



Energy Collector Based on Piezoelectric Nano Materials in the Power Supply System to Improve the Efficiency of Industrial Internet of Things (IIoT) for Industry 4.0

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ABSTRACT

Due to the strong electromechanical coupling, small size and high sensitivity, piezoelectric nanomaterials have been widely used in generators, sensors and other fields. In this paper, the characteristics of energy collector in IIoT power supply system based on piezoelectric nano-materials are analyzed. PVDF piezoelectric nanofibers are prepared by electrospinning technology. The material and control chips are integrated into a bimodal piezoelectric energy collector. The effectiveness is analyzed experimentally. The experimental results show that the resonant frequency of energy collection varies with the length of the cantilever arm. When the length of the cantilever arm is 12mm, the installation error of 1.0mm length leads to 3.5% of the resonant frequency error. The optimal load of piezoelectric vibration collectors with different cantilever arms is 400K. The output power of CUB, BRG and BTG are $50.7 \mu W$, $55.6 \mu W$ and $51.8 \mu W$, respectively. At the same time, the working frequency band of energy collectors with various cantilever structures is 12Hz to 18Hz. The optimal excitation frequency is 16Hz. In summary, the energy collector of power system constructed by piezoelectric nano-materials proposed by many researchers has high efficiency, which can provide a quick solution for IIOT in Industry 4.0 and enhance the power generation mechanism. It is of great significance to the development of IIOT in practice.

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1. INTRODUCTION

The mini energy collectors based on environmental energy acquisition and conversion technology have received extensive attention at industry 4.0 [1]. The micro-vibration energy collector converts the vibration energy in the environment into electric energy, which has the advantages of green environmental protection. The technology has the advantages of simple structure, low maintenance cost and small size. It has important practical value in wireless sensor network systems such as environmental safety and structural health monitoring and has become the potential research direction in the field of micro energy for industry 4.0. The vibration energy collector has a high-quality factor and high output performance during resonance, but the resonant frequency cannot be changed with the vibration frequency of the environment. The bandwidth is narrow.

It cannot work with the vibration environment with a large frequency variation. However, for a specific application environment, the vibration generally has some dominant frequencies. At these dominant frequencies, the vibration energy density is large, and the peak point is corresponding to the spectrogram. To maximize the output power of the micro-vibration energy collector, the resonant frequency must be consistent with the dominant frequency in the environment.

The Industrial Internet of Things (IIoT) is powered by traditional batteries. The battery life is limited and needs frequent replacement. This conventional technology increases environmental pollution as well. The energy collector supplies power to ultra-low-power microprocessor devices by extracting energy from the surrounding environment (such as wind, heat and vibration). Since the vibration energy collector has the characteristics of low cost and high power, it has attracted

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the interest of researchers. At present, the vibration electromechanical conversion mechanism is mainly realized by three mechanisms of electrostatic field, electromagnetic field and piezoelectric energy. Among them, piezoelectric vibration energy collectors do not require additional power when converting mechanical energy to electrical energy. It has positives of easy fabrication, simple electromechanical structure and high power density. Therefore, the piezoelectric vibration energy collector became a hot area of research in the field of micro energy research for industry 4.0. The energy collector in the IIoT power supply system can convert the surplus mechanical energy into electrical energy in the environment. It has the advantages of wide application range and high output voltage. It can supply power to low-power sensors [2]. However, most of the research on piezoelectric energy collectors focuses on the energy harvesting performance in the atmospheric environment, and the characteristic analysis has still to be further explored. In addition, traditional piezoelectric power generation materials such as ZnO still have problems such as high toxicity, poor flexibility or low mechanical durability, which restricts their practical application in the field of micro-nano-scale piezoelectric power generation in industry 4.0. Polyvinylidene fluoride (PVDF) is an organic piezoelectric material with excellent piezoelectric properties, good flexibility and biological phase fusion. PVDF piezoelectric nano fibers are prepared by electrospinning technology. The material can be applied to the energy collector in an IIoT power supply system based on piezoelectric nano materials, which is of great significance for improving collection performance and promoting the development of the IIoT [3]. The energy collector based on piezoelectric nanomaterials has attracted wide attention from researchers. This piezoelectric "Nano-generator" converts dynamic mechanical energy into a higher piezoelectric energy, producing a pulsed AC high-voltage output to the external circuit that can be used to drive low-power microelectronic devices and nano-sensor devices in industry 4.0 to promote IIoT. It has shown great potential for building self-powered systems.

Most of the research studies on piezoelectric nano materials, piezoelectric power generation devices and self-powered systems focus on the collection of energy generated during solid state contact. It is necessary to artificially input mechanical energy and control it to produce stable dynamic changes to achieve stable continuous electric pulse output [4]. The spontaneous acquisition should also be achieved along with the continuous electric pulse. Compared with the air flow in an open environment [5], the microfluidic chip technology can control the gas phase or liquid phase fluid in a smaller enclosed space. Therefore, it is an ideal platform for constructing micro-nano-scale power supply systems. The challenge is the assembly of piezoelectric materials in the chip and the oscillation under the action

of micro fluids to construct the microfluidic energy collectors. In addition, it has also been widely used in the manufacture of masks. In the modern medical market, this material can effectively reduce the harm of airborne virus transmission [6]. In the nano biosensor, it also effectively reduces the impact of plant pathogens on crop productivity [7]. During COVID-19, nanomaterials played an important role in the medical Internet of Things industry, effectively improving the performance of biosensors [8].

