Experimental study on the natural frequency of tunable piezoelectric cantilever plate

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Abstract. PEH (piezoelectric energy harvester) outputs a higher voltage when the natural frequency matches ambient vibration frequency. How to widen working frequency band is a hot issue in study of PEH. In this paper, an auto-tuning PEH is presented by attaching a box to each corner of its free sides and a ball is placed in each box. Change of the balls position makes natural frequency of PEH variable, which expands working bandwidth of the device to accommodate complex ambient vibration. Fixing the equipment on experimental platform by designing fixture, hammering experiments are carried out to measure natural frequency of the structure when balls are in different positions. It is found that the maximum and minimum natural frequencies exist in the auto-tuning PEH, which form a resonance bandwidth. Moreover, there are multiple position combinations of two balls at the same natural frequency in the range of resonance bandwidth. Fixed the apparatus on exciter by the fixture, and a constant excitation frequency is selected in the bandwidth to perform auto-tuning experiments on the instrument. It is observed that location of balls is automatically changed to make natural frequency of the system coincide with the excitation, and the law of variation in balls position is obtained. The converter is subjected to sweeping experiments through an exciter and an oscilloscope. Using voltage-frequency diagrams, it is shown that the auto-tuning PEH outputs a higher voltage and its frequency band is wider when the ball rolls freely compared to two cases where balls are fixed.

1. Introduction

Vibration energy widely exists in daily life and practical engineering. Vibration energy harvester is an effective way to convert vibration energy of surrounding environment into electrical energy [1, 2]. The advantages of the piezoelectric energy harvester is high conversion efficiency, simple structure, no additional power supply, environment-friendly, etc., and its application prospect is broad [3-7]. Generally, working bandwidth of piezoelectric energy harvester is relatively narrow, and power of the harvester can be maximized when external excitation frequency is consistent with natural frequency of the system. Because of low frequency and wide frequency band of external vibration, natural
frequency of piezoelectric energy harvester cannot match the external excitation frequency, which leads to a great reduction of the output power [8, 9].

To improve efficiency of piezoelectric energy harvester, it is necessary to automatically adjust natural frequency of the device according to the frequency of external environment vibration to achieve resonance. The earliest tunable energy harvester relied on manually varying place of additional mass [10] to adjust natural frequency. After that, some other auto-tuning instruments need not manual operation but additional energy [11], such as electromagnetic [12] to change the stiffness of the system, so the actual capture efficiency was low. In addition, there was a literature that combines several cantilever beams with different natural frequencies to form a complex structure, but it occupied a large space [13]. The facilities in the literature [14, 15] have achieved auto-tuning, but the frequency is higher and the tunable range is narrower. Reference [16] designed an auto-tuning instrument by attaching a box and two cylinders based on cantilever beam structure, and did not further study the relationship between position and frequency/bandwidth. Based on cantilever plate, this paper proposes an auto-tuning PEH with additional balls and boxes. By changing location of two balls, auto-tuning function in broad-frequency vibration environment is realized. Through experimental studies, it is verified that the energy conversion efficiency of the device is high and its auto-tuning ability is excellent.

2. Model

The research is based on a cantilever plate structure fixed at left and freed at right. A box is attached to each corner of free end, and a ball is placed in each box. The material and dimensional parameters of the structure are shown in Table 1. The experimental model of the auto-tuning PEH is shown in Figure 1. Natural frequency of the instrument is adjusted by changing situation of balls within boxes.

| Table 1. Material and dimensional parameters of other parts (mm) |
|---------------------------------------------------------------|
| Structure            | Box         | Ball | Piezoelectric layer |
|----------------------|-------------|------|---------------------|
| Cantilever plate     | Acrylic plastic | Steel | PVDF |
| 140 × 60 × 0.6       | 60 × 20 × 20 | 16   | 60 × 60 × 0.03      |

![Fig 1. Experimental model of the auto-tuning PEH](image1)

![Fig 2. The clamping equipment](image2)

Because the device needs to be fixed, a fixture is designed, which consists of a C-shaped base and a platen. During the experiment, the base is bolted to the exciter or the experimental platform, and then the device is fixed to the top plane of the base by the platen. Figure 2 shows model of the fixture.

