Research on piezoelectric stacked generator and its application

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Abstract: In response to the energy density and fast activation requirements of small caliber ammunition fuzes for power supplies, this paper designs a piezoelectric stacked physical power supply that can generate electrical energy using the setback acceleration generated at the moment of ammunition firing as a power source. The paper designs the structure of the power supply according to the performance parameters of the selected piezoelectric materials and tests the power generation performance of the power supply using a simulated experimental setup. The experimental results demonstrate that the output voltage of the piezoelectric power supply has a linear relationship with the load. When the piezoelectric power supply charges the capacitor, the voltage across the energy storage capacitor also increases approximately with the increase of load, and the piezoelectric stacked power supply designed in this paper can meet the requirements of small caliber ammunition.

1. Introduction

Fuze power supplies can be divided into two categories according to their operating principles: chemical power supply and physical power supply. Chemical power supply is a device that converts chemical energy into electrical energy through chemical reactions [1]. Due to the good performance of the long storage and short activation time of the physical power supply, it can meet the demand of the fuze for power supply. In addition, the physical power source for fuzes can be non-destructively tested before use, which improves the reliability of fuzes [2]. The requirements of small caliber ammunition fuze for power supply are small size, high energy density, short activation time, etc., and the traditional fuze power supply has become a bottleneck for miniaturization and intelligence of small caliber ammunition fuze [3].

Piezoelectric power generation technology has a wide range of applications in weapons and equipment, such as aerial bomb trigger fuze power, armor-piercing ammunition fuze power, etc.. Fuze with piezoelectric generator power generation according to the piezoelectric mode is divided into three types of impact, energy storage and explosive power. Impact is the use of projectile contact, collision with the target generated by the force of the piezoelectric material to generate detonation signal; energy storage is the use of the setback of the projectile launch piezoelectric material to generate electrical energy and stored in a capacitor, constituting a power supply; burst electricity is the use of fuze internal fire cap generated by the instantaneous high pressure gas acting on the piezoelectric ceramic stack, and it can be used as a new high-power pulse power. C.Keawboonchuay [4] conducted a loading impact test on a piezoelectric generator, and the test yielded a peak current of 58.2 A and a peak power of 28.4 W. C.Keawboonchuay also developed a mechanical model of a piezoelectric power generator and analyzed the factors affecting the power generation of a piezoelectric power supply, and pointed out that the peak voltage increases with the thickness of the piezoelectric oscillator increases with the ratio of the thickness
of the piezoelectric oscillator cross-sectional area. Hui Li [5] proposed a new piezoelectric jet generator and pointed out the prospect of the application of piezoelectric jet generator in fuze energy in their research. The operating principle of the piezoelectric jet generator is approximately the same as that of the conventional electromagnetic jet generator. Compared with the conventional electromagnetic jet generator, the piezoelectric jet generator removes the electromagnetic component and replaces the metal diaphragm in the resonant cavity with a piezoelectric sheet.

Fuze firing systems require a fuze power supply with rapid establishment, and piezoelectric power supplies are of general interest to fuze workers because of their fast activation performance. However, the power generation of single-layer piezoelectric crystals is very small and cannot meet the power supply requirements of fuze firing systems. The power generation of piezoelectric materials is proportional to the impact load and the piezoelectric constant. To increase the power generation of piezoelectric power supply, multi-layer piezoelectric ceramic sheets are usually stacked together to form piezoelectric stacks. In this paper, a piezoelectric stacked power supply is designed by using the high setback acceleration generated during the firing of a small caliber projectile as the power source of the piezoelectric power supply. The paper designs the structure of the piezoelectric stack and completes the processing and testing of the piezoelectric power supply according to the design results.

2. Theoretical model of piezoelectric power supply

The energy excited by a single piece of piezoelectric material is very limited, and in order to obtain a higher power generation, multiple piezoelectric wafers are often connected in parallel or in series to form a piezoelectric stack. When the projectile is accelerated in the chamber, the setback force generated by the mass block acts on the piezoelectric stack, and the deformation of the piezoelectric stack leads to the generation of charge on both ends of the piezoelectric wafer; when the projectile stops accelerating, the force disappears, and the deformation of the piezoelectric stack then recovers, leading to the disappearance of the charge on both ends of the piezoelectric wafer; therefore, the storage of charge must be carried out simultaneously with the generation of charge. In this paper, a capacitor is used as the energy storage element for the piezoelectric ceramic charge. The piezoelectric power supply studied in the paper consists of a mass block, a piezoelectric stack, and a power management circuit.

