RESEARCH ON MECHANICAL STRUCTURES FOR VIBRATION ENERGY HARVESTING

Shuai PANG[1], Jiangming KAN [2], Wenbin LI[3]

Piezoelectric energy harvesting (PEH) is an efficient way of vibration energy harvesting. This paper introduces the performance of two different mechanical structures for PEH. Model A is that one side of the piezoelectric element is shaking with the exciter and the other side is fixed. Model B is that just one side is shaking with the exciter and the other side is free. A circuit for collecting and storing energy is applied and analyzed. The results show that different mechanical structures have different performances and can be applied in different situations. The model A structure may be a good choice for collecting vibration energy in low frequency conditions since the generated voltage of the piezoelectric element in such situations is stable and larger than that of model B structure. Meanwhile, with the model A structure and circuit mentioned in the paper, piezoelectric energy can be well stored for further application.

Keywords: PEH, Vibration, Electrical Interface, Low Frequency

1. Introduction

Vibration is everywhere and has high energy density, a variety of studies have been conducted on the application and conversion efficiency of it. There are three kinds of vibration energy harvesting system: magnetic harvesting construction [1], static harvesting construction [2] and piezoelectric harvesting construction [3]. Each of them has its own features and specific applications. In terms of the complexity of the mechanical part, the piezoelectric energy harvesting system is the simplest compared to the electromagnetic and electrostatic ones.

Collecting the vibration energy in practical use is one of the most promising research topics. Previous research includes that special shoes that can collect energy from people's walking have not been used well since researchers failed to make the collected energy able to charge the telephone or other portable electronic devices [4]. Wireless sensors can be charged to operate but they can't work only with vibration energy [5]. Researchers are trying to make the vibration energy better used in practice. To increase the efficiency of vibration energy harvesting, researchers find that PEH is more efficient compared with magnetic

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[1] PhD, School of Technology, Beijing Forestry University, Beijing 100083, China
[2] Associate Prof., (Corresponding Author), School of Technology, Beijing Forestry University, Beijing 100083, China.
[3] Prof. , School of Technology, Beijing Forestry University, Beijing 100083, China

and static ways [6]. Different piezoelectric materials, size, mechanical structures may come with different electricity performance [7]. As the voltage of the generated electricity is sinusoidal, different performances of various rectifiers have been studied including the full-bridge rectifier [8], voltage doubling rectifier, CMOS full-bridge rectifier [9]. The matching resistor theory is also a key of improving the performance of the harvesting [10].

Many researchers focus on adapting the vibration frequency to the resonant frequency to acquire higher energy. But the resonant frequency is high in many cases. But there are some low frequency situations, such as frequency of people's walking on the floors which is lower than many other kinds of vibrations such as the electric motors. So the vibration structure model better for low frequency conditions is worth researching. This paper first introduces the experimental setup, and then introduces the performance of two different mechanical structure models for PEH, including the modal analysis. The electrical interface which connects the piezoelectric element to the terminal electrical load is a critical point in the optimization of a PEH system. A circuit for collecting energy has been applied and analyzed. Finally, the results and conclusions have been given in the paper.

2. Experiments

The schematic diagram of PEH is shown in Fig. 1. The experimental devices include a signal generator GFG-8015G, a power amplifier B&K 2706, a vibration exciter B&K 4809, a designed fixed station, an oscilloscope NEC omniace RA110, multimeters and so on. The experimental setup is shown in Fig. 2.
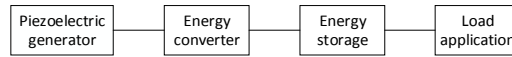

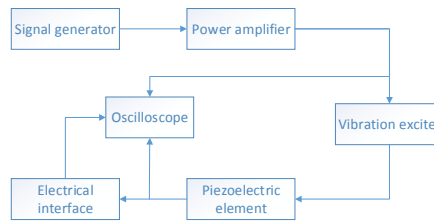Fig. 1. Schematic diagram of piezoelectric energy harvesting

Fig. 2. Experimental setup

2.1 Piezoelectric element

The piezoelectric transducer is composed of the copper base plate and the PZT-5H ceramics. The Schematic diagram of the piezoelectric transducer is

shown in Fig. 3. The plate is bimorph. Its working model is d31 whose generated voltage is perpendicular with the applied stress. More detailed parameters are shown in Table 1. The parameters were confirmed by measurements except modules of elasticity. If the piezoelectric element is larger, the capacity of generating electricity will be bigger.
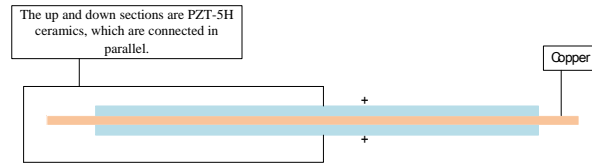
Fig. 3. Schematic diagram of the piezoelectric transducer

