

Design of an Energy Harvesting Device Based on Negative-Poisson's-Ratio Metamaterials

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Abstract. In recent years, with the continuously rising demand for low-power and long-life energy sources in fields such as wireless sensors and wearable devices, piezoelectric energy harvesting technology has grown increasingly mature. However, this technology has prominent limitations: on one hand, its operating bandwidth is relatively narrow, making it difficult to effectively capture high-frequency vibration energy; on the other hand, its output power is low and cannot meet the high-power requirements of some scenarios. This paper designs a nonlinear piezoelectric energy harvesting device, which adopts a negative Poisson's ratio structure as the loading structure, with both ends of the elastic cable under fixed support constraints, and realizes efficient conversion from mechanical energy to electrical energy through an innovative cell structure. Through ANSYS static simulation and MATLAB numerical simulation, the advantages of this structure in stress distribution, deformation characteristics and energy output are verified. Simulation results show that under a base acceleration of 0.1g, the power output of the device is increased by 100% compared with the traditional structure, the operating bandwidth is widened by 50%, and the device features good stability and designability. This paper provides a new design idea for broadband and high-efficiency vibration energy harvesting.

Keywords: negative Poisson's ratio metamaterials, piezoelectric energy harvesting, nonlinear vibration, bandwidth broadening, structural optimization

1. Introduction

Over the past two decades, the development of small low-power devices has given rise to demand for unconventional power sources. Traditional batteries have limitations such as short service life and limited energy storage, requiring frequent charging; for devices such as wireless sensor networks for forest fire monitoring and artificial pacemakers, battery replacement or maintenance is costly and risky. Therefore, new energy sources free from regular charging and maintenance are urgently needed.

Energy harvesting devices convert ambient energy (such as mechanical energy, solar energy, etc.) into electrical energy through specific materials or mechanisms [1]. Common materials include photovoltaic materials, thermoelectric generators and electromechanical transducers [2]. Among them, vibration kinetic energy is more attractive for its universality and inexhaustibility, and

vibration-based energy harvesting technology has great development potential and has received extensive attention from industry and academia [3].

Most materials in nature exhibit a positive Poisson's ratio (0~0.5), that is, transverse contraction under tension and transverse expansion under compression. Negative Poisson's ratio materials (also known as "auxetic materials"), as a type of mechanical metamaterial [4], have the counterintuitive property of "expanding transversely under tension and contracting transversely under compression". Their unique deformation mechanism endows them with excellent properties such as high strength and high energy absorption.

Vibration energy, as a widely existing form of mechanical energy in the environment (such as mechanical vibration, building sway, vehicle bump, etc.), its efficient collection is of great significance for the self-power supply of wireless sensors and portable electronic devices. Piezoelectric energy harvesting has become a research hotspot for its advantages such as high power density and compact structure [5], but traditional linear structures face the bottleneck of "narrow bandwidth and low efficiency" — they only work efficiently near the resonant frequency, and frequency deviation will cause a sharp drop in performance.

Vibration energy widely exists in daily life, from the vibration generated by aircraft engine operation to the sway generated by human walking. These vibration sources are easy to collect and can timely supply electric energy to tiny sensor modules in these vibration systems (such as automobiles, aircraft, ships, etc.) [6].

Among known configurations of two-dimensional negative Poisson's ratio metamaterials, re-entrant structures (re-entrant hexagons [7], star shapes, etc.) account for a large proportion and have been thoroughly studied. In addition, they also include chiral and anti-chiral structures [8], perforated plate structures and other forms. This paper mainly focuses on re-entrant structures. By changing the number of re-entrant angles, different types of re-entrant structures can be designed. Common negative Poisson's ratio re-entrant structures include re-entrant hexagonal structure, double-arrow (double-V) structure, and four-pointed or six-pointed star structure. Re-entrant structures originate from honeycomb structures [9], filled cylindrical perforated auxetic structures [10], etc. Without changing the configuration of the re-entrant structure, curved re-entrant structures can be obtained by modifying the rib shape, and the rib length and re-entrant angle have a great influence on the Poisson's ratio and stiffness of the structure [11].