3. Hammer experiment result and analysis

The auto-tuning PEH is fixed to the stationary experimental platform by the clamping equipment, and two balls are fixed in the box with tape. The purpose of hammer experiment is to obtain the influence regulation of the sphere site on the natural frequency. The first-order natural frequency is obtained, and three special changes cases of sphere position are studied:

1) Initial locations of both balls are at left end of box, changing two balls sites equidistantly toward free end of the plate until two balls reach the right end of the boxes, and modal analysis is carried out at each new situation of two balls.
2) Initial positions of two balls are the same as in case 1. A ball is fixed and location of another is changed equidistantly to the right end of box. Modal analysis is performed once for each change of the balls’ spots.

3) Initially, two balls are placed on the left and right sides of box respectively. The sphere at the free end is fixed, and place of left sphere is changed equidistantly to the right until the sphere reaches the free end. Modal analysis is carried out each time when the ball site is changed.

![Hammering experimental platform](image)

The experimental system consists of acceleration sensor, force hammer, signal collector (SCADAS) and analysis software (LMS-Modal Impact), as shown in Figure 3. The free end of the auto-tuning PEH is struck by the force hammer. Force sensor on the hammer and accelerometers glued to the facility are connected to SCADAS through signal wires. SCADAS collects and processes the signal, and then communicates with computer using the cable. Finally, the experimental results are gained from LMS-Modal Impact.

In every case, there are six positional states, each of which corresponds to a color. The initial situation of each case is represented by a brown line. As the sphere moves towards the free end, the natural frequency decreases gradually, as shown in Figure 4a-c, until the sphere reaches the right end, the natural frequency is lowest and is indicated by a black line. The experimental results of the three cases are compared in Figure 5. When both balls are at the right end of the box (free end), the natural frequency of the system is the lowest (16.22Hz), and when both balls are at the left end, the natural frequency is the highest (24.23Hz). The difference between the maximum and minimum natural frequencies forms the bandwidth (8.01Hz) of the instrument, and the natural frequency varies with the sphere position over the bandwidth. Meanwhile, it can be observed that for any one of natural frequency within the bandwidth range, there are multiple situations of ball position corresponding to the natural frequency.
4. Sweeping experiment

The working principle of PEH is to convert the vibration energy of the external environment into electrical energy using piezoelectric material. In order to verify that the working bandwidth of the auto-tuning PEH is wide, the sweep frequency experiment is carried out. The output of the signal generator is sweep signal in 0-30Hz, and the voltage between the two poles of the piezoelectric layer is measured by the digital oscilloscope.

Three cases are analyzed and compared. In the first case, when the two balls are both fixed in the right end of box and do not roll, the device is 16Hz. In the second case, both balls are fixed in the left end of box, which corresponds to the natural frequency of 24Hz. The last case is that the two balls rolls freely with a tuning range of 16-24Hz. The output voltage of results comparison after data handling is shown in Figure 6. It can be seen that compared with the first two cases, the structure can output higher voltage within the range of around 16-24Hz in the last case.
Figure 6. Comparison of voltage-frequency response curve

5. Conclusion
This paper fabricates a PEH which achieves automatically tuning and broad bandwidth by the variety of balls location in the case. After manufacturing fixture, three different experiments are performed. The first is the hammering experiment, which measures the natural frequency of the structure, indicating that the operating band of the energy harvester is broad. Then the auto-tuning experiment shows that multiple position situations of the two spheres correspond to a natural frequency that matches external excitation frequency, which lead to resonance. After comparison, the sweep tests show that relying on the rolling of the ball to change the natural frequency, the device resonates with the external excitation and outputs a larger voltage in the range of 16-24 Hz.

6. References
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