The energy collector is usually composed of a cantilever beam and a mass, which is a typical second-order vibration system. The resonant frequency is determined by the stiffness of the cantilever beam, the equivalent mass of the system and the pre-stress. The commonly used adjustment methods include cantilever beam length adjustment, pre-stress adjustment and mass adjustment. The cantilever beam length adjustment method is simpler [9]. However, for the mini energy collector of a micro-electromechanical system, once the length of the cantilever beam cannot be changed after the process is completed, other adjustment methods can be used. In addition, smart masks driven by the nano Internet of Things can effectively resist hazardous substances in the air, so as to protect human health. At the same time, the nano Internet of Things has inspired the emergence of intelligent plant pathogen diagnosis biosensors, making them develop towards the fifth generation of intelligent biosensors based on 2D MXenes, and gradually being applied to hospitals. It is worth noting that by 2021, the global market scale of the nano Internet of Things has reached 38.8 billion yuan, with a huge market scale and broad prospects. However, there is still a gap in the scale of the current nano Internet of Things market in China, which is mainly reflected in the investment of private capital. There are also gaps in the corresponding research. The research on nanotechnology in China is still in infancy, and there is still a big gap between China and foreign countries.

1. 1. Related Work To produce dynamic changes to achieve stable electric pulse output, Hao et al. [6] have assembled an airflow conditioning structure and combined it with a piezoelectric power generation device. The spontaneous pulse without interference in the mechanical energy of the fluid form can produce a stable electrical output. This result is of great significance for promoting piezoelectric power generation devices and their applications in industry 4.0 for self-powered systems. Almonacid et al. [10] have changed the pre-stress of the cantilever beam by magnetic attraction and repulsive force. The resonance frequency is adjusted between 67.6-98Hz, but the structure is somewhat complicated. Zhuang et al. [11] have processed the cantilever beam using MEMS technology, and printed the colloidal mixture of zinc particles. By changing the mud concentration and viscosity at the resonant

frequency of 0.1, Hz can be changed at a minimum, but the operation is difficult. Wang et al. [12] have changed the centroid of the mass by rotating the screw on the mass to realize the adjustment of the resonant frequency of the device. The screwing and unscrewing of the screw can increase or decrease the resonant frequency. The result can be directly adjusted in the range of 130-180 Hz for generating quick power.

Many scholars have done a lot of research work to improve the performance of piezoelectric energy collectors for industry 4.0. Lu et al. [13] have used the method of optimizing parameters to establish mathematical theoretical models to broaden the frequency. But they ignore the relationship between internal impedance and optimal load impedance of energy collectors. It does not accurately indicate the nature of maximizing output power. Abasian and Tabesh [14] have studied broadband by using the method of adjusting the frequency. However, this kind of situation can only work when the frequency changes slowly. The accuracy of the frequency regulator is higher, and the intelligent micro-regulator is difficult to implement. Arunkumar et al. [15] have introduced the dynamic amplifier to build the mathematical model to study the broadband piezoelectric energy collector, but it ignores the electromechanical coupling effect of the energy collector.

Xie et al. [16] have used dynamic amplifiers to determine the electromechanical model and studied the effects of dynamic amplifiers on output power, but they ignored the effects of system damping and load resistance on system performance. In response to the above drawbacks, the characteristics of the energy collector in the IoT power supply system based on piezoelectric Nano materials are analyzed. The prepared PVDF Nano fibers are used to construct the piezoelectric energy collector in the IoT power supply system. The characteristics are analyzed effectively by the characteristic analysis method, which provides a basis for improving the performance of the piezoelectric energy collector.

There is a scope for further innovations to generate quick power for Industrial IoT and for industry 4.0, Hence, the energy collector based on piezoelectric Nano materials in the power supply system is proposed in this paper.

1. 2. Research Contributions In this paper, the author has described PVDF piezoelectric Nano fibers.

By using electrospinning technology, these PVDF piezoelectric Nanofibers are prepared, which are then applied to the energy collector of the IoT power supply system to analyze the features of the energy collector. This concept assists in improving the performance of the piezoelectric energy collector.

Piezoelectric Energy Collector Modeling and theoretical concepts are discussed in the paper. The

distributed parameter model and Single-degree-of-freedom model are also analyzed.

To analyze the characteristics of the vibration energy collector, a single-degree-of-freedom model is used.

The characteristics of energy collectors in power supply systems based on piezoelectric nanomaterials are discussed with three topologies, including CUB (uniform cantilever beam structure), BRG (the non-uniform cantilever beam structure with rectangular grooves) and BTG (the non-uniform cantilever beam structure with triangular grooves).

The results show that the output voltage and performance of the non-uniform cantilever beam structure (BRG) with rectangular grooves is significantly higher than that of CUB and BTG under different load conditions. The output power is much larger than that of the uniform cantilever beam structure.

The specific latest technology is shown in Figure 1.