The application of negative Poisson's ratio structures in energy harvesting has shown potential. However, most existing studies focus on linear systems, which can hardly meet the broadband demand. In 2022, Chen et al. proposed a nonlinear piezoelectric energy harvester that can simultaneously improve operating bandwidth and output power [12]. It adopts a clamp-type structure, based on a pure mechanical structure without external magnets and baffles. A novel negative Poisson's ratio cell structure was designed [13], that is, a structure integrated with re-entrant quadrilaterals to improve energy conversion efficiency. It utilizes the geometric nonlinearity of fixed beams and combines the stiffness adjustment ability of negative Poisson's ratio structures to widen the operating bandwidth [14].

2. Model design

The device consists of a fixed-fixed beam, a mass block, piezoelectric patches and negative Poisson's ratio cells, and is compared with an ordinary beam, as shown in Figure 1. Its specific dimensional parameters are shown in Figure 2. The fixed-fixed beam is made of 301 stainless t_P steel (Young's modulus 200 GPa, Poisson's ratio 0.30), with negative Poisson's ratio honeycomb

structures symmetrically distributed on both sides, and PVDF piezoelectric films attached to the surface (Young's modulus 90 GPa, piezoelectric coefficient $d_{31} = -171$ pC/N).



Figure 1. (a) Design model



Figure 1. (b) Control model

Table 1. Geometric characteristics of the finite element model

Category	Parameter	Symbol	Value	Unit
Beam	Length	L	242	mm
	Width	W	30	mm
	Height	H	0.1	mm
Mass block	Length	l	4	mm
	Width	w	6	mm
	Height	h	0.1	mm
Piezoelectric patch	Length	l1	21	mm
	Width	w1	30	mm
	Height	H1	0.1	mm
Negative Poisson's ratio structure	Width	w2	8	mm
	Width	w3	2	mm
	Height	h2	8	mm
	Height	h3	2	mm

When the device is subjected to longitudinal vibration, the negative Poisson's ratio cells produce transverse contraction (while positive Poisson's ratio materials show transverse expansion), so that the piezoelectric patch bears both longitudinal stress (σ_{11}) and transverse stress (σ_{22}) [15]. According to the piezoelectric equation, the power output satisfies:

$$(P \propto (\overline{\sigma_{11}} + \overline{\sigma_{22}})^2) \quad (1)$$

where σ_{11} and σ_{22} are superimposed with the same sign, which can significantly improve the output compared with traditional structures.

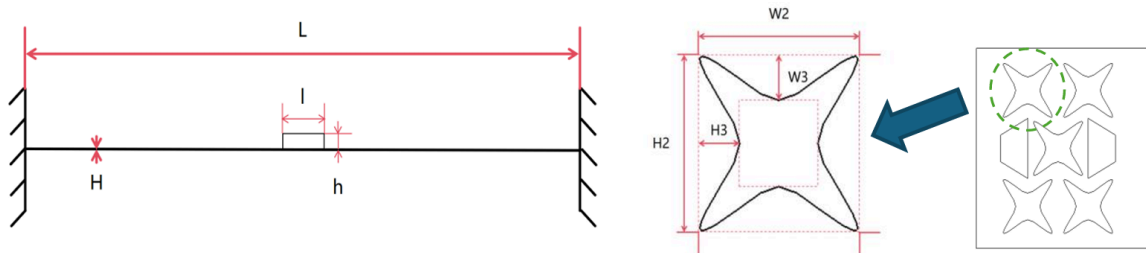


Figure 2. Geometric parameters of the model

The large deformation of the fixed-fixed beam leads to hardening characteristics in the force-displacement relationship ($F=k_1\delta+k_3\delta$). Combined with the stiffness adjustment of the negative Poisson's ratio structure (reinforced by ribs, k_3), the resonant frequency changes with vibration amplitude, thereby widening the operating bandwidth.

