AN IMPACT-TYPE VIBRATION ENERGY HARVESTER USING THE PENDULUM AND ITS MULTIPHYSICS FINITE ELEMENT ANALYSES

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This paper presents experiments and finite element (FE) analyses of an infrasonic vibration energy harvesting device in which a low-frequency pendulum impacts a cantilever beam type energy harvester. The experiments demonstrate that the energy harvester operates in the frequency range of 2~8 Hz and has output power of several microwatts under 0.1 g excitation acceleration. Moreover, a finite element model with a coupling of impact, vibration, piezoelectricity and circuit is established and used to analyze the output voltage and power. The frequency response characteristics at different pendulum lengths and the distances between the pendulum ball and cantilever beams are measured and calculated, respectively. Useful guidelines for designing the energy harvester are obtained.

1. Introduction

The energy harvester from ambient vibration in the environment, used as a power supply for small-scale electronics, has attracted a lot of attention in the last decade. There are three mechanisms for vibration-based energy harvesting, including electromagnetic, electro-static and piezoelectric mechanisms. Most harvesters reported in the literatures are linear vibration resonator and operate at several tens of Hertz, or even more than 100 Hz. However, in some special cases, such as human or wind motions, frequency of the vibration sources is lower than 10 Hz in the infrasonic range.

The maximum electrical power harvested from ambient vibration depends on the ambient vibration frequencies and drops greatly at low frequencies. To improve output power of the harvesters at low frequency vibration, frequency up-conversion technologies have been presented to harvest low-frequency vibration energy by amplifying the source vibration frequency. One idea for the frequency up-conversion is to use an impact process to transmit energy. Umeda et al. first proposed an impact frequency up-conversion technology for energy harvesting, in which a steel ball impacts on a piezoelectric membrane and transforms mechanical energy to electric energy. Gu et al. demonstrated an impact-driven, frequency up-converting mechanism coupled vibration energy harvesting device, in which a compliant driving beam with a low resonant frequency impacts a high frequency piezoelectric energy harvester, resulting in energy harvesting predominantly at the system's resonance frequency.

This paper presents an infrasonic vibration energy harvester. It includes a low frequency pendulum and two high frequency piezoelectric cantilevers. Section 2 describes the details of the har-
vester’s structure. Section 3 describes the finite element model with the coupling of piezoelectricity, circuit, vibration and impact, used to analyze the performance of the energy harvester. Section 4 presents the experimental method and results of piezoelectric harvester. Section 5 gives the experimental and calculated characteristics, and discussion for them.

2. Structure

The energy harvester consists of a pendulum and two piezoelectric cantilevers. Figure 1 shows the structure of the energy harvester. The pendulum is hanged in the middle of two piezoelectric cantilevers. Under an ambient excitation, the pendulum swings and impacts the two cantilevers. Through periodical mechanical impact between the pendulum ball and two cantilevers, the energy harvester converts the ambient vibration with low frequency to vibration of the cantilevers with high frequency, and produces electrical output power.

The cantilever is made of a lead zirconate titanate (PZT) plate and stainless steel (SS) substrate. A cross-sectional view of the PZT-SS cantilever is shown in Figure 2. The piezoelectric plate (HAIYING Enterprise Group Co., Ltd) of 1 cm (length) × 1 cm (width) × 0.2 mm (thickness), is bonded at the root of the substrate of 10 cm (length) × 1 cm (width) × 0.5 mm (thickness), by conductive epoxy. The cantilever with unequal lengths of the piezoelectric plate and substrates allows large tip displacement. The piezoelectric plate is poled along the thick direction and is coated with thin electrodes at the top and bottom surfaces.

The pendulum is made of a nylon string and steel ball. The pendulum line’s length is 9 cm, the steel ball’s diameter is 1 cm and the gap between the ball and cantilevers is 1.0 mm. The pendulum can swing under low-frequency ambient exciting. So the pendulum ball impacts the cantilevers and converts the energy of low-frequency ambient vibration to the high-frequency vibration of the cantilevers. The property constants and dimensions of the materials in the harvester are listed in Table 1.

3. Finite element analysis with the coupling of multiple physical processes

The finite element analysis (FEA) software ANSYS is used to build a numerical model with the coupling of piezoelectricity, circuit, vibration and impact for the energy harvester connected directly with a load resistor. Figure 3 shows the built numerical model for the prototype described in Section 2.

The 8-node hexahedral coupled-field element SOLID5 is used for the piezoelectric material. The 8-node linear structural element SOLID45 is used for the metal material. The 2-node 3-D string element LINK10 is used for the pendulum line. The CIRCU94 element is a circuit element for using in piezoelectric-circuit analyses and can model resistors, inductors, capacitors, current source, or voltage sources. It is used to model the load resistor to calculate the output voltage or power, and is connected to the electrodes on the piezoelectric plate.