The research is structured into 5 sections. The proposed research is described in section 2. Results are discussed in section 3. Development of the Industrial IoT's and devices are discussed in section 4. The outcome is discussed in section 5 as conclusions.

2. PROPOSED METHOD

2. 1. Preparation of PVDF Nanofibers The PVDF piezoelectric nano fibers are prepared through electrospinning technology. The material is applied to the energy collector of the IoT power supply system based on piezoelectric nano materials to analyze the features of the energy collector. The PVDF powder (molecular weight 534000, Sigma-Aldrich) is used as a precursor. Acetone and N-dimethylformamide (DMF, both purchased from Sinopharm Group) are used to configure an electrospinning precursor. Microelectrodes and microfluidic chip abrasives are prepared using AZ5214-ESU9-GM1070 photoresist. Microfluidic chips are assembled using polydimethylsiloxane two-component silicone rubber (PDMS, Sylgard 184).

DMF and acetone are mixed in a ratio of 3:7 by volume and stirred uniformly. The concentration of the PVDF precursor fluid is configured as needed. A certain amount of PVDF powder is weighed, mixed with the

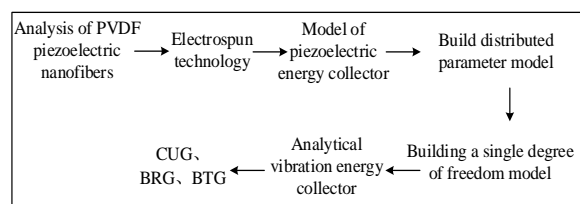


Figure 1. Schematic diagram of the overall concept and corresponding technologies of the research organization of the paper

mixture of DMF and acetone. It is heated and stirred for 2 hours at 60°C to obtain the clear transparent liquid as the electrospinning precursor solution. The precursor fluid is drawn into the syringe and the syringe is mounted on a microinjection pump (Longerpump TJP-3A/W0109-1B). The syringe needle is joined to the positive pole of the DC voltage source, and the two aluminum foils attached to the receiving plate are joined to the negative pole of the DC voltage source [17]. The direction of the needle is perpendicular to the surface of the receiving plate and the distance is 15 cm. Thereafter, spinning is carried out under the conditions of a voltage of 13 kV, a propulsion speed of 50 L/min, an ambient temperature and humidity of 35°C and 30% RH, respectively. The PV wafer is attached to the parallel aluminum foil of the receiving plate to receive PVDF nanofibers. The spinning time is 30 min. After the end of the spinning, the substrate covered with the PVDF nanofibers is taken out and placed in a drying oven at 80°C for 1h to remove excess solvent. The obtained white fiber membrane is the prepared PVDF Nanofiber.

2. 2. The Construction of Piezoelectric Energy Collector and Theoretical Model

The prepared PVDF nanofibers are applied to an energy collector of an IoT power supply system. The structural diagram of the piezoelectric vibration energy collector in the IoT power supply system is shown in Figure 1. The entire energy collector consists of the single-degree-of-freedom piezoelectric bimorph cantilever system with a concentrated mass M_t at the end and the elastic-amplifier system consisting of a spring-mass-damping. The piezoelectric cantilever system consists of the metal substrate, the bimorph (integrated by piezoelectric nanofibers and a control chip), the terminal concentrated mass M_t , and the load circuit. The bimorphs PZT1 and PZT2 are bonded to the upper and lower surfaces of the metal substrate by epoxy resin. They are polarized in the thickness direction [18]. The polarization directions are opposite (as shown in Figure 2 “↓” and “↑”). They are connected in series to the applied load resistor R_L . The resistance is the equivalent impedance of the AC-DC circuit, filter circuit, and resistor R connected to the electrical output of the energy collector. The change in load resistance R_L reflects the change in the equivalent impedance at the output.

The Elastic Amplifier system consists of a spring mass damping system, with mass, stiffness and damping coefficients of M_b , K_b and C_b , respectively. The left end of the piezoelectric bimorph cantilever is fixed to the mass M_b of the elastic amplifier. The elastic amplifier is mounted on the foundation. y is the fundamental vibration displacement. i is the current flowing through the load resistor R_L . Through the elastic amplifier

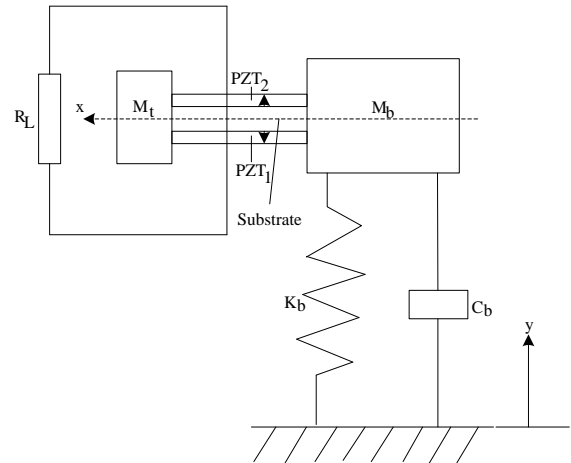


Figure 2. Piezoelectric cantilever vibration energy harvester structure

system, the vibration generated by the foundation is amplified and transmitted to the piezoelectric bimorph cantilever system. It amplifies the bending vibration displacement of the piezoelectric bimorph cantilever system to improve the output capacity of the energy collector.