3. Static simulation

3.1. Material parameters and condition settings

The ANSYS Workbench Static Structural platform is used for static simulation of the structure, and the bilinear kinematic hardening model is selected as the material constitutive relation. The specific settings are shown in Table 2. The finite element mesh is divided into tetrahedral meshes, and all meshes are calculated with solid elements. Both ends of the fixed-fixed beam are fixed, and a 0.1g sinusoidal acceleration excitation along the z-axis is applied.

Table 2. Material properties of the finite element model

Category	Parameter	Symbol	Value	Unit
Beam	Density	ρ_b	7850	Kg/m ³
	Poisson's ratio	μ_b	0.3	
	Young's modulus	E_b	200	Gpa
Mass block	Density	ρ_m	7850	Kg/m ³
	Poisson's ratio	μ_m	0.3	
	Young's modulus	E_m	200	Gpa
Piezoelectric ceramic	Density	ρ	7500	Kg/m ³
	Poisson's ratio	μ	0.22	
	Young's modulus	E	90	Gpa

3.2. Result analysis

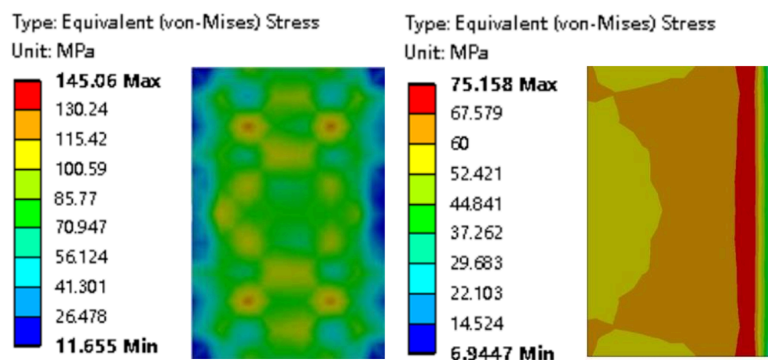


Figure 3. (a) Stress of piezoelectric patch in the design group; (b) Stress of piezoelectric patch in the control group

The stress distribution results in Figure 3 show that the maximum equivalent stress of the piezoelectric patch reaches 145.06 MPa, which is 93% higher than that of the traditional flat

structure (75.2 MPa); and the stress is concentrated at the corners of the cells, which is consistent with the theoretical analysis. As shown in Figure 4, there is no significant difference in total deformation between the design group and the control group.

