A NONLINEAR VIBRATION-BASED MAGNETOELECTRIC ENERGY HARVESTER

Yang Zhu, Jean Zu
Department of Mechanical and Industrial Engineering, Faculty of Applied Science and Engineering,
University of Toronto, Toronto, Ontario, Canada, M5S3G8

Summary This paper discusses the design and analysis of a novel vibration-based energy harvester that uses magnetoelectric laminate to harvest energy from nonlinear vibration created by magnetic levitation. The nonlinear vibration is described as an asymmetric Duffing oscillator with linear stiffness. Nonlinear vibration analysis is performed using harmonic balance method. It is shown that the proposed magnetoelectric energy harvester can generate a significantly large power over a wide frequency range.

INTRODUCTION

Vibration-based energy harvester has received a growing interest during the past decade. The motivation of such technology is to power small-scale electronic devices by converting wasted vibrations into electrical energy. Currently, the widely investigated piezoelectric cantilevered energy harvesters have two major limitations: small output power and narrow working bandwidth. In order to overcome these shortcomings, this paper presents the design and analysis of a magnetoelectric energy harvester that can generate relatively large power over a broad range of frequency. Due to the high energy density and strong magneto-mechanical coupling effect of magnetostrictive material, the proposed energy harvester can generate much higher power than that of cantilevered piezoelectric energy harvesters.

MAGNETOELECTRIC ENERGY HARVESTER MODEL

Fig. 1(a) shows the system configuration of the proposed magnetoelectric energy harvester. The harvester consists of one Terfenol-D/PZT-5A/Terfenol-D laminate, three ring magnets and a plastic pipe. The laminate is made of a PZT-5A layer bonded between two Terfenol-D layers, and is fixed to the pipe's inner surface at the centre. Terfenol-D possesses magnetostrictive effect [1], in which a changing magnetic field will change the shape of the Terfenol-D layer. PZT-5A possesses piezoelectric effect [2], in which a deformation of the PZT-5A layer will generate a voltage drop on the PZT-5A layer. The top and the bottom magnets are fixed to the pipe's outer surface, while the middle magnet is free to move. The poles of the magnets are placed in such a way that the middle magnet is levitated. When a base excitation is applied, due to the nonlinear magnetic force, the middle magnet undergoes a nonlinear oscillation that accordingly creates a changing magnetic field around the laminate. The changing magnetic field will alter the shape of the Terfenol-D layer and consequently deform the PZT-5A layer. Such deformation will then cause the PZT-5A to generate a voltage.

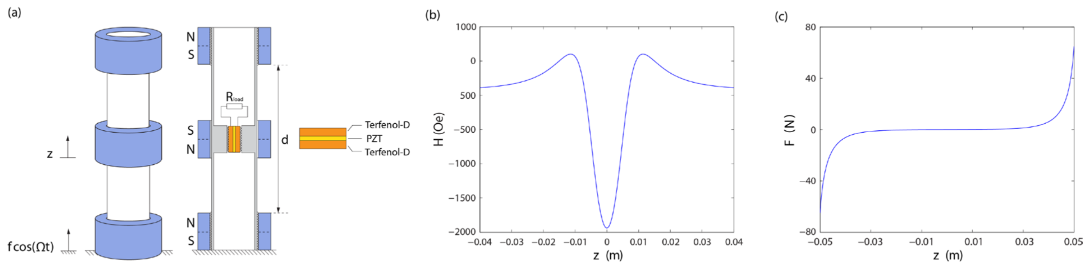

Fig. 1. (a) A schematic of proposed magnetoelectric energy harvester; (b) $z-H$ relationship; (c) $z-F$ relationship

With the piezoelectric layer polarized in its thickness direction and the magnetostrictive layers magnetized in their plane directions, the Terfenol-D/PZT-5A/Terfenol-D laminate works in *L-T* mode. Using an equivalent circuit method [3], the electrical outputs of the ME laminate can be expressed as:

$$V = \frac{j\Omega\alpha_{ME}C_0R_l}{1+j\Omega C_0R_l}H \quad , \quad P = \frac{V^2}{R_l} = \frac{(j\Omega\alpha_{ME}C_0)^2R_l}{(1+j\Omega C_0R_l)^2}H^2 \tag{1}$$

where Ω is the excitation frequency, α_{ME} is the ME voltage coefficient, C_0 is the ME equivalent capacitance, R_l is the load resistance, and H is the external magnetic field on the laminate. Once the laminate size and the load resistor are chosen, the electrical outputs solely depend on the external magnetic field H. Under a base excitation, H is related to the central magnet displacement as $H = f_H(z)$. Fig. 1(b) shows the $z-H$ relationship predicted using finite element analysis in COMSOL. Furthermore, z can be calculated from the system's equation of motion by considering the magnetic force F, the force of gravity mg and the effect of damping c:

$$m\ddot{z} + c\dot{z} + p_1z + p_3z^3 = -mg - mf\Omega^2\cos(\Omega t) \tag{2}$$

in which the nonlinear magnetic force is realized as $F = p_1z + p_3z^3$, where p_1 and p_2 are coefficients associated with the separation distance d between the top and the bottom magnets. The $z-F$ relationship is shown in Fig. 1(c).