When analyzing piezoelectric power management circuits, the piezoelectric stack can be described as a charge source or voltage source by the equivalent circuit method. In this way, the complex process of generating electrical energy for a piezoelectric generator and supplying it to a circuit can be transformed into a single circuit problem. The piezoelectric stack has an equivalent capacitance of $C_t$ and an external energy storage capacitor $C_1$. To avoid rapid release of electrical energy from $C$, a diode is added in front of the energy storage capacitor, so the resistance $R$ in the circuit includes two parts: line resistance and diode on-resistance. The schematic diagram of the piezoelectric generator energy storage circuit is shown in Figure 1, and the circuit is analyzed.

![Figure 1. Schematic diagram of the energy storage circuit of the piezoelectric power.](image)

The total charge $Q$ generated by the piezoelectric sheet is,

$$Q = d_{33} F_{\text{max}} = U_1 C_1$$  \hspace{1cm} (1)

Therefore the higher the value of $d_{33}$ the more charge is generated by the piezoelectric sheet and the higher the total high energy $E_t$ generated by the piezoelectric sheet.
\[ E_1 = \frac{1}{2} C_1 U_1^2 = \frac{1}{2} \frac{Q^2}{C_1} \]  
\[ (2) \]

\( Q \) is stored in the piezoelectric intrinsic capacitor \( C_1 \) and the energy storage capacitor \( C_1 \). When the charge is no longer transferred, the voltage across the capacitor \( C_1 \) and the voltage across \( C_1 \) are equal to \( U \). At this time, the following equation is available.
\[ Q = U_0 C_1 + U_1 C_1 \]  
\[ (3) \]

The energy stored in \( C_1 \) is.
\[ E_1 = \frac{1}{2} C_1 U_1^2 = \frac{1}{2} C_1 \left( \frac{Q}{C_1 + C_1} \right)^2 \]  
\[ (4) \]

Then the energy conversion efficiency is.
\[ e = \frac{E_1}{E_1} = \frac{C_1 \left( \frac{Q}{C_1 + C_1} \right)^2}{C_1 \left( \frac{Q}{C_1} \right)^2} = \frac{1}{2 + \frac{C_1}{C_1} + \frac{C_1}{C_1}} \]  
\[ (5) \]

As can be seen from equation (5), when \( C_1 = C_1 \), the energy conversion efficiency of the piezoelectric sheet is maximum, which is 25%. Usually the value of energy storage capacitance is much larger than the inherent capacitance of the piezoelectric ceramic itself. To improve the energy conversion efficiency, a parallel stack form should be selected to improve the overall capacitance of the piezoelectric stack.

3. Piezoelectric power supply structure design

3.1. Piezoelectric stack design

The piezoelectric stack is the energy output element of the piezoelectric generator, and its performance determines the output performance of the piezoelectric generator. The total amount of charge generated by the piezoelectric stack is related to the piezoelectric material and the structure form of the piezoelectric stack. In this paper, PZT-5H is selected as the piezoelectric material with the piezoelectric constant \( d_{33} = 670 \text{ pC/N} \) and the thickness of a single piezoelectric sheet is \( h = 0.2 \text{ mm} \).

The piezoelectric stack consists of several parts such as piezoelectric sheet, electrodes, bonding material and leads, etc. The piezoelectric sheet is polarized along the thickness direction. From the content of Chapter 2, it is known that the charge generated by the piezoelectric stack satisfies the following equation.
\[ Q(t) = nd_{33} a(t)(m_a + 0.5m_b) \]  
\[ (6) \]

Therefore, the power generation performance of the piezoelectric stack is related to the mass block mass, the piezoelectric sheet mass and the number of stack layers. Since the space inside the fuse is limited, the volume space of the piezoelectric stack is determined. Since the mass of a single piezoelectric sheet varies little, increasing the number of layers in a given space becomes the main method to improve the power generation performance of the stack. Reducing the thickness of the bonding material and the electrode thickness is an effective way to increase the number of piezoelectric stack layers, and a copper conductive layer with a thickness of 0.02 mm is used as the electrode in the paper. The structure and dimensions of the designed parallel piezoelectric stack are shown in Fig. 2, with a total height of 3.5 mm, an outer diameter of 16.5 mm and an inner diameter of 7 mm.
3.2. Energy storage capacitor selection

Based on the structural dimensions of the piezoelectric stack and the parameters of the PZT-5H piezoelectric material, the overall capacitance of the piezoelectric stack is calculated as 

$$C_t = \frac{n\varepsilon S}{d} = 0.128 \mu F.$$ 

According to equation (6), the charge generated by the piezoelectric stack is \(92.97 \times 10^{-6} \text{ C}\) under 50,000 g overload.