Table 1

Parameters of the materials

Materials and dimension	PZT-5H	Copper
Density(Kg·m^{-3})	6790	8300
Modules of elasticity(GPa)		131
Thickness(mm)	0.2	0.2
Width(mm)	50	50
Length(mm)	50	70

2.2 Two mechanical structures

The two mechanical structures' simplified schematic diagrams are shown in Fig. 4. Model A is the cantilever beam structure in forced vibration conditions and model B is the cantilever beam structure in free vibration conditions. Model A is that one side is shaking with the exciter and the other side of the piezoelectric element is fixed. Model B is that just one side is shaking with the exciter and the other side is free.
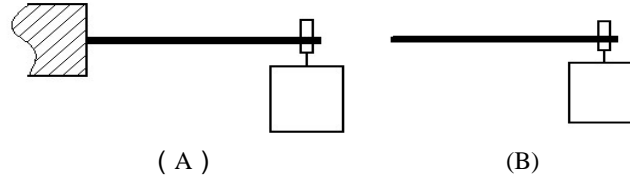
(A)   (B)

Fig. 4. Two models of mechanical structures

As shown in Fig. 2, The signal generator can produce a sine wave of a certain frequency. The power amplifier makes the wave large enough to shake the exciter. The piezoelectric plate shakes with the exciter and the generated sine output voltage of the plate can be seen with the oscilloscope.

2.3 Modal analysis of the mechanical system

The natural frequency w_n can be calculated through the parameters in Table 1 and by the equations from (1) to (5) [11]. From equation (1), we can conclude that increasing the mass of m_1 can reduce the natural frequency. In our experiments, there is no m_1, so m_1 is equal to zero.

$$w_n = \sqrt{\frac{k}{m_1 + m_2}} = 2\pi f_n , \tag{1}$$

$$\delta = \frac{Pl^3}{3EJ} , \tag{2}$$

$$k = \frac{P}{\delta} , \tag{3}$$

$$m_2 = \frac{33ql}{140} , \tag{4}$$

$$J = \frac{bh^3}{12} , \tag{5}$$

where k is the spring stiffness, m_1 is the weight of mass fixed at the free end of the beam, m_2 is the equivalent weight of the cantilever's free end, δ is the deflection, P is static load of the cantilever's free end, E is modulus of elasticity, J is the moment of inertia, q is the mass per meter, l is the length of the cantilever beam, b is the width of the cantilever beam and h is the thickness of the beam. l is 61mm in the experiment.

Modal analysis is the study of the dynamic properties of structures under vibration excitation. The first mode analysis results of model A and model B are presented in Fig. 5 and Fig. 6 respectively using the finite elements analysis software ANSYS 13.0. The side with a circle is the side that shakes with the exciter. The results show the total deformation in the first mode. The simulation first mode frequency which is the lowest in the first three modes was a little different from the experimental results due to the damping parameters of the system. The resonant frequency w in damping conditions can be shown in equation (6) [11]:

$$w = \sqrt{1 - 2\xi^2}\, w_n , \tag{6}$$
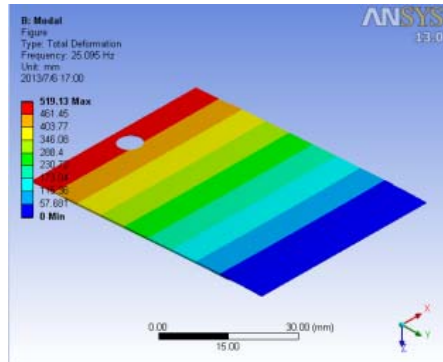
Where ξ is the damping ratio.
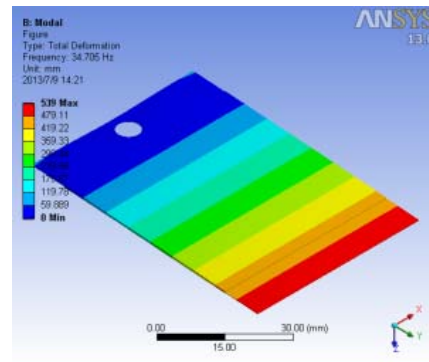
Fig. 5. Modal analysis of model A   Fig. 6. Modal analysis of model B

2.4 The electrical interface

In the experiment, structure of model A mentioned above is used to generate electricity since it works well in low frequency. The chips LTC3588-1 and CBC3112 were used for collection and storage of energy. LTC3588-1 is for piezoelectric energy harvesting power supply. It owns an integrated low-loss full-wave bridge rectifier. With input operating range from 2.7V to 20V, the output voltage can be selected to one of the following voltage: 1.8V, 2.5V, 3.3V and 3.6V. And the continuous output current can be up to 100mA, which is much larger than the original output current in μA level. We choose 3.6V to carry out our experiment. CBC3112 is the world's first intelligent thin film energy storage device. A 12 μAh thin film energy storage is integrated. 3.6V is in the range of the input of CBC3112. The experimental electrical circuit is shown in Fig. 7.
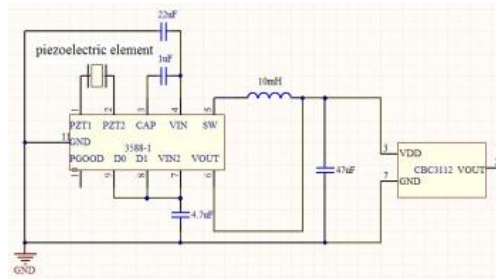