NONLINEAR VIBRATION ANALYSIS OF HARVESTER HOUSING

The equation of motion in Eq. (2) is an asymmetric Duffing oscillator with linear stiffness. An approximate solution corresponding to the steady-state response in the region of primary resonance is analytically obtained using the harmonic balance method [4]. The solution consists of a biased term A_0 and a harmonic term A_1 as $z = A_0 + A_1 \cos(\Omega t + \theta)$. The frequency-response curves for a 1g base excitation are plotted in Fig. 2(a) and 2(b). By slowly raising excitation frequency, A_0, A_1 and $|z|$ increase subsequently until the excitation frequency reaches 11Hz, where jump phenomena is observed. It can be seen that nonlinearity creates large-amplitude vibrations over a wide range of frequencies.

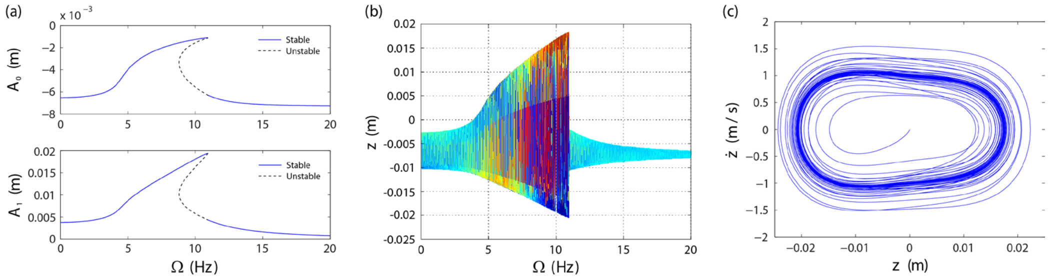

Fig. 2. (a) Frequency-response curves of A_0 and A_1; (b) frequency history of z based on A_0 and A_1; (c) time-domain displacement vs. velocity trajectories with zero initial conditions at 10*Hz*. (All with 1g base acceleration, *d*=80*mm*, *m*=0.012*kg* and c=0.03*Ns/m*)

Using zero initial conditions, Fig. 2(c) shows the numerical results of z vs. $\dot{z}$ under 1g base excitation at 10 Hz. The results are obtained from the direct integration of Eq. (2) using MATLAB ode45 function. A comparison between Fig. 2(b) and 2(c) shows that z is predicted reasonably well using the harmonic balance method.

ELECTRICAL OUTPUTS

A parametric study is carried out for the proposed magnetoelectric energy harvester. Three NdFeb ring magnets are used, each with a size of 19 mm (od) $\times$ 12.7mm (id) $\times$ 9.5mm (thickness), a remnant flux density of 1.32 T and a relative permeability of 1. In the laminate, the sizes of PZT-5A layer and the Terfenol-D layer are $10mm \times 10mm \times 0.2mm$ and $10mm \times 10mm \times 1.5mm$, respectively. The material parameters of PZT-5A and Terfenol-D are available in [3].

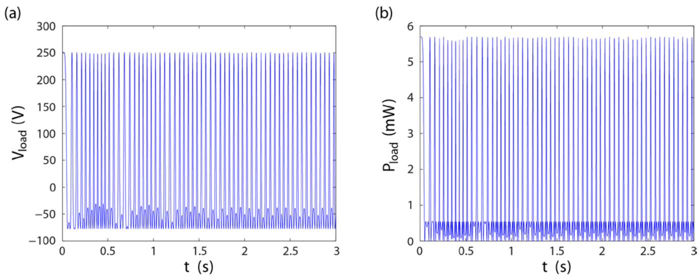

Fig. 3 Electrical outputs of energy harvester for a 1g base excitation at 10Hz with zero initial conditions
(a) open-circuit voltage; (b) output power on load resistor. (Both with d=80mm, m=0.012kg and c=0.03Ns/m)

For a 1g base excitation at 10*Hz*, Fig. 3 shows that the harvester can generate a 250V peak voltage and a 5.70mW peak power over a 10$MOhm$ resistor. Moreover, the maximum power density of the harvester can reach as large as 17.94 mW/cm^3 when only the volume of the laminate is taken into account. This power density is much larger than that of most cantilevered piezoelectric energy harvesters.

CONCLUSIONS

This paper presents a novel nonlinear vibration-based energy harvester that uses magnetoelectric transducer to harvest energy from nonlinear vibration created by magnetic levitation. Nonlinear vibration analysis based on harmonic balance method shows that the harvester has a large bandwidth at low frequency. Numerical simulation shows that the harvester can generate a large power and has a significantly high power density when the volume of the laminate is considered.

References

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[2] Arnau A.: Piezoelectric Transducers and Applications Second Edition. Springer, Heidelberg 2008.
[3] Dong S., Li J. F., and Viehland D.: Longitudinal and Transverse Magnetoelectric Voltage Coefficients of Magnetostrictive/Piezoelectric Laminate Composite: Theory. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*. vol. 50, no. 10: 1253-1261, 2003