The above piezoelectric characteristic equation is limited to the elastic range, when the stress exceeds the elastic limit, the linear relationship between stress and strain no longer exists, and the value of \(d_{33}\) will change under high overload, when the energy generated by the piezoelectric material will be 5~10 times that of working in the linear zone, so the value of the charge generated in the actual situation may be greater than \(92.97 \times 10^{-6} \text{ C}\).

From Equation (5), it can be seen that choosing a suitable energy storage capacitor can help improve the energy conversion efficiency, and the conversion efficiency is highest when the equivalent capacitance of the piezoelectric stack is equal to the capacitance of the energy storage capacitor. However, a small energy storage capacitor has limited energy storage capacity, and the stored energy can hardly meet the demand of the load circuit; in addition, the small capacitance value will definitely lead to the increase of the voltage across the capacitor under the equal energy, and the excessive voltage will bring a burden to the load circuit. Since the energy storage capacitor supplies power directly to the load circuit, it is necessary to choose the energy storage capacitor reasonably according to the load demand.

It is known that the required operating voltage of each part of the fuze mounting circuit in addition to the output part is higher, the rest can work normally below 5 V. As the piezoelectric ceramic recovery deformation will lead to the generation of secondary voltage, let \(k\) be the energy coefficient introduced by the subsequent deformation of the piezoelectric ceramic, ignoring the change of \(d_{33}\) under large load, the energy of the energy storage capacitor can be obtained from Equation (5).
Also available:

\[ E_i = \frac{1}{2} C_i U_i^2 \]  

The voltage across the energy storage capacitor is:

\[ U_i = \sqrt{\frac{ek}{C_i C_i} \left( \frac{Q^2}{2 + \frac{C_i}{C_i} \frac{C_i}{C_i} \frac{C_i}{C_i}} \right)} \]  

Equation (9) provides the basis for the selection of the energy storage capacitor. From the literature [6], it is known that the total energy required for the whole loading process (decoding, standby, and detonation) is 1602 μJ (for a 4.7 μF capacitor charged to more than 26 V) when the muzzle loading fuze circuit of small-caliber ammunition is designed with low power consumption, of which the voltage required from the power supply in the fuze chamber to the completion of decoding is 3 V, and the power consumption is only 182 μJ; the standby process is up to 10 s, and the power consumption is 42 μW and an operating voltage of 3 V.

Therefore, the piezoelectric generator needs to provide at least \((182 + 42 \times 10^{-3} + 1/2 \times 4.7 \times 5^2) \) μJ of energy for the mounting circuit, i.e.: charge the 4.7 μF capacitor to more than 11 V; when the voltage across the storage capacitor reaches 16.8 V, its energy can power the whole decoding and standby process.

Substituting equation (6) into axiom (9), the relationship between the voltage across the energy storage capacitor and the acceleration load can be derived, and it can be seen that the voltage across the energy storage capacitor is proportional to the acceleration load when the variation of \(d_{33}\) is neglected.

\[ U_i = \sqrt{\frac{ek}{C_i C_i} \left( m_d + 0.5m_n \right)} d_{33} a \]  

4. Experimental study of piezoelectric generator simulation

The output performance of the piezoelectric stack was analyzed by theoretical derivation in the previous section, and the piezoelectric stack structure was designed based on it, and the energy storage capacitor was selected. In this section, the power generation performance of the piezoelectric power supply will be verified by means of simulated experiments. The fabricated piezoelectric stack capacitance value is 0.117 μF, which differs from the theoretical calculation by 8.59%.

4.1. Simulation experimental setup

The experimental setup shown in Figure 3 is used to simulate the setback overload during the operation of the piezoelectric generator. The standard sensor and the piezoelectric stack power supply are fixed on the force hammer at the same time, and the setback overload of the projectile is simulated by the overload generated by the force hammer hitting the cast iron plate, and the pulse width of the load can be changed by laying a cushion between the force hammer and the cast iron plate. Since the piezoelectric stack and the force hammer have the same acceleration, the acceleration felt by the piezoelectric stack can be read by a standard.
4.2. Experimental results

4.2.1. Output results of single-layer piezoelectric sheet. Piezoelectric stacks are made of piezoelectric sheets connected in parallel, so ideally the voltage waveform of the piezoelectric stack should be consistent with the output waveform of the piezoelectric sheet voltage. However, due to the bonding process and leads, the waveform output of the piezoelectric stack under high shock loads can appear abnormal and other phenomena. Therefore, before testing the piezoelectric stack, the output waveform of the single-layer piezoelectric is first observed to determine the form of the normal output waveform of the piezoelectric stack under shock loads.