2. 3. Theoretical Models

The theoretical model of cantilever beam-mass block structure has distribution parameter model and single degrees of freedom model. The distributed parameter model requires an equation to calculate the frequency. This process is complicated and has high precision. In the actual operation process, because of installation error in the dimensions of the piezoelectric cantilever beam, the distributed parameter model also causes an error in the resonant frequency of the structure.

The single-degree-of-freedom model simplifies the structure into a spring-mass system. The single-degree-of-freedom model is used to analyze the characteristics of the vibration energy collector. The single degree of freedom model of the vibration energy collector is shown in Figure 3.

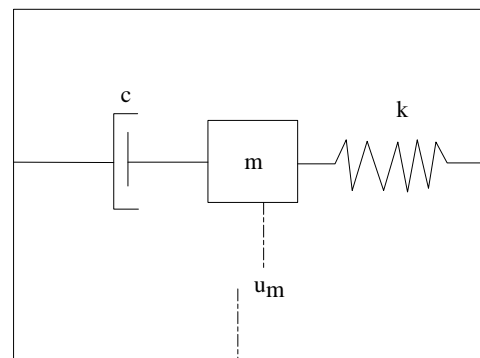


Figure 3. Single degree of freedom equivalent model

The cantilever beam is equivalent to the spring with a spring constant k . The system mass m is the sum of the mass m_0 and the equivalent mass m^* of the piezoelectric cantilever. Where, $m^* = \frac{33}{140}m_b$. m_b is the mass of the cantilever beam. The damping coefficient c of the system includes mechanical damping and electrical damping, which is approximately equivalent to linear viscous damping [8]. The vibration Equation (1) is as follows:

$$m\ddot{u}_m + c\dot{u}_m + ku_m = ma \quad (1)$$

where u_m is the displacement of the centroid in the z direction. a is the environmental acceleration.

The resonant frequency of the vibrating energy collector is given in Equation (2).

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad (2)$$

By changing the mass m , the adjustment of the structural resonance frequency can be achieved [19]. In the equilibrium state, the concentrated force F_m is exerted by the centroid of the mass. The elastic restoring force $F = -ku_m$ of the cantilever is balanced.

The displacement $u(x)$ of the cantilever beam is shown in Equation (3):

$$u(x) = \frac{F_m}{6EI} x^2 [3(l + l_m/2) - x] \quad x \in [0, l] \quad (3)$$

where EI is the section bending stiffness of the cantilever beam; l and l_m are the length of the cantilever beam and the mass. The centroid displacement of the mass is shown in Equation (4):

$$u_m = u(l) + \frac{l_m}{2} \left. \frac{\partial u(x)}{\partial x} \right|_{x=l} \quad (4)$$

The elastic coefficient of the cantilever beam can be obtained from the mechanical equilibrium relationship as given in Equation (5).

$$k = \frac{F}{u_m} = \frac{12EI}{4l^3 + 6l^2l_m + 3ll_m^2} \quad (5)$$

2. 4. Characteristics of Energy Collector (EC)

The piezoelectric EC theoretical model is used to analyze the characteristics of the energy collector. The characteristics are based on energy collected, voltage amplitude, motion displacement and output voltage. This sub-section derives the EC characteristics through mathematical modeling.

The energy collector output voltage amplitude and phase angle expression are given in Equations (6) and (7).

$$V = \frac{U\omega^2}{\kappa \sqrt{(\lambda_e^2(A) - \omega^2)^2 + 4\delta_e^2(A)\omega^2}} \quad (6)$$

$$\vartheta_V = \tan^{-1} \left[-\frac{2\delta_e(A)\omega}{\lambda_e^2(A) - \omega^2} \right] + \tan^{-1} \frac{a_3}{\lambda} \quad (7)$$

where, $\delta_e(A)$ represents the attenuation coefficient of the amplitude function of piecewise linear piezoelectric system with single degree of freedom. $\lambda_e(A)$ represents the equivalent linear natural frequency of a single-degree-of-freedom piecewise linear piezoelectric system. $\kappa = \sqrt{\alpha_2^2 + \lambda^2} / (\alpha_2\lambda)$ represents the proportional parameter between the system's motion displacement and the output voltage.

Considering the proportional relationship between the output voltage of the energy collector and the motion displacement [20], the displacement solution characteristics of the energy collector are first determined. Assuming that the motion displacement kinetic singularity of the energy collector dynamic differential equation is (A_0, ϑ_0) , the expressions of the energy collector's displacement and the initial phase angle versus time are given in Equation (8).

$$\begin{cases} \frac{dA}{dt} = -\frac{U\omega^2}{2\lambda} \sin \vartheta - \delta_e(A)A \\ \frac{d\vartheta}{dt} = -\frac{U\omega^2}{2\lambda A} \cos \vartheta + \lambda_e(A) - \omega \end{cases} \quad (8)$$

The singularity (A_0, ϑ_0) corresponding to the steady-state motion needs to satisfy the following relationship as given in Equations (9) and (10).

