression of $F_m(z)$ and $B(z)$ need to be determined. Inasmuch as the theoretical analysis of the magnetic field and the magnetic force is difficult, we use the Ansoft’s Maxwell 2D to determine the expression of $F_m(z)$ and $B(z)$. And the 2D Field Simulator’s transient solver is employed to simulate the magnetic circuit moving relative to the ME transducer. When the Terfenol-D layers are assigned the material properties, the relative permeability should be set to 1 for analyzing the magnetic field of the ME transducer because the magnetic field of the magnetostrictive constitutive equations is in the air. However, for analyzing the magnetic force, the $B$-$H$ characteristic of Terfenol-D should be defined by fitting the curve given by the manufacturers.

The ME transducer induces the magnetic field by the upper and lower Terfenol-D layers. The induced magnetic field of the upper and lower Terfenol-D layers is different because the magnetic field distribution of the air gap is nonuniform. On the other hand, the Terfenol-D material elongates both in the forward and reverse magnetic field. Therefore, the induced magnetic field of the ME transducer can be defined by calculating the absolute value of the magnetic fields induced by the two Terfenol-D layers respectively and taking the average of them.

Because the ME voltage of the ME transducer by the $y$-directional magnetic field component is greater than that by the $x$ or $z$ directional magnetic field components [8], we ignore the influence of the $x$ and $z$ directional magnetic field components. Otherwise, the magnetic flux density is variable along the $y$-direction, thus we regard the average magnetic flux density of the $y$-direction, $B$, as the induced magnetic flux density of the ME transducer. $B$ can be computed by the field calculator of the simulation software. Fig.5a illuminates the FEA predictions of $B$ versus the displacement of the ME transducer. Fig. 5b shows the FEA predictions of the magnetic force of the ME transducer ($F_m$) versus the displacement of the ME transducer.

The relative position of the ME transducer and the magnetic circuit at the static equilibrium has an important effect on the power output of the ME transducer. It is necessary to determine the optimal initial position of the ME transducer at the static equilibrium, which makes the ME transducer induce larger magnetic field variations at a smaller displacement. This initial position can be set at a distance of 7.9 mm from the center of the magnetic circuit, where the magnetic force in the negative direction is maximal. In this position, the slope of $B$ with respect to the displacement is higher, which indicates that the ME transducer can experience larger magnetic field variations at the same vibration amplitude. When the ME transducer is placed at the position of the negative maximal magnetic force, the primary curves in Fig. 6 show the magnetic force and the induced magnetic flux density to the ME transducer versus displacement. It can be seen from Fig. 6 and Fig. 5 that Fig. 6 can be obtained by translating the longitudinal axis of Fig. 5 to a distance of $+7.9$ mm from the origin of coordinate. The magnetic force expression of the magnetic circuit, $F_m(z)$, and the expression of the induced magnetic flux density of the ME transducer, $B(z)$, can be obtained by the method of curve fitting. As the maximal vibration amplitude does not exceed 3 mm, we only fit the curves over the range of $-3$ mm to $+3$ mm. The fitting curves are also illustrated in Fig. 6. The expressions of $B(z)$ and $F_m(z)$ are given by

$$B(z) = \sum_{n=0}^{3} b_n z^n,$$  \hspace{1cm} (10)

where $b_0=0.1959 \ T$, $b_1=37.63 \ T/m$, $b_2=-495.4 \ T/m^2$, $b_3=-1.0151 \times 10^4 \ T/m^3$; and

$$F_m(z) = \sum_{n=0}^{5} a_n z^n,$$  \hspace{1cm} (11)

where $a_0=3.458 \ N$, $a_1=96.88 \ N/m$, $a_2=-3.623 \times 10^5 \ N/m^2$, $a_3=-5.494 \times 10^6 \ N/m^3$, $a_4=9.621 \times 10^8 \ N/m^4$, $a_5=-2.292 \times 10^{12} \ N/m^5$.

IV. RESULTS AND DISCUSSION

After the expressions of $B(z)$ and $F_m(z)$ are solved, the vibration and electrical-output performances of the harvester can be obtained by the theoretical analysis in Section II. From (5), the theoretical resonant frequency and vibration
amplitude of the prototype for 1 g acceleration are 49.3 Hz and 2.3 mm, respectively. The experimental resonant frequency and vibration amplitude are 50.7 Hz and 2.2 mm, respectively. Fig. 7 shows the measured voltage without load versus frequency at 1g acceleration levels. It can be seen that the frequency bandwidth is approximately 8 Hz. The experimental ME voltage coefficient, $\alpha_V$, is $\sim 78.2$ mV/Oe. From (9), the theoretical open-circuit peak voltage is 58.8 V for 1 g acceleration at resonance. Fig. 8 shows the measured open-circuit voltage versus time under the same condition. It can be seen from Fig. 8 that the experimental open-circuit peak voltages is 56.8 V. This shows a good agreement between theory and experiment.

When the prototype is excited by a shaker at 1 g acceleration and at resonant frequency, the output voltage and power on the external resistive loads are shown in Fig. 9. It can be seen from Fig. 9 that the experimental maximum output power reaches 1055.1 $\mu$W across a 564.7 k$\Omega$ resistor. The output power density of the prototype is 0.472 mW/cm$^3$ when only the volume of the cantilever beam, magnetic circuit, and transducer are considered.

FIGURE 7. Measured peak voltage without load versus frequency at 1g acceleration.

FIGURE 8. Measured open-circuit voltage versus time for 1 g acceleration at resonance.

V. CONCLUSION

This paper presented a vibration energy harvester to scavenge energy from ambient vibrations using magnetostrictive/piezoelectric laminated magnetoelectric transducer. An analytical model is developed to analyze the nonlinear vibration and electrical-output performances of the harvester. The experimental results are in agreement with the analytical results. The prototype produced a load power of 1.055 mW across 564.7 k$\Omega$ resistor from an acceleration of 1 g at a resonant frequency of 51 Hz.

REFERENCES