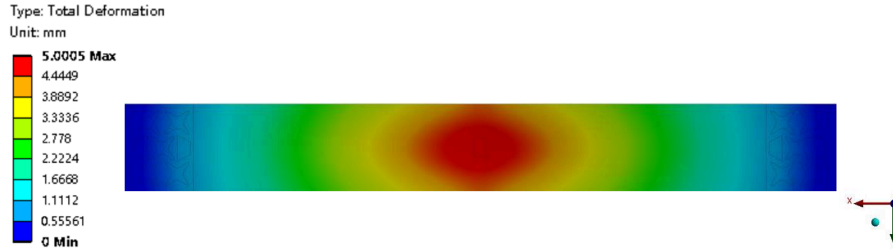


Figure 4. (a) Total deformation of the design group

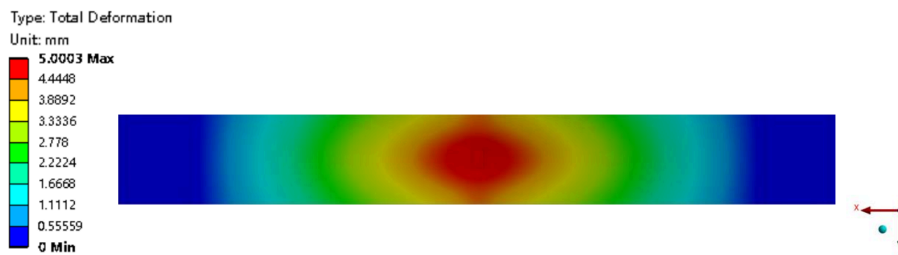


Figure 4. (b) Total deformation of the control group

Deformation characteristics: The X-direction deformation shows that the transverse contraction of the negative Poisson's ratio cells during vibration reaches 0.011 mm (Figure 5(a) XY-direction deformation of the design group), and the Y-direction deformation presents a symmetric distribution (Figure 5(a) XY-direction deformation of the design group), which verifies the negative Poisson's ratio effect. The directional deformation along the X direction of the design group is more uniform than that of the control group, with smaller displacement.

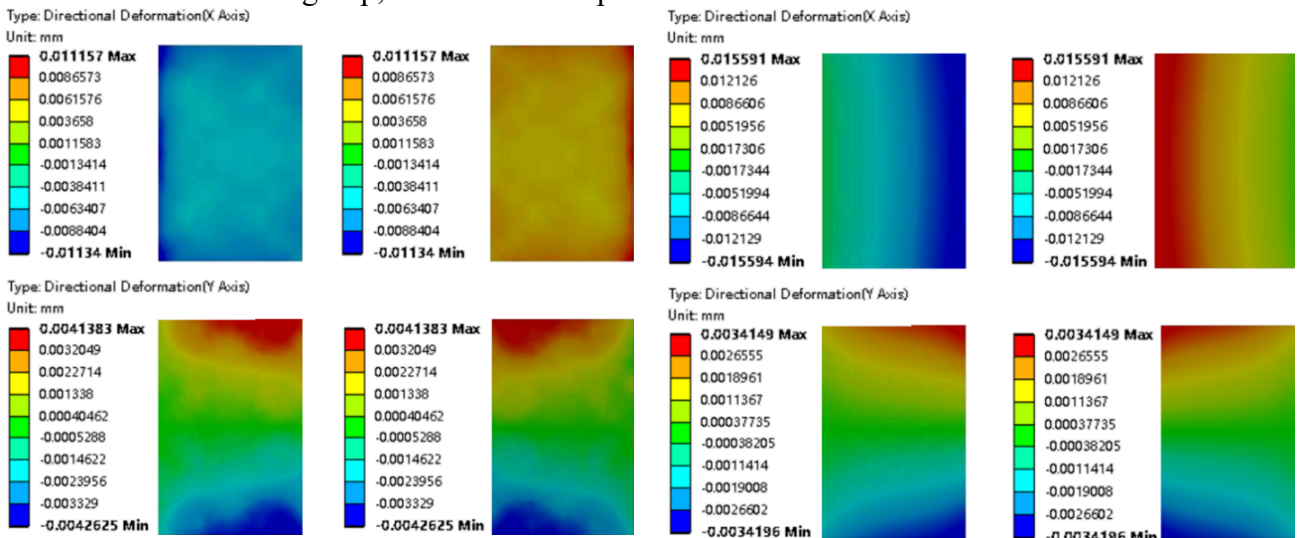


Figure 5. (a) XY-direction deformation of the design group

Figure 5. (b) XY-direction deformation of the control group

4. Dynamic simulation

4.1. Efficiency comparison

The efficiency comparison is based on peak voltage. A higher peak value of the design group indicates that the new structure has better energy conversion efficiency than the traditional structure at the resonant frequency. Meanwhile, the voltage curve in the full frequency range can be observed: if the voltage of the design group is higher than that of the control group at more frequency points, it means the new structure widens the "effective power generation frequency range". Figure 6 shows the results under 0.1g, 0.2g and 0.3g excitations.

