Theoretical analysis and experimental study of a perforated piezoelectric cantilever

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Abstract. Piezoelectric energy harvesters have been studied extensively because they show considerable promise for use in both military and commercial applications. In order to improve the output capability of the piezoelectric energy harvester, the perforated piezoelectric cantilevers were designed in this work. To study how the hole on the cantilever affected the output characteristics, this paper analysed the position and size of the hole separately. The results show that, perforating the cantilever can cause stress concentration of the piezoelectric cantilever, and improve the output capacity.

1. Introduction
The cluster munition is a weapon that opens the cabin door in the air through the warhead and throws out submunitions. It has the advantages of large coverage and wide range of damage [1]. Because of its characteristics of "deep attack" in modern warfare, it occupies a very important position in weapons and ammunition. Due to its own structural characteristics, the biggest problems with the currently equipped submunitions are: the fuzes for the submunitions have low reliability when working, resulting in high rate of duds. In order to reduce the hazard of duds, self-destruction is the best measure [2-4]. According to the current development trend of self-destruction technology, the use of electronic or electromechanical self-destruction fuze is a major direction for the development of future submunitions and ammunition fuze technology. However, due to the limited space of the submunition's fuze, there is not enough space to install a power supply that can power a self-destruct device.

In order not to occupy the internal space of the fuze, this paper proposes a design scheme of a flexible piezoelectric cantilever, which uses the wind energy generated by the uniform falling stage after the submunition is thrown, and the positive piezoelectric effect of the piezoelectric material to generate power for the submunition.

2. Principle
A piezoelectric energy harvester was installed in a submunition to supply the energy for its fuze, as shown in Figure 1. When this submunition was ejected from the cluster munition into the air, it would initially fly at high speed and then fall at a constant speed (30 - 50 m/s) before eventually hitting its target[5]. During the free-fall period, the piezoelectric cantilevers would flutter under the action of the wind, and electric energy would thus be generated by the fluttering piezoelectric cantilever; this
energy could then be stored using a storage capacitor. When the submunition hit its target, the storage capacitor then supplied the energy to its fuze.

The piezoelectric cantilever is composed of piezoelectric layers, base layer, bonding layer and electrodes, as shown in Figure 2. When the piezoelectric cantilever flutters in a wind field, it converts the wind energy into mechanical energy. The piezoelectric layer is periodically subjected to tensile and compressive stresses, and the top and bottom surfaces of the piezoelectric layer then periodically generate positive and negative charges via the piezoelectric effect, which can convert the vibrational energy into electrical energy. In the piezoelectric cantilever, the low-order vibration plays a leading role at this wind speed. In this work, to simplify the required mathematical model, only the vibrations of the piezoelectric cantilever at low-order natural frequencies (i.e., first order or second order) are analyzed.

![Figure 1. Piezoelectric cantilevers installed on a submunition](image1)

![Figure 2. A piezoelectric cantilever](image2)

3. Design ideas
A complete piezoelectric energy harvester consists of a piezoelectric cantilever and its management circuit. The mechanical properties of the piezoelectric cantilever and the acquisition efficiency of the management circuit affect the output of the piezoelectric energy harvester.

The geometry, cross-sectional shape, mass distribution and surface condition of the piezoelectric cantilever change the stress distribution in the piezoelectric layer, which may affect the power generation performance. Studies have shown that triangular piezoelectric cantilevers can effectively improve the surface stress distribution and increase the output voltage when the same piezoelectric material volume. Theoretical derivation shows that the output power of a triangular cantilever is 3.3 times that of a rectangular cantilever. At the same time, studies have shown that the cross-sectional shape of the piezoelectric cantilever can effectively improve the power generation efficiency. Increasing the end quality for the piezoelectric cantilever also improves the output voltage, power and current.

Although the method of increasing the end mass and the triangular cantilever can effectively improve the output performance of the piezoelectric energy harvester, the size, mounting position and working environment limitation make the above two methods impossible to use on the submunition. In order to increase the stress distribution on the surface of the flexible piezoelectric cantilever, the perforated piezoelectric cantilevers are designed to cause stress concentration during the vibration of the cantilever to achieve the purpose of increasing the power generation. The paper will study the influence of the position and size of the circular hole on the power generation performance of the piezoelectric cantilever.