The voltage output of the single-layer piezoelectric sheet is shown in Fig. 4(a). The light curve is the piezoelectric sheet output waveform, and the dark curve is the sensor output waveform, i.e., the waveform of impact acceleration. It can be seen from the figure that when the shock acceleration reaches a large value, the piezoelectric sheet is subjected to the maximum load, and the output voltage of the piezoelectric sheet is the highest at this time. Due to the impedance mismatch problem, the voltage drops again during the transfer of the piezoelectric sheet surface charge to the oscilloscope. When the shock load disappears, the piezoelectric resumes deformation reverse excitation charge, thus leading to reverse voltage generation. Since the oscilloscope impedance is larger resulting in a slower charge transfer rate, the voltage decreases at a lower rate than the acceleration signal decay rate. The output curve of the acceleration sensor shows that the acceleration signal remains after the end of one shock, which may be caused by the stress wave propagation between the solids, which may also lead to the deformation of the piezoelectric sheet generation.

Figure 4(b) shows the output waveform of the single-layer piezoelectric sheet after thickening the buffer pad. It can be seen that the piezoelectric sheet waveform is smoother and the pulse width of the waveform becomes wider, but because the impact energy is certain, the amplitude of the output waveform will drop significantly after adding the buffer pad impact, so the subsequent experiments are still loaded by hammering without the buffer pad.

Figure 4. Output waveform of single-layer piezoelectric sheet.
4.2.2. Output results of the piezoelectric stack. To test whether the piezoelectric stack has a normal output waveform, the voltage output of the piezoelectric stack is tested, and the experimental results are shown in Figure 5. The output waveform of piezoelectric stack is consistent with that of single-layer piezoelectric sheet, i.e., when the acceleration is the highest, the piezoelectric sheet is under the maximum force and the output voltage is the highest, and the voltage decreases gradually with the transfer of charge, and the secondary voltage is generated due to the recovery of the deformation of the piezoelectric sheet.

The voltage output corresponding to different shock accelerations is shown in Fig. 6, from which it can be seen that the output voltage of the piezoelectric stack tends to increase approximately linearly as the shock acceleration increases.

4.2.3. Charging performance of piezoelectric stacks. The piezoelectric stack power management circuit uses a full-bridge rectifier circuit, and the energy storage capacitor is selected to be 4.7 μF. The charging curve of the capacitor under 17400 g shock overload is shown in Figure 7. The power generated by the piezoelectric stack charges the 4.7 μF capacitor to 7.8 V within 400 μs after the power management circuit.

The charging voltages of the capacitors under different impact accelerations are shown in Fig. 8. From Fig. 8, it can be seen that the voltage values across the capacitor are proportional to the load applied to the stack, and after fitting, the peak input load and the output voltage satisfy.

\[
U = 3.94153 \times 10^{-4} a + 0.64667 \tag{11}
\]

The experimental results in the literature [7] show that the voltage across the energy storage capacitor is linearly related to the pressure when the piezoelectric stack is subjected to a load in the range of 0-15 kN. The paper produced a composite generator with a piezoelectric stack subjected to a pressure less than 15 kN under a 50,000 g overload, so this equation (11) is applicable to the whole ballistic overload process. Using this linear relationship, it is estimated that the piezoelectric generator can charge the 4.7 μF capacitor to 20.35 V under 50,000 g overload, which is much larger than 16.8 V. In addition, the
experiments show that the time required to charge the capacitor voltage to a stable value under different loads is less than 1 ms, so the piezoelectric generator can reliably supply power for decoding and standby processes.

5 Conclusion
The experimental results show that the output voltage of the piezoelectric generator increases with the increase of the load, and the output voltage of the generator shows a linear relationship with the load; when the piezoelectric power supply charges the capacitor, the voltage across the storage capacitor also shows an approximately linear relationship with the load, and the linear relationship is used to deduce that the piezoelectric generator can charge the 4.7 $\mu$F capacitor to 20.35 V under 50000 g overload, which meets the demand of physical power supply for small caliber ammunition.

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