# Evaluation and verification of energy recovery for piezoelectric vibration

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**Abstract**

Due to the piezoelectric effect of piezoelectric ceramics, it was used to convert environmental vibration energy into electrical energy for storage and utilization. This energy recovery method is widely used in the microelectronics field. In order to be able to quickly match the piezoelectric vibrator with higher energy conversion efficiency, focus on the copper-based material and its thickness, and loading mass. In an experimental environment with random vibration at a=2m/s^2, frequency 25 Hz-125 Hz, controlled a single variable to carry out which could be better. It is concluded that when the copper-based material was beryllium copper with a thickness of 0.25 mm and the mass of the mass is 30g or more, the power generation performance was optimal. At the same time, the theoretical analysis of the power generation of the piezoelectric vibrator is carried out in this paper, and the experimental results are in agreement with the theoretical results.

**Keywords**

piezoelectric vibrator; energy recovery; mechanical structure; equivalent circuit

**Introduction**

In the modern microelectronics technology field, energy recovery is becoming more and more important. Information technology has not driven the rapid development of energy technology(Roundy S et al. 2005). In order to solve the environmental pollution caused by current chemical energy batteries, it is difficult to recycle, waste materials, etc. Recycling power generation is carried out for many research and exploration. Research on piezoelectric ceramic vibration power generation technology has made great progress, and it has broad application prospects in wireless sensor network self-power supply.

The piezoelectric ceramics will generate electric charge and accumulate on the surface. Silver plating can be used as the positive and negative poles of the power supply, but the energy of this part is weak, due to the limitation of the piezoelectric material. Related research shows the open voltage of the tested piezoelectric oscillator (58 mm ×30 mm ×0.7 mm) is 14.8V at vibrating frequency of 44.3 Hz. Accordingly, the optimal analytical/ tested load resistance of the AC2 and DC2 circuit s are 72/ 71 kΩ and 113/ 110 kΩ, and the maximal analytical/ tested power are 0.76/ 87 mW and 0.49/ 4.7 mW, respectively (Tang et al. 2009). The temperature and humidity sensor node developed by piezoelectric ceramic, which can transmit the detected information through a wireless transmitter. These sensors include a small piezoelectric power generating device that can convert the vibration energy in the environment into electrical energy to maintain the sensor node work, so there is no need to replace the battery or charge (S W. Arms et al. 2005). Priya, an electrical engineer at the University of Texas, designed a pocket windmill that uses a cam to rotate a series of piezoelectric crystals to produce electricity (Priya et al. 2005). In terms of theoretical research, the composite ceramic series-parallel theoretical model method, these characteristics are simple and easy to understand. But it ignores the influence of internal electric field on energy conversion efficiency, so that the derived expression can't accurately reflect the power generation characteristics of the piezoelectric device. The model obtained by simulating the electromechanical coupling process of the piezoelectric crystal by the equivalent converter is equivalent to the circuit, and the difficulty is that the acquisition of the simulation parameters must be determined experimentally (S.ROUNDYS & P.K.WRIGHT 2003). Domestic scholars have revised the foreign models to propose a theoretical model using the new 1-3-2 piezoelectric ceramic node parameters and piezoelectric constants. The disadvantage is that the positive polarity is too strong for other types of piezoelectric ceramics (Li et al. 2007). Using the equivalent circuit to establish the differential equation of the output circuit, solving the differential equation, and then deriving the relationship between the performance parameters to derive the expression between the performance parameters, the model is more versatile (Wei et al. 2008).

The research on piezoelectric ceramic power generation technology has made great progress, but there is no more detailed means and theoretical basis for its vibration energy evaluation. In this paper, the parameters affecting the performance of piezoelectric ceramics, such as piezoelectric substrate material and thickness, vibration environment and loading quality, are analyzed and experimentally verified, and a more complete energy recovery evaluation method is obtained.

## Theoretical analysis

### Copper based material

Piezoelectric ceramics are brittle and need to be combined with statistical materials to withstand vibrations in the environment. The choice of copper-based materials mainly requires attention to two basic parameters of strength and elastic modulus, where the strength includes tensile strength and hardness, and the elastic modulus includes Young's modulus and shear modulus. According to the relevant literature investigation and parameter comparison, three kinds of copper-based materials with more common performance and excellent performance were selected, and manganese white copper was used as the thickness sample, and the substrates of 0.2 mm and 0.25 mm were prepared for testing.