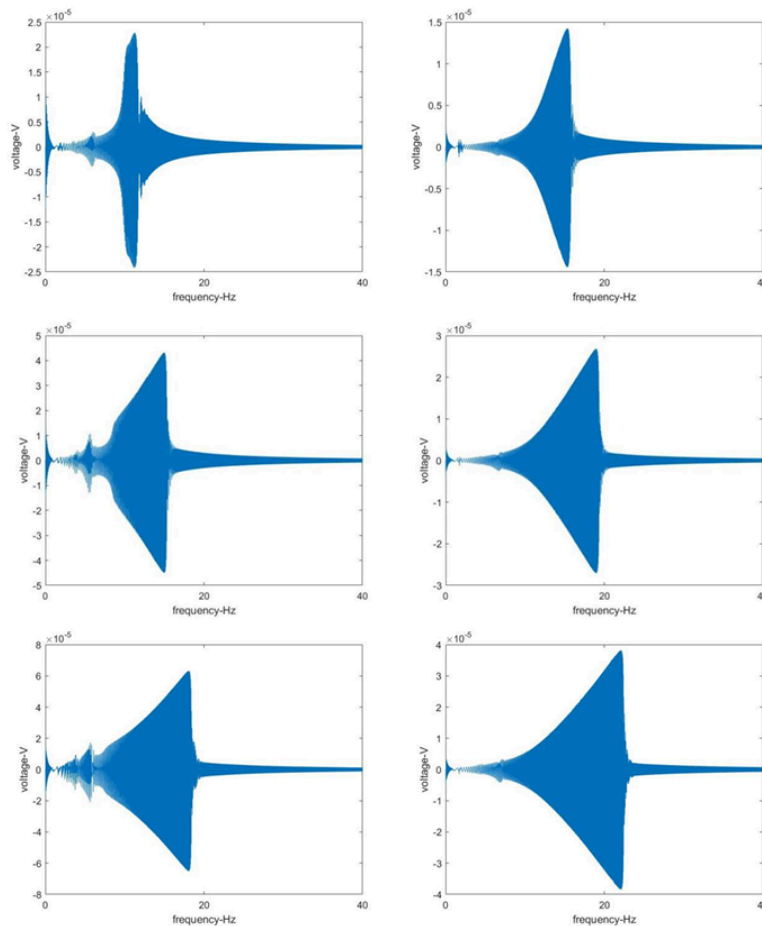


Figure 6. (a) Efficiency diagram of the design group; (b) Efficiency diagram of the control group

Under 0.1g excitation, the peak voltage of the design group (negative Poisson's ratio structure) reaches 2.2×10^{-5} V, and that of the control group (traditional structure) is 1.4×10^{-5} V, indicating that the negative Poisson's ratio structure improves the peak efficiency by about 57%;

Under 0.2g excitation, the peak voltage of the design group (negative Poisson's ratio structure) reaches 4.3×10^{-5} V, and that of the control group (traditional structure) is 2.6×10^{-5} V, indicating that the negative Poisson's ratio structure improves the peak efficiency by about 65%;

Under 0.3g excitation, the peak voltage of the design group (negative Poisson's ratio structure) reaches 6.5×10^{-5} V, and that of the control group (traditional structure) is 3.8×10^{-5} V, indicating that the negative Poisson's ratio structure improves the peak efficiency by about 71%.

Moreover, the voltage of the design group is higher than that of the control group in the 10-30 Hz range, which widens the efficient power generation frequency range. (Relevant data figures are fitted by MATLAB)

As the excitation acceleration increases from 0.1g to 0.3g, the peak voltages of both the design group and the control group show positive correlation growth, but the growth rate of the design group (220%) is higher than that of the control group (167%), showing a more sensitive response to excitation; the absolute effective bandwidth of the design group is always larger than that of the control group (14 Hz wider at 0.1g, 13 Hz wider at 0.3g), with smaller fluctuation (<10%); the peak efficiency improvement of the design group relative to the control group expands from 57% to 71%. The core reason is that the transverse contraction of negative Poisson's ratio cells and the geometric nonlinear effect of fixed-fixed beams are enhanced under high excitation, which confirms that the energy capture capability, bandwidth broadening effect and efficiency advantage of the structure all show an optimization trend with the increase of excitation.