Fig. 7. The experimental electrical circuit

3. Results and Discussions

For each mechanical model, in different amplifier's output voltage and different frequency, the generated peak voltage was recorded. Fig. 8 and Fig. 9

respectively show the relationship between frequency and the generated peak voltage with model A and model B structure as shown in Fig. 4. Meanwhile, Fig. 10 shows the performance of the two models when the output voltage of the power amplifier is 3V. Fig. 8 and Fig. 9 demonstrate that the larger the input voltage of the piezoelectric transducer is, the larger the output voltage of the piezoelectric transducer is. Fig. 10 shows that different mechanical structures have different performances. They can be used in different situations. If the environmental vibration frequency is lower than 15 Hz, model A is better to collect energy since its output voltage is larger than that of model B. But if the environmental vibration frequency is easy to reach the resonant frequency, it's better to use model B.
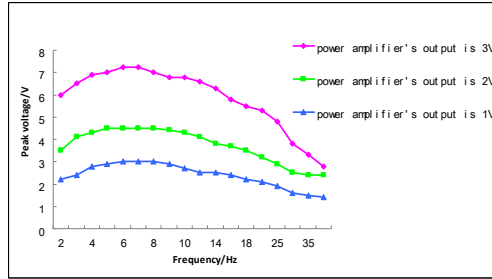

Fig. 8. Relationship between frequency and generated peak voltage with model A
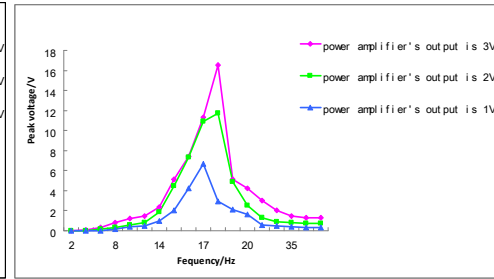

Fig.9. Relationship between frequency and generated peak voltage with model B
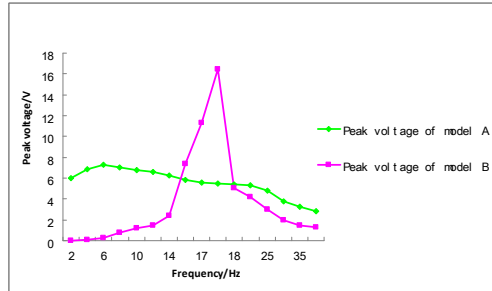

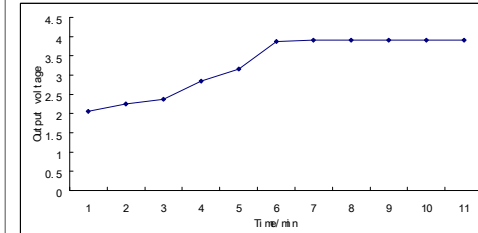Fig. 10. Comparison of two models' frequency and generated peak voltage relationship

Fig. 11. Storage performance of CBC3112

When the piezoelectric element is relatively still which means the exciter doesn't shake it but there is also vibration in the environment, the resistor is ranging from about 26MΩ to 38MΩ. The resistor is changing when the piezoelectric element is shaking. The output voltage of the piezoelectric element can be changed by adjusting the frequency and the output of power amplifier.

Because the resistor of the piezoelectric element is in the level of $M\Omega$, the output current is limited to the level of μA.

Using LTC3588-1, the output current of the chip can be up to 100mA. With CBC3112, the energy can be stored in a short time for further use. It's seen that the output voltage of CBC3112 can be from 2.06V to 3.90V in about 5 minutes as shown in Fig. 11. So the energy can be well collected and stored.

4. Conclusions

In this paper, two mechanical structure models used for PEH have been analyzed. Structure of model A is more suitable for low frequency conditions and the generated output voltage of the piezoelectric element with the structure is stable and larger compared with model B, which is helpful for the later collection and storage of energy.

Various kinds of frequencies added to the piezoelectric element should be tested further to see the performance of generating electricity. The design of the mechanical system should make sure it can be better fit to the surroundings, especially considering the frequency. The resonant frequency can cause the largest displacement of the piezoelectric element, but that doesn't mean it's the optimal frequency to choose. Too large deformation may reduce the performance of the piezoelectric element in a short time since the piezoelectric element may be damaged. In experimental situations, each time only one frequency can be selected, but in reality, there're various kinds of frequencies which are hard to analyze. In addition, how to collect and store the energy more efficiently is worth researching. To create and use integrated micro circuit chips instead of discrete component circuits is a good way to reduce the loss of the circuit.

Acknowledgements

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