$$-\frac{U\omega^2}{2\lambda} \sin \vartheta_0 - \delta_e(A_0)A_0 = 0 \quad (9)$$

$$-\frac{U\omega^2}{2\lambda A_0} \cos \vartheta_0 + \lambda_e(A_0) - \omega = 0 \quad (10)$$

To analyze the characteristic of the output voltage cycle of the EC [21], a small amount of disturbance $(\Delta A_0, \Delta \vartheta_0)$ is applied to the stable point of the energy collector. The expression is given in Equation (11).

$$\begin{cases} A = A_0 + \Delta A \\ \vartheta = \vartheta_0 + \Delta \vartheta \end{cases} \quad (11)$$

Equation (9) is substituted into Equation (11) to obtain Equation (12).

$$\begin{cases} \frac{dA_0}{dt} + \frac{d(\Delta A)}{dt} = -\frac{U\omega^2}{2\lambda} \sin(\vartheta_0 + \Delta \vartheta) - \delta_e(A_0)(A_0 + \Delta A) \\ \frac{d\vartheta_0}{dt} + \frac{d(\Delta \vartheta)}{dt} = -\frac{U\omega^2}{2\lambda(A_0 + \Delta A)} \cos(\vartheta_0 + \Delta \vartheta) + \lambda_e(A_0) - \omega \end{cases} \quad (12)$$

where, $\frac{dA_0}{dt}$ and $\frac{d\vartheta_0}{dt}$ are substituted into Equation (12), and the results are subjected to Taylor series expansion processing. Considering that ΔA and $\Delta \vartheta$ are small

disturbances, the higher order values of ΔA and $\Delta \vartheta$ are negligible relative to the one-time term. Therefore, only the ones of ΔA and $\Delta \vartheta$ are retained, and the expressions of $\frac{d(\Delta A)}{dt}$ and $\frac{d(\Delta \vartheta)}{dt}$ are show in Equation (13).

$$\begin{cases} \frac{d(\Delta A)}{dt} = (-\delta_e(A_0))\Delta A + \left(-\frac{U\omega^2}{2\lambda}\cos\vartheta_0\right)\Delta \vartheta \\ \frac{d(\Delta \vartheta)}{dt} = \left(-\frac{U\omega^2}{2\lambda A_0^2}\cos\vartheta_0\right)\Delta A + \left(-\frac{U\omega^2}{2\lambda A_0}\sin\vartheta_0\right)\Delta \vartheta \end{cases} \quad (13)$$

To obtain the characteristic criteria of increments ΔA and $\Delta \vartheta$, the expression including excitation frequency ω and steady-state motion singularity A_0 is used to replace $\frac{U\omega^2}{2\lambda}\cos\vartheta_0$ and $\frac{U\omega^2}{2\lambda}\sin\vartheta_0$, as shown in Equation (14).

$$\begin{cases} \frac{d(\Delta A)}{dt} = -\delta_e(A_0)\Delta A + (\omega - \lambda_e(A_0))A_0\Delta \vartheta \\ \frac{d(\Delta \vartheta)}{dt} = (\omega - \lambda_e(A_0))\frac{1}{A_0}\Delta A - \delta_e(A_0)\Delta \vartheta \end{cases} \quad (14)$$

The characteristic Equation (14) is derived by Equations (15) to (17).

$$\begin{vmatrix} C_1 - i & C_2 \\ C_3 & C_4 - i \end{vmatrix} = \begin{vmatrix} -\delta_e(A_0) - i & (\omega - \lambda_e(A_0))A_0 \\ (\omega - \lambda_e(A_0))\frac{1}{A_0} & -\delta_e(A_0) - i \end{vmatrix} = 0 \quad (15)$$

Then

$$p = -(C_1 + C_4) = 2\delta_e(A_0) \quad (16)$$

$$q = (C_1C_4 - C_2C_3) = \delta_e^2(A_0) - (\omega - \lambda_e(A_0))^2 \quad (17)$$

The characteristic equation of Equation (15) can be derived by Equation (18).

$$i^2 + pi + q = 0 \quad (18)$$

At the same time, the value of the discriminant Δ can be obtained as in Equation (19).

$$\begin{aligned} \Delta &= p^2 - 4q = (2\delta_e(A_0))^2 - 4(\delta_e^2(A_0) - (\omega - \lambda_e(A_0))^2) \\ &= 4(\omega - \lambda_e(A_0))^2 \geq 0 \end{aligned} \quad (19)$$

Based on the theory of motion stability, since the value of the discriminant Δ is always greater than or equal to zero, the characteristics of the energy collectors is determined by the value of p and q .

When $q < 0$, the two roots of Equation (18) are real roots and different signs. The singularity at this time is unstable, and the steady state motion of the energy

collector cannot be achieved [22]. When $q > 0$ and $p > 0$, the singularity is stable, and the steady state motion of the energy collector can be achieved. At the same time, since $p = 2\delta_e(A_0)$ is the equivalent attenuation coefficient of the energy collector amplitude, indicating that the positive damping $p > 0$ is always true. Therefore, the piecewise linear system stability condition is given in Equation (20).

$$q = \delta_e^2(A_0) - (\omega - \lambda_e(A_0))^2 > 0 \quad (20)$$

Combined with Equation (19), the relationship between the output voltage and the motion displacement

of the energy collectors is $V = \frac{a_2\lambda}{\sqrt{a_3^2 + \lambda^2}}$. The branch characteristics of the energy collector's output voltage amplitude-frequency curve are analyzed.