**Table1. the properties of copper-based material**

| copper-based material | strength | | Elastic Modulus | |
|---|---|---|---|---|
| | tensile strength (MPa) | Hardness (HV) | Young's modulus (E/GPa) | Shear modulus (GPa) |
| Phosphorus copper | 686-980 | 160-260 | 103 | 45 |
| Beryllium copper | 1098-1373 | 350-430 | 130 | 48 |
| Manganese white copper | 1470 | 450 | 153 | -- |

The same copper-based material of 0.2 mm is loaded with 30g mass in the random vibration environment with acceleration a=2m/s^2 and frequency 25 Hz~125 Hz, and the open circuit voltage is fixed by the simple support at both ends. 3.6V to charge 680 microfarad capacitors, the largest charging power is beryllium copper, up to 0.9792 mW.

**The thickness of copper base material**

The sample that measures the influence of the variation of the thickness of the statistical material on the power generation efficiency is only a group of manganese white copper. Under the same experimental environment, the manganese white copper with a thickness of 0.25 mm is more excellent than 0.2 mm.

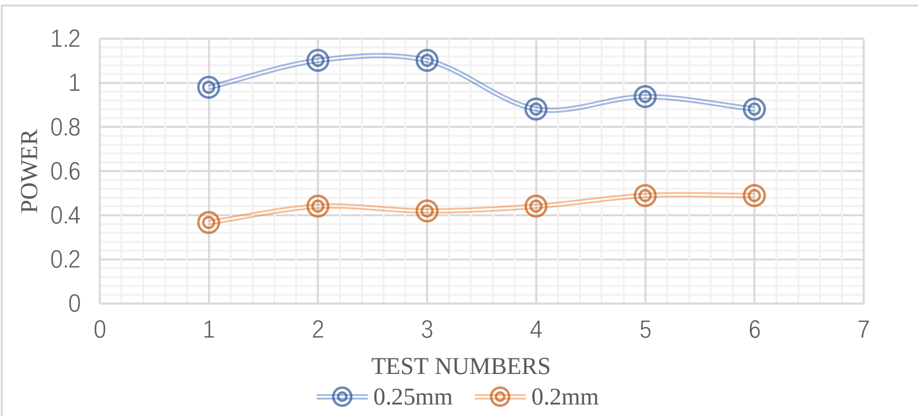


**Fig 1. the power of differences thickness with Manganese white copper**

In comparison, 0.25 mm manganese white copper is more efficient than 0.2 mm beryllium copper under the same experimental conditions. However, due to the lack of experimental samples, it is not clear whether the 0.25 mm copper beryllium charging effect will be better. Will be further verified.

It can be seen from the experimental data that the thickness variation of the copper-based material has a great influence on the charging efficiency of the piezoelectric ceramic. The manganese white copper only increases the thickness by 0.05 mm, and the charging efficiency is obviously improved, which is more than doubled.

**power**

Piezoelectric materials have a piezoelectric effect. The piezoelectric effect is caused by the deformation (elongation and compression) of the crystal under the action of mechanical force, causing the relative displacement of the charged particles (offset from the equilibrium position), so that the total electric moment of the crystal changes. The result is divided into two aspects: positive piezoelectric effect and inverse piezoelectric effect, which are coupled together. If a variable electric field is applied to the piezoelectric ceramic, it will alternately elongate and compress, that is, vibration will occur. Conversely, when the piezoelectric ceramic mechanically vibrates, an electric field will also be generated. Therefore, the piezoelectric ceramic can be used to generate electricity by vibration.

In this article, a rectangular metal substrate is attached to the piezoelectric ceramic on both sides, and a mass is added to increase the shape variable of the piezoelectric ceramic to improve the efficiency of converting vibration energy into electrical energy. The fixed simple support method can restrain the square vibration of the piezoelectric vibrator formed by the combination of the mass, the metal substrate and the piezoelectric ceramic in addition to the vertical vibration, which increases the stability and reliability of the piezoelectric vibrator. The schematic diagram of the piezoelectric vibrator is as follows:

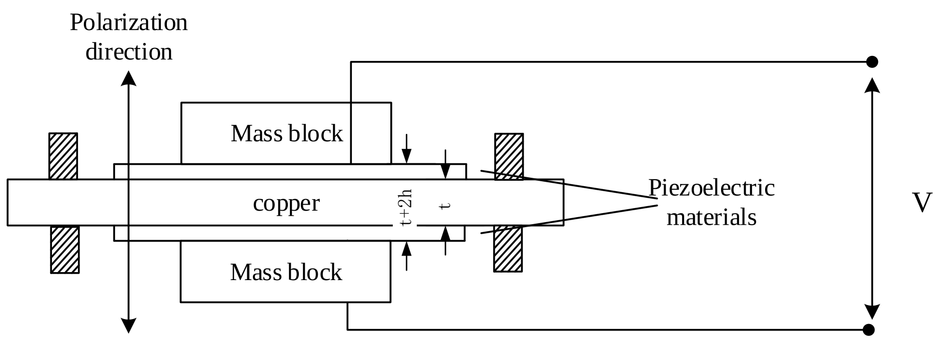


**Fig 2. Piezoelectric vibrator**

When the piezoelectric ceramic is deformed, electric charge $Q$ can be generated on the surface to form an electric field. The generated charge can be stored by an external storage circuit. The expression of the charge generation amount is as follows:

$$Q = d_{33}F \tag{1}$$

The equivalent capacitance $C$ of piezoelectric ceramics is calculated as follow:

$$C = \frac{\varepsilon S}{h} \tag{2}$$

Where $\varepsilon$ and $h$ are the dielectric constant and thickness of the piezoelectric ceramic, respectively, and $C$ is the internal equivalent capacitance of the piezoelectric ceramic. $S$ is the surface area of the piezoelectric ceramic.

Since the piezoelectric material is an elastic material and satisfies Hooke's law, the relationship between the force $F'$ acting on the sheet ceramic and causing the shape variable $\Delta x$ to occur is as follows:

$$F' = K\Delta x \tag{3}$$

In the voltage $V = Q/C$ generated in the thickness direction of the piezoelectric ceramic, than substituting equation (1) and equation (2) ,the voltage can be expressed as follow:

$$V = \frac{Q}{C} = \frac{d_{33}F'h}{\varepsilon S} \tag{4}$$

Substituting (1)-(4) with the power $P = V^2 / r$ generated by the piezoelectric element, the specific expression as follow:

$$P = \frac{V^2}{r} = \frac{d_{33}K^2\Delta x^2 h^2}{\varepsilon^2 S^2 r} \tag{5}$$

The above power is the power generated by the monolithic piezoelectric ceramic. Once the size and material of the piezoelectric vibrator are determined, the change in power is generally only related to the shape variable $\Delta x$, and the factors affecting the shape variable include the characteristics of the vibration environment, and the support mode. And the quality of the loaded mass.

Actually, there are many key characteristic parameters of piezoelectric materials can affect conversion efficiency, such as piezoelectric ceramic area $S$ (Cho et al.2005), dielectric constant $\varepsilon$ (Yang et al. 2005), number of layers of piezoelectric crystal (NG & LIAO 2005) and so on.

**Calculate the shape variable** $\Delta x$

The model with mass is excited by the outside. The love excitation is a sinusoidal excitation with amplitude A and frequency w. In the model of the excitation transmission band, it can be regarded as the force acting on the piezoelectric oscillator. Point at the center of the piezoelectric vibrator (because the mass between the mass and the piezoelectric vibrator is bolted, it can be seen as the point of force at the midpoint).

Under this excitation, the deflection at the midpoint is the largest, and the angular machine angle change rate at this point is zero, so it can be equivalent to the fixed end. Moreover, the model should be symmetrical and the force is the same, so only half of it can be calculated.

The model can ultimately be equivalent to a variable-section cantilever beam structure, as shown on the right side of the figure below:

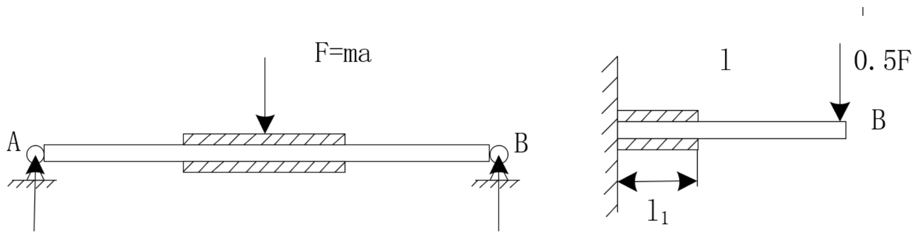


**Fig 3. Equivalent cantilever beam deflection calculation**

The force applied at the center is the force $F$ of the acceleration change. After it is equivalent to the cantilever beam variable section model, the force at the free end is $0.5F$ , and the deflection of the free end is the deflection of the midpoint.