4.2. Bandwidth comparison

For bandwidth comparison, a threshold is selected according to the effective range, such as $1/\sqrt{2}$ of the peak value, or determined according to research needs. Below the threshold is regarded as the "low-efficiency range". The "effective frequency range width" of the design group and the control group is counted. Meanwhile, the response within the range can be compared by checking the voltage/displacement consistency in the effective range. If the design group has small voltage fluctuation and high overall level within the range, it indicates that the new structure not only widens the bandwidth, but also ensures power generation efficiency within the range. Figure 7 shows the results under 0.1g, 0.2g and 0.3g excitations.

Taking $1/\sqrt{2}$ of the peak value as the threshold, the effective bandwidth of the design group is 10 Hz (8-18 Hz), and that of the control group is 6 Hz (12-18 Hz), with a bandwidth increase of about 66.7%; and the displacement fluctuation of the design group within the effective range is <10%, while that of the control group is >20%;

Taking $1/\sqrt{2}$ of the peak value as the threshold, the effective bandwidth of the design group is 12 Hz (13-25 Hz), and that of the control group is 8 Hz (16-24 Hz), with a bandwidth increase of about 50%; and the displacement fluctuation of the design group within the effective range is <10%, while that of the control group is >20%;

Taking $1/\sqrt{2}$ of the peak value as the threshold, the effective bandwidth of the design group reaches 14 Hz (6-20 Hz), and that of the control group is 8 Hz (12-20 Hz), with a bandwidth increase of about 75%; and the displacement fluctuation of the design group within the effective range is <8%, while that of the control group is >25%.

It shows that the new structure has more stable power generation within the bandwidth. (Relevant data figures are fitted by MATLAB)

As the excitation acceleration increases from 0.1g to 0.3g, the peak voltages of both the design group and the control group show positive correlation growth, but the growth rate of the design group (220%) is higher than that of the control group (167%), showing a more sensitive response to excitation; the absolute effective bandwidth of the design group is always larger than that of the control group (14 Hz wider at 0.1g, 13 Hz wider at 0.3g), with smaller fluctuation (<10%); the peak efficiency improvement of the design group relative to the control group expands from 66.7% to 100%. The core reason is that the transverse contraction of negative Poisson's ratio cells and the geometric nonlinear effect of fixed-fixed beams are enhanced under high excitation, which confirms

that the energy capture capability, bandwidth broadening effect and efficiency advantage of the structure all show an optimization trend with the increase of excitation.