3. RESULTS

3. 1. Experimental Environment

PVDF piezoelectric Nano fibers prepared by electrospinning technology are used to construct energy collectors in piezoelectric nano material-based IoT power supply systems. The characteristic test instrument of the energy collectors in the constructed piezoelectric nano material-based IoT power supply system is shown in Figure 4.

The energy collector is mounted on the exciter. The sinusoidal signal generated by the signal generator drives the exciter through the power amplifier. The data acquisition module acquires the signal of the acceleration sensor. At the excitation acceleration of 6m/s^2 , the frequency is swept from small to large. The output voltage of the collector is measured by an oscilloscope, and the output voltage at resonance maximized. The resonance frequency of the collected vibration energy collector varies with the length of the cantilever beam as shown in Figure 5.

3. 2. Experimental Observations

From the experimental results in Figure 5, the theoretical



Figure 4. Piezoelectric micro-vibration energy harvester physical map

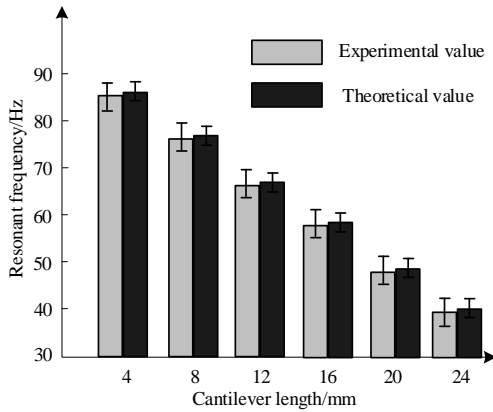


Figure 5. Vibration energy collector resonant frequency with cantilever beam length results

calculation results of the single degree of freedom model established in this paper are slightly higher than the experimental measurements. The error is extremely small. The main reason for the error is that the bending moment of the cantilever beam and the rotation effect of the mass are not considered in the single degree of freedom model. It is not suitable for the characteristic analysis of the mass collector and the short cantilever beam structure energy collector. In addition, the looseness of the base to the cantilever beam causes the increase in the effective length of the cantilever beam. When the length of the cantilever beam is 12 mm, an installation error of 1.0 mm length will cause an error of 3.5% of the resonance frequency.

To effectively analyze the characteristics of energy collectors in IoT power supply systems based on piezoelectric nano materials, the energy collector characteristics of three topologies with CUB, BRG and BTG are studied. When the excitation frequency is 11 Hz and the acceleration is $6m/s^2$, the voltage effective values of the three piezoelectric vibration energy collectors vary with load, as shown in Figure 6.

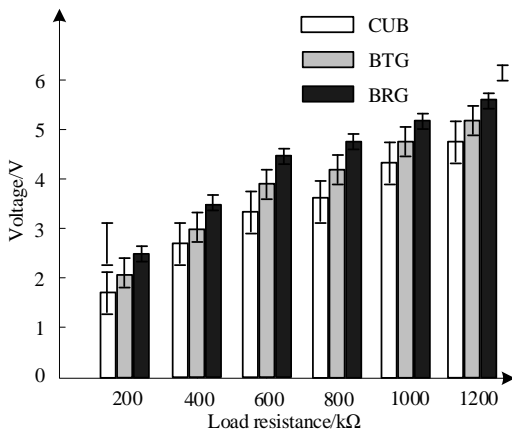


Figure 6. Output voltage varies with load

From Figure 6, the output voltage of the non-uniform cantilever beam structure (BRG) with rectangular grooves is significantly higher than that of CUB and BTG under different load conditions. This shows that BRG with rectangular grooves outperforms the other two topological energy collectors.

When the excitation frequency is 11 Hz and the acceleration is $6m/s^2$, the output power of the three piezoelectric vibration energy collectors varies with load in Figure 7.

From the experimental results in Figure 7, the optimal load of the piezoelectric vibration collectors of different cantilever structures is 400 K, but their output powers are different. The uniform cantilever beam structure (CUB), the non-uniform cantilever beam structure (BRG) with rectangular grooves, and the non-uniform cantilever beam structure (BTG) with triangular grooves have output powers of $50.7 \mu W$, $55.6 \mu W$ and $51.8 \mu W$, respectively. The experimental results show that the output of the piezoelectric vibration energy collector of the non-uniform cantilever beam structure with grooves is high. Among the cantilever beams with different topologies, the non-uniform cantilever beam structure with rectangular grooves has the best performance. The output power is much larger than that of the uniform cantilever beam structure.

The characteristics of piezoelectric vibration energy collectors are studied and the relationship between the output power and the excitation frequency is explored experimentally. When the excitation amplitude is 1mm, the load impedance is 250 kΩ. The excitation acceleration is $6m/s^2$. The relationship between the output voltage and the excitation frequency of the three kinds of topological piezoelectric vibration energy collectors is shown in Figure 8.

When the excitation amplitude is 1mm, the load impedance is 250 kΩ, and the excitation acceleration is $6m/s^2$. The relationship between the output power and the excitation frequency of the three topological piezoelectric vibration energy collectors is shown in Figure 9.