Due to it is symmetrical model, so it can be equivalent to a cantilever beam. The deflection of the middle portion before the equivalent is the deflection of the free end of the cantilever beam. Because the model can be regarded as a variable-section beam and equivalent tempering, it can be calculated and calculated according to the calculation formula of the material mechanics variable-section beam ( $F$ is external incentives, that is mass block in this paper ) . And the expression of shape variable $\Delta x$ show as follow:

$$\Delta x=\frac{\frac{1}{2}Fl_1^3}{3E_1I_1}+\frac{\frac{1}{2}F(l-l_1)l_1^2}{2E_1I_1}+\left(\frac{\frac{1}{2}Fl_1^2}{2E_1I_1}+\frac{\frac{1}{2}F(l-l_1)l_1}{E_1I_1}\right)(l-l_1)+\frac{\frac{1}{2}F(l-l_1)^3}{3E_2I_2} \tag{6}$$

The moment of inertia of a rectangular beam is:

$$I_1 = \frac{bh^3}{12} \tag{7}$$

$$F = ma \tag{8}$$

$$a = A\sin(\omega t) \tag{9}$$

It is known from the simple derivation of material mechanics that the size of the shape variable is related to the quality of the mass and also to the environment. The acceleration a in the equation (9) is an environmental vibration acceleration which is set to sinusoidal vibration. The conclusions obtained are consistent with the conclusion of the maximum power above.

**Mass block**

The m in formula (8) is the quality of the loaded mass. The greater the weight of the mass, the greater the force applied to the piezoelectric ceramic. The larger the deformation of the piezoelectric ceramic, the mass and energy of the loaded mass. Conversion efficiency should be positively related as follow:

$$m \propto P \tag{9}$$

However, considering the service life of the piezoelectric vibrator and the size of the device, it is a good choice to use a brass holder mass with a high density. The mass of the mass should not be too large, otherwise the piezoelectric vibrator is prone to damage. Piezoelectric vibrators with piezoelectric ceramics on both sides, the effect of mass distribution on both sides is better than that of single-side plus mass. The 30g mass is significantly faster than the 20g and 10g masses, and the specific comparison of the two charges is as follows:

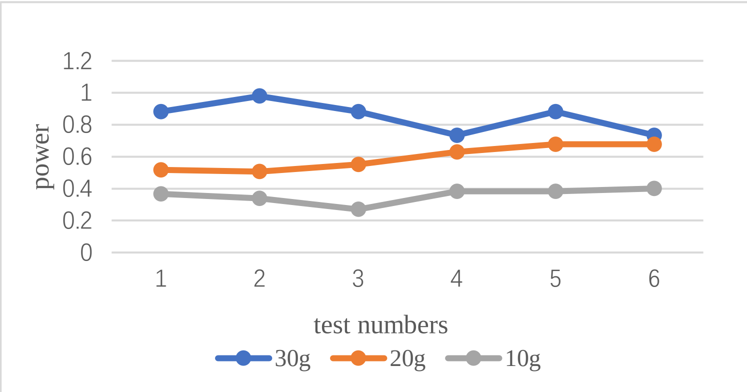


**Fig 4. The power of beryllium copper among different quantity masses**

If load mass quantity is less than 10g, almost no power were generated when Piezoelectric vibrator converted vibration energy into electric energy. But there is no doubt that the quantity of mass block should be more than 30g, which can meet the exchange power requirements.

## Conclusion

The base material has a great influence on energy conversion. For the selection of copper-based materials, two key parameters of strength and elastic modulus should be concerned. Suitable copper-based materials can improve the working performance and service life of piezoelectric ceramics. The thickness of the copper-based material is not reflected in the power calculation, but according to the experiment, it can be concluded that the statistical material with a thickness of 0.25 mm has better energy conversion performance and can increase the strength of the piezoelectric oscillator. The external loading mass can increase the deformation of the piezoelectric ceramic, accelerate the charge accumulation speed, and increase the energy. The quality of the mass needs to reach more than 30g to ensure that the collected energy meets the trigger value of the general sensor.

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