The cantilever has the largest stress value near the fixed end when it is vibrating, and the stress near the free end is smaller. According to the piezoelectric equation, the output electric charges of the
piezoelectric cantilever is proportional to the sum of the stresses of the micro-elements on the structure. Effectively distributing stress and increasing the internal stress of the structure under the condition of ensuring the strength of the cantilever play an important role in improving the output. The paper uses the perforated piezoelectric cantilever to concentrate the stress inside the cantilever to achieve more charge. Due to the limitation of the manufacturing process, only one circular hole is made on each cantilever.

4. Experimental results and analysis

4.1 Static simulation of perforated piezoelectric cantilever

The purpose of static analysis is to study the influence of the hole position on the average surface stress of the piezoelectric vibrator. The position of the hole is the most significant factor for the stress distribution, and the hole diameter has relatively less influences. The size of the vibrator is 50 mm × 10 mm, and a circular hole with a hole diameter of 2 mm is perforated on the vibrator. The displacement of the center of the circular hole from the free end is 5 mm × i (i is the number of the vibrator, i = 1, 2, ..., 9). In the calculation, a pressure of 0.25 Pa is applied to the surface of the vibrator for static simulation. The calculation results in Figure 3 indicate that the general rule of the influence of the position of the circular hole on the average stress is that the further the hole is from the free end of the piezoelectric vibrator, the larger the average stress.

![Figure 3. The influence of the position of the hole on the average stress](image)

![Figure 4. Stress distribution when the circular hole is close to the fixed end](image)

That is not to say it would be better to make the hole closer to fixed end. As shown in Figure 4, when the position of the hole was very close to the fixed end, a large concentrated stress was generated around the circular hole, which easily exceeded the strength range of the material, resulting in the vibrator to break. Therefore, the punching position should not be too close to the fixed end.

4.2 Power generation performance experiment

Compared with the unpunched vibrator, the vibrator with a circular hole has a reduced stiffness and concentrated stress around the circular hole, which increases the overall average stress on the surface of the vibrator. From the theoretical analysis, the critical wind speed of the perforated piezoelectric vibrator in the experiment is lower than that without the perforation, and the voltage generated at the same wind speed is higher.

As mentioned above, due to the limitation of production difficulty, only one round hole is made on the surface of each vibrator during the research. The piezoelectric vibrator has a horizontal dimension of 50 mm × 10 mm which comprises of a 0.03 mm thick PVDF thin film and 0.01 mm thick stainless steel metal substrate. Experiments were carried out by selecting a piezoelectric vibrator with a diameter of 2 mm and a center hole of 30 mm from the free end. Wind tunnel experiments were carried out under different wind speeds on the perforated vibrator and the unpunched vibrator, as
shown in Figure 5. Figure 5(a) shows the wind speed-voltage curve, and Figure 5(b) shows the wind speed-frequency curve. The red curve in the figure represents the piezoelectric vibrator with a circular hole, and the black curve represents the unpunched piezoelectric vibrator.

![Wind speed-voltage curve](image1)

(a) Wind speed-voltage curve  

![Wind speed-frequency curve](image2)

(b) Wind speed-frequency curve  

Figure 5. Voltage and frequency comparison of perforated and unpunched vibrator

It can be seen from Figure 5(a) that the critical wind speed of the piezoelectric vibrator with a circular hole is about 8 m/s, and the critical wind speed of the unpunched vibrator is about 12 m/s. After the vibrator starts to vibrate, the red curve is slightly higher than the black curve at the same wind speed, which indicates that the power generation performance of the piezoelectric vibrator after perforating is better than that of the unpunched vibrator. When the wind speed rises to 23 m/s, the vibrating instability of the vibrator with a circular hole will occur, which limits its use in high wind speed applications.

Figure 5(b) shows that the frequency of the output voltage signals of the two piezoelectric vibrators changes abruptly at the critical wind speed, and changes approximately linearly with the increase of the wind speed. Similarly, when the wind speed reaches about 23 m/s, the frequency of the output voltage signal of the vibrator with a circular hole no longer increases steadily but fluctuates. However, in the interval from the vibration of the piezoelectric vibrator to the entry into the unstable wind speed, the piezoelectric vibrator with a circular hole has better power generation performance than the unpunched flat vibrator.

5. Conclusions

Through the above analysis of the mechanical properties and power generation performance of a piezoelectric vibrator with a circular hole, the following conclusions were obtained:

Perforating can cause stress concentration of the piezoelectric vibrator, which can increase the amount of power generation;

The position of the circular hole has a great influence on the mechanical properties and power generation performance of the piezoelectric vibrator;

The critical wind speed of the perforated piezoelectric vibrator is much lower than the critical wind speed of the unpunched piezoelectric vibrator.

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