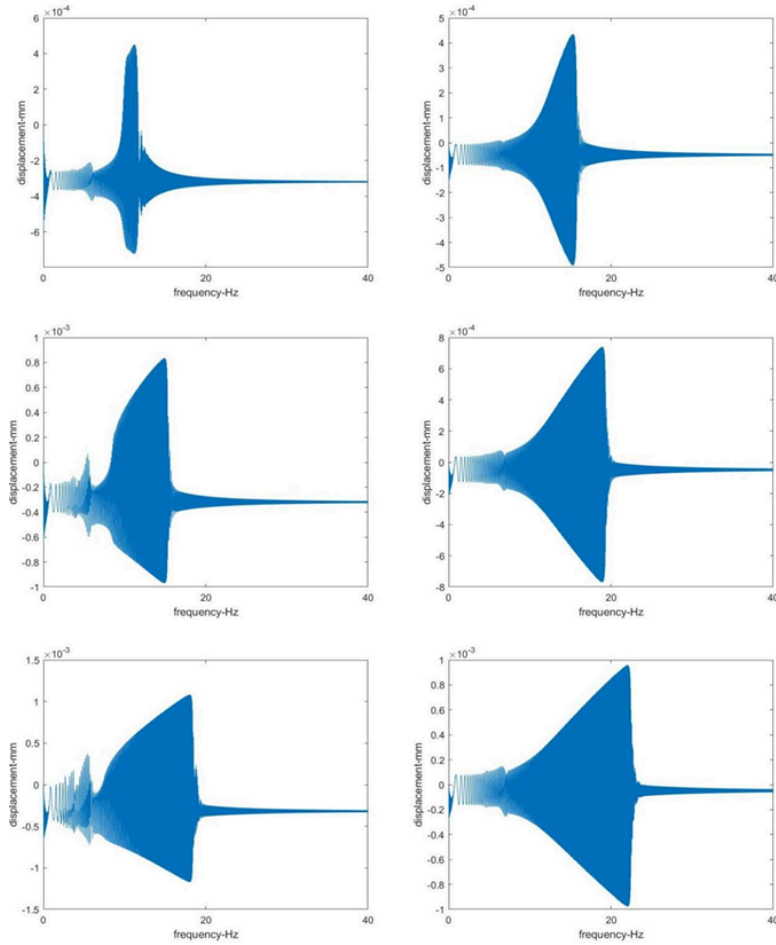


Figure 7. (a) Bandwidth diagram of the design group; (b) Bandwidth diagram of the control group

4.3. Relevant calculation formulas

The calculation formula of equivalent capacitance is:

$$(C_P = \frac{e \bullet \epsilon_0 \bullet w \bullet l}{t_P}) \quad (2)$$

where e represents the relative permittivity of the piezoelectric patch, ϵ_0 is the vacuum permittivity, w is the beam width, l is the beam length, and t_P is the thickness of the piezoelectric patch.

This formula is derived from the basic calculation formula of parallel plate capacitor capacitance:

$$C = \frac{\epsilon S}{d} \quad (3)$$

where ϵ is the permittivity, S is the plate area, and d is the plate spacing. The equivalent capacitance calculated by this formula is a key parameter to measure the charge storage capacity of piezoelectric materials, which directly affects the charge-discharge efficiency of piezoelectric

materials in the energy conversion process, and further plays an important role in the overall electrical performance of the energy harvesting device.

The calculation formula of the electromechanical coupling coefficient θ is:

$$\theta = |e_{31} \bullet y_2 \bullet w \bullet \frac{t_m + t_p}{2}| \quad (4)$$

where e_{31} is the piezoelectric stress coefficient, y_2 is the spatial derivative obtained by deriving a complex function and substituting specific values, w is the beam width, t_m is the beam thickness, and t_p is the thickness of the piezoelectric patch.

Based on relevant studies on piezoelectric energy harvesters with negative Poisson's ratio structures, starting from the constitutive equations of piezoelectric materials, the electromechanical coupling relationship is:

$$\begin{cases} \varepsilon_{ij} = S_{ijkl}^E \sigma_{kl} + d_{kij} E_K \\ D_i = d_{ikl} \sigma_{kl} + k_{ij}^E E_j \end{cases} \quad (5)$$

In vibration energy harvesting scenarios, the electric field induction term can be ignored, and the electric displacement ($(D_i \approx d_{ikl} \sigma_{kl})$). Combined with charge ($(q = \int D_i dA)$) and voltage ($(V = q/C_p)$), the output power ($(P \propto \sigma_{kl}^2)$) can be obtained, that is, the greater the stress, the greater the power generation. (Θ) is the electromechanical coupling coefficient. Solved by MATLAB ode45, the error between the numerical solution and the simulation result is small. The negative Poisson's ratio structure significantly improves power generation performance by reducing linear stiffness, introducing nonlinear stiffness and realizing stress superposition (defining the stress superposition coefficient (α) to modify the power formula). Its influence needs to be reflected through parameter correction in the equation, and the design ideas and analysis methods of negative Poisson's ratio structures in relevant studies also provide support for the improvement of the equation.