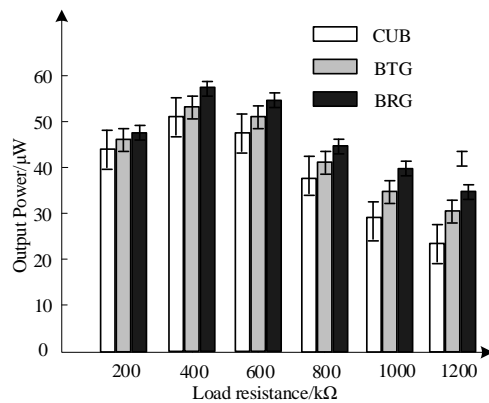


Figure 7. Output power varies with load

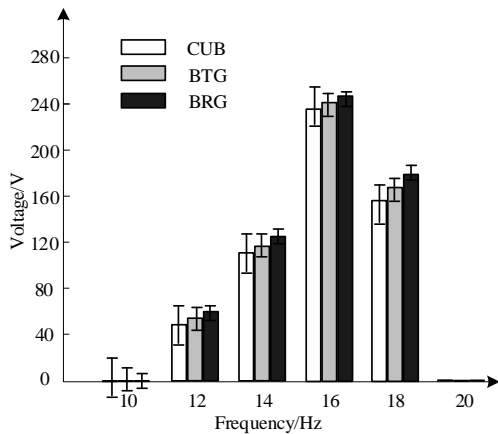


Figure 8. Output voltage varies with load

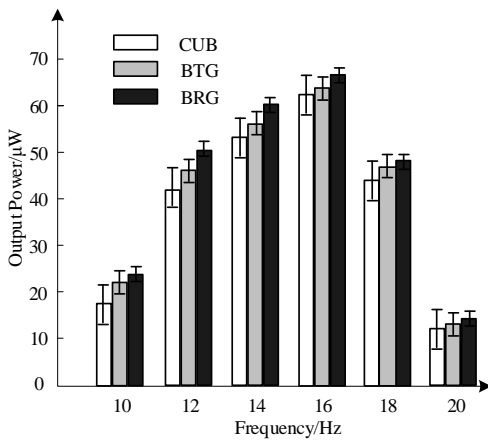


Figure 9. Output power varies with load

It can be seen from the experimental results of Figures 8 and 9 that the operating frequency of the piezoelectric vibration energy collector is between 12 Hz and 18 Hz. The working bandwidth is 6 Hz. In the entire operating frequency band, the output voltage and output power of the piezoelectric energy collector with the rectangular and triangular grooved beam topology is always greater than the power of the piezoelectric energy collector of the uniform beam topology. Among the different structural grooves, the performance of the rectangular groove is the best. The optimum excitation frequency of all piezoelectric vibration generators is 16 Hz. The maximum output power at the optimum excitation frequency is 60.5 μW, 62.4 μW and 66.1 μW, respectively. The experimental results show that the energy collector output voltage and output power based on the rectangular slot are significantly larger than the uniform cantilever beam structure. The output power of the energy collector based on different topologies is related to the excitation frequency.

The above experimental results show that the performance of the piezoelectric energy collector based

on the non-uniform thickness of the cantilever beam is better than that of the piezoelectric energy collector based on the uniform cantilever beam structure. The non-uniform cantilever beam with rectangular groove has the best performance. The energy collectors of various cantilever structures have an operating frequency band of 12 Hz to 18 Hz and an optimum excitation frequency of 16 Hz. The characteristics of the single-degree-of-freeness energy collector under the best matching resistance are shown in Table 1.

The experimental results in Table 1 are compared with those of the single-free elastic system piezoelectric cantilever energy collector made by Wang et al. [12]. The piezoelectric crystal materials have different characteristics, and the resonant frequencies are different between the short-circuit state and the open-circuit state. However, the electrical output characteristics and vibration characteristics of the two have the same trend with the frequency and the output power with the load resistance. The validity of the energy collector characteristic analysis in the IoT power supply system based on piezoelectric nanomaterials is verified.

4. DISCUSSION

The development of the Industrial IoT is the most promising technology for the promotion of industry 4.0 and global market opportunity. In 2020, there are more than 30 billion IoT devices in the industry supporting IIoT worldwide. Ideally, billions of smart devices will connect to the wireless networks through IIoT. The battery life of devices is a significant topic to study, because installing a battery in a small device is not feasible in all circumstances. In addition, battery maintenance and replacement costs are very high.

In recent years, the development of the IIoT has attracted a large amount of investment, especially for improving the battery life of the devices. However, generating power quickly for billions of devices is a challenging game. Researchers have proposed innovative

TABLE 1. Comparison of energy harvester characteristics under the best matching resistance

Resistance	Node	Single degree of freedom
		Peak
43.4 kΩ	Working frequency/Hz	44.7
	Output Power/mW	444.9
91.8 kΩ	Working frequency/Hz	45.4
	Output Power/mW	436.3
140.2kΩ	Working frequency/Hz	46.1
	Output Power/mW	427.7
	Bandwidth/Hz	6

solutions for this problem. Although traditional battery power supplies can solve the power supply problem, they must be purchased, maintained, and post-processed. When the equipment is installed in a remote location, it is more difficult to maintain the power supply [23]. As an alternative, energy harvesting technology can directly power remote IoT devices and sensors with great performance. The energy collector of the IoT power supply system based on piezoelectric Nano materials studied in this paper is an effective power supply facility designed by energy harvesting technology. PVDF piezoelectric Nano fibers are prepared by electrospinning technology with excellent piezoelectric properties and good flexibility and bio-phase PVDF organic piezoelectric materials. The energy collector applied to the IoT power supply system is prepared using this material to increase collection performance.