Mechanical impact as a classic mechanical problem has been studied widely and most studies use approximate analytical solutions. Now ANSYS software can model the impact processing by a contact pair. In the model, a surface-to-surface contact pair, in which the impacted cantilever surfaces are defined as target surface and the pendulum ball surface as contact surface, is established and used to simulate the impact between the pendulum ball and cantilevers. In the target and contact surfaces, 3D 8-nodes surface-to-surface contact elements TARGE170 and CONTA174 are employed, respectively. For those elements are applicable to 3-D structural and coupled field analyses.
The material properties and geometric parameters of the model are listed in Table 1. The modal analysis result of the cantilever shows that the fundamental resonance frequency is 55 Hz, corresponding to bending vibration of the cantilevers. Using the 55 Hz resonance frequency and the capacitance of the piezoelectric plate (=7.1nF), the matched load resistance can be estimated as

$$ R_{opt} = \frac{1}{\omega_c C_p} $$

(1)

$R_{opt}$ is calculated to be 410 kΩ.

A transient analysis was performed to obtain the output voltage on the load resistor. The Rayleigh damping form is introduced into the transient analysis. In equation (2), $[C]$ is the damping matrix, $[M]$ is the elementary mass matrix, and $[K]$ is the mechanical stiffness matrix. $\alpha$ and $\beta$ are the coefficients for the mass and stiffness matrices, respectively. In the model, $\alpha$ is zero and $\beta = \frac{2\zeta}{\omega_i} = 5.8e^{-4}$, where $\zeta$ is the damping ratio for the first mode of the system (about 0.01).

The calculated waveform of the instantaneous output voltage under 0.1g acceleration at ambient excitation frequency of 4, 5, 6 and 7 Hz is shown in Figure 4. It is found that the impact period is equal to the ambient exciting period, and the output voltage peaks are caused by the impact between the ball and cantilevers. A close-up view of one cycle of the output voltage waveform is shown in Figure 5. The voltage waveform has two parts. The first part is the low-frequency component which is directly caused by the impact between the pendulum ball and cantilevers. The second part has a higher frequency of 55 Hz, which indicates that the fundamental resonance mode is excited in the cantilevers. Figure 6 shows the calculated normal strain in the Y-direction of the cantilevers under impact. The max strain occurs at the root of the cantilevers.

4. Experiments

Figure 7 shows a schematic diagram of the experimental setup. The energy harvester is attached to an electric shaker. The gap $\Delta$ between the pendulum ball and cantilevers should be chosen to ensure that the pendulum ball can impact the cantilever within the frequency range of the interest.

The electric shaker is driven by power amplifier (HED-2A) and a signal generator (Tektronix AFG3022B). An accelerometer (LANCE ULT2056) is attached onto the shaker near the energy harvester to measure the acceleration. The output voltage was measured by oscilloscope (Tektronix TDS2014). The load resistance of the energy harvester is 410 kΩ.

Figure 8 shows output voltage of the energy harvester vs. time under an ambient excitation of 0.1g acceleration and 5 Hz frequency. It confirms the calculated results shown in Figure 4. Measured frequency of the decaying vibration in the cantilevers is about 52.5 Hz, which is very close to the computed one (55 Hz).

5. Characteristics and discussion

Figure 9 plots the measured output power vs. excitation frequency with different pendulum lengths. It is seen that when the pendulum length is shortened from 9.5 cm to 6.5 cm, the output power increases about 300%. As the pendulum length is shortened further to 3.5cm, the output power does not increase, but the frequency response range becomes narrower. So the pendulum length affects the output power and frequency response range.
6. Conclusions

An infrasonic vibration energy harvester with a pendulum was presented and investigated to harvest the energy of low-frequency ambient vibration. It is found that the output voltage has two frequency components. One has the same frequency as the pendulum impact, and another the same frequency as the fundamental mode of the cantilevers. It is also found that the output power and frequency band width are affected by the pendulum length and distance between the pendulum ball and cantilevers. Moreover, the finite element model for calculating the coupling of piezoelectricity, circuit, vibration and impact in the energy harvester has been verified by experimental results, and is useful for optimizing the design of the energy harvester.

7. Acknowledgements

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8. Tables

Table 1 The geometric and material parameters of the prototype

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<td>Gap between the ball and substrate $\Delta$ (mm)</td>
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9. Figures

Figure 1. The impact-type vibration energy harvester with a pendulum and two piezoelectric cantilevers. (a) Schematic. (b) Image.

Figure 2. Cross-sectional view of the composite cantilever.
Figure 3. FE model of the energy harvester.

Figure 4. Calculated output voltage for different excitation frequencies under 0.1g excitation acceleration. (a) 4 Hz. (b) 5 Hz. (c) 6 Hz. (d) 7 Hz.

Figure 5. (a) Calculated output voltage versus time for the excitation of 0.1g acceleration and 5 Hz frequency. (b) A close-up view of one cycle of the output voltage waveform.
Figure 6. Calculated Y-directional normal strain of the cantilever beam under impacting.

Figure 7. The experiment setup.

Figure 8. Measured output voltage waveform vs. time under an excitation of 0.1g acceleration and 5 Hz frequency.
Figure 9. Measured output power of the harvester vs. excitation frequency under different pendulum lengths and 0.1g excitation acceleration.

REFERENCES