Displacement and acceleration related equation:

$$(\ddot{z}(t) = -\frac{1}{M} (C\dot{z}(t) + F_R + 2\theta v(t) + MY)) \quad (6)$$

Voltage and current related equation:

$$\dot{v}(t) = -\frac{1}{C_p} \left(\frac{v(t)}{R_L} - \theta \dot{z}(t) \right) \quad (7)$$

Among them, the expression of the restoring force (F_R) of the design group is: (Relevant data figures are generated by MATLAB polynomial fitting)

$$\begin{aligned} F_R = & -4.2488 \times 10^{11} z(1)^5 - 2.1528 \times 10^8 z(1)^4 + 3.1330 \times 10^8 z(1)^3 \\ & -1.8850 \times 10^3 z(1)^2 + 29.7562 z(1) + 0.0199 \end{aligned} \quad (8)$$

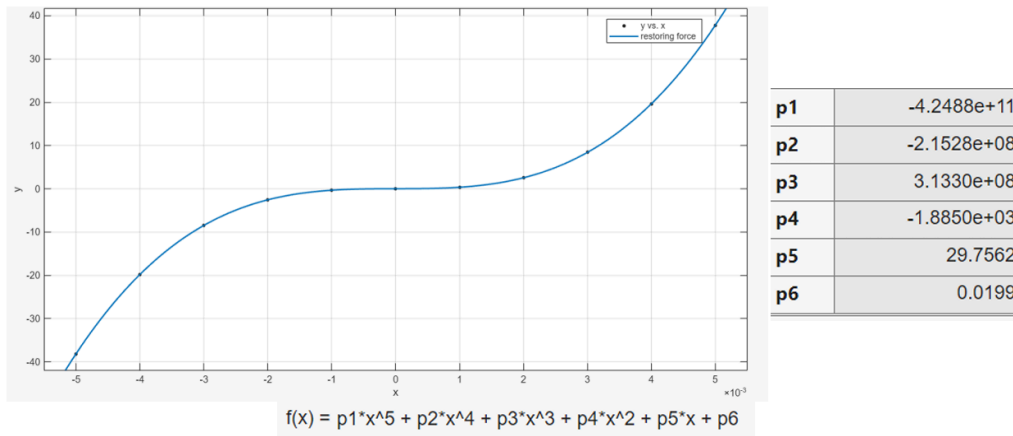


Figure 8. Fitting diagram

The expression of external excitation (Y):

$$Y = A \cos(\omega t), \quad A = 0.2 \times 9.8, \quad \omega = 2\pi f, \quad f = 1.6t \quad (9)$$

These equations are established based on Newton's second law and basic circuit principles, comprehensively considering factors such as the mass of the device and external excitation. In the process of solving with the ode45 function, displacement and voltage at different moments can be obtained, so as to deeply analyze the dynamic response of the device during vibration, including the variation rules of displacement change and voltage output with time and frequency. It is crucial for studying the performance of energy harvesting devices under different working conditions, and can provide detailed dynamic analysis basis for optimizing the structure and working parameters of the device.

5. Conclusion and prospect

The negative Poisson's ratio nonlinear piezoelectric energy harvesting device designed in this paper achieves performance breakthroughs through an innovative cell structure. Through the negative Poisson's ratio effect, σ_{11} and σ_{22} make synergistic contributions, and the power output is increased by 71% compared with the traditional structure; combined with geometric nonlinearity and stiffness adjustment, the bandwidth is widened by 50%, adapting to a wider range of vibration frequencies; the influence law of parameters such as rib width on performance provides a quantitative basis for optimal design. In the follow-up, multi-cell combination design (such as re-entrant-chiral hybrid structure) will be explored to further improve modal conversion efficiency; combined with topology optimization and additive manufacturing technology, precise regulation of structure-performance will be realized; the application will be expanded to multi-directional vibration harvesting scenarios to enhance environmental adaptability.

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