With the energy harvesting solution, the power system can operate independently. Energy harvesting is a procedure to collect energy that is available in the environment and transform it into electrical energy. The converted power can be utilized directly or can be preserved for future use. For remote deployment devices that do not have access to the local grid, energy harvesting solutions excel in providing alternative power to a wide range of electronic devices. The energy collected can be derived from radio energy, vibrational kinetic energy of the piezoelectric element, pressure energy, or light energy of the photovoltaic cell. The collected energy is transformed into electrical energy and stored in the durable storage battery. Energy harvesting systems typically include circuitry for generating or harvesting energy. In this paper, the nano materials are used to collect energy and to transform it into electric energy to promote renewable solutions in industry 4.0.

5. CONCLUSIONS

Industrial development for generating renewable energy solutions is the most promising research area nowadays. The renewable solutions are utilizing science and technologies to achieve the goal. The battery life of devices/equipment is a serious issue to address. Battery maintenance and replacement costs are very high. The innovative technique is proposed based on nano materials to generate renewable energy solutions by using energy collector. The energy is then converted into the desired form to generate renewable energy solutions. In this paper, the renewable energy solution is presented by utilizing the characteristics of the energy collector in the power supply systems of industry 4.0 based on piezoelectric nano materials to enhance the quick power generation. The PVDF piezoelectric nano fibers with high aspect ratio are prepared by electrospinning technology. The prepared PVDF piezoelectric nano fibers are applied to the energy collector of the power

supply system in industry 4.0, and their characteristics are further analyzed. Two models are discussed in the paper, namely, single-degree-of-freedom model and distributed parameter model. Piezoelectric vibration energy collectors and the relationship between the output power and excitation frequency has been studied in this paper. The results demonstrate that the performance of the rectangular groove is the best. The optimum excitation frequency of all piezoelectric vibration generators is 16Hz. The maximum output power at the optimum excitation frequency is 60.5 μ W, 62.4 μ W and 66.1 μ W, respectively. The energy collector in the IIoT power supply system based on piezoelectric Nano materials adopts dynamic technique to improve collection performance and generate quick power for improving the performance of energy-based equipment in industry 4.0. In future, energy harvesting solution can be applied where the power system can operate independently. It collects energy that is available in environment and transforms it into electrical energy. This converted power can be utilized directly or can be preserved for future use. The research work has important reference significance for the future industry 4.0 energy collection and conversion. The research still has some defects. Due to limited time and resources, sample data collection is relatively simple. Further analysis is needed in the future.

6. DATA AVAILABILITY

The data can be shared on valid request.

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Persian Abstract

چکیده

با توجه به اتصال الکترومکانیکی قوی، اندازه کوچک و حساسیت بالا، نانومواد پیزوالکتریک به طور گسترده ای در ژنراتورها، حسگرها و سایر زمینه ها استفاده شده است. در این مقاله، ویژگی های کلکتور انرژی در سیستم منبع تغذیه IIoT مبتنی بر نانومواد پیزوالکتریک تحلیل می شود. نانوالیاف پیزوالکتریک PVDF با فناوری الکتروریسی تهیه می شوند. مواد تراشه های کنترل در یک جمع کننده انرژی پیزوالکتریک دوجبهی یکپارچه شده اند. اثربخشی به صورت تجربی تجزیه و تحلیل می شود. نتایج تجربی نشان می دهد که فرکانس رزونانس جمع آوری انرژی با طول بازوی کنسول تغییر می کند. هنگامی که طول بازوی کنسول ۱۲ میلی متر است، خطای نصب ۱۰ میلی متر طول منجر به ۳۰٪ از خطای فرکانس رزونانس می شود. بار بهینه کلکتورهای ارتعاش پیزوالکتریک با بازوهای مختلف کنسول K ۴۰۰ است. توان خروجی BRG، CUB و BTG به ترتیب ۵۰.۷ μ W، ۵۵.۶ μ W و ۵۱.۸ μ W است. در عین حال، باند فرکانس کاری کلکتورهای انرژی با ساختارهای مختلف کنسولی ۱۲ هرتز تا ۱۸ هرتز است. فرکانس بهینه تحریک ۱۶ هرتز است. به طور خلاصه، جمع کننده انرژی سیستم قدرت ساخته شده توسط نانومواد پیزوالکتریک که توسط بسیاری از محققان پیشنهاد شده است، راندمان بالایی دارد که می تواند راه حلی سریع برای IIoT در Industry 4.0 ارائه کند و مکانیسم تولید برق را افزایش دهد. برای توسعه IIoT در عمل اهمیت زیادی دارد.
