

Article

Motion Characteristics of Self-Sensing Piezoelectric Actuator for Yarn Micro-Gripper

Laihu Peng ^{1,2}, Yuan Sun ¹, Yubao Qi ² and Xin Ru ^{1,*}
¹ College of Mechanical Engineering, Zhejiang Sci-Tech University, Hangzhou 310018, China; laihup@zstu.edu.cn (L.P.); 202120601043@mails.zstu.edu.cn (Y.S.)

² Longgang Research Institute of Zhejiang Sci-Tech University, Wenzhou 325000, China; 202020601042@mails.zstu.edu.cn

* Correspondence: ruxin@zstu.edu.cn; Tel.: +86-15088666221

Abstract: In order to solve the problem of low response frequency and poor consistency of conventional yarn grippers in weft accumulators, in this study, a piezoelectric yarn gripper is used instead of conventional yarn grippers and the motion characteristics of its actuator are studied. This gripper uses a bimorph piezoelectric bending actuator with a low-cost, well integrated self-sensing method based on charge measurement. The modeling of the piezoelectric micromanipulator is based on the piezoelectric and Euler–Bernoulli beam equations. The static and dynamic characteristics of the piezoelectric actuator as well as the self-sensing capability were experimentally tested. The experimental results show that the maximum output displacement at the end of the piezoelectric actuator is 834 μm , and the maximum output force is 388 μN at 150 V driving voltage. The stability and consistency of its response are also very good, with a response speed of 24 ms. The self-sensing test of the output force also proved the feasibility of the self-sensing method used, with an error of 0.74%. The piezoelectric yarn gripper studied in this paper is promising for practical clamping applications.

Keywords: yarn gripper; bimorph piezoelectric bending actuator; characteristic test; self-sensing



Citation: Peng, L.; Sun, Y.; Qi, Y.; Ru, X. Motion Characteristics of Self-Sensing Piezoelectric Actuator for Yarn Micro-Gripper. *Appl. Sci.* **2024**, *14*, 2620. <https://doi.org/10.3390/app14062620>

Academic Editor: Nicola Pio Belfiore

Received: 20 February 2024

Revised: 16 March 2024

Accepted: 19 March 2024

Published: 21 March 2024



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1. Introduction

The micro-gripper is a device that has been widely used in the field of micromanipulation and micro-assembly, such as MEMS [1–3], bio-engineering [4–6], advanced optics [7–9], precision instruments [10], and other fields. As an end-effector that performs micro-assembly and micro-manipulation tasks, it directly interacts with the manipulated object. The actuator provides force and displacement to the clamp and is the power source to ensure the smooth progress of the work. In addition, the clamping stroke and resolution of the micro-clamp mainly depend on the performance of the actuator, and an excellent driving method is conducive to improving its performance. Different micro-grippers have been investigated according to different actuation principles. They can be driven by vacuum [11–13], electrostatic [14,15], electrothermal [16–18], shape memory alloy (SMA) [19–21], or piezoelectric [22–30] activity. Compared with other micro-grippers, piezo-electric materials exhibit advantages such as simple structure, high resolution, and fast response capabilities.

Depending on the structure, piezoelectric micro-grippers can be classified into the compliant mechanism type [22–24] or the bimorph type [25–30]. The compliant mechanism type uses a stacked piezoelectric actuator to drive a lever amplification mechanism to achieve clamping of micro-objects by the gripper. The finger clamping force of the compliant-mechanism-type micro-gripper is large. Nevertheless, greater finger displacement must be achieved by amplifying the compliant mechanism, making it complex and extensive. This gives it no advantage in compact applications.

Each finger of the bimorph micro-gripper is a cantilever beam consisting of two piezoelectric elements glued to either side of the substrate. One is used for expansion and

one for contraction in response to the driving voltage. The two fingers produce opposite bending micro-displacements for clamping the object. The bimorph micro-gripper has less clamping force but more displacement. It can be fabricated using IC technology and can be miniaturized for greater advantage in applications.

To meet the demands of micromanipulation tasks with very accurate and fast response times, a variety of sensors can be used. However, these external sensors are not ideal for the micrometer scale. This is due to the limitations of size, performance, and degrees of freedom of piezoelectric ceramic actuators. Therefore, self-sensing methods have subsequently become a hot research topic [31]. Meanwhile, self-sensing of piezoelectric ceramics can also be used to significantly reduce the cost of control systems by eliminating expensive sensors. There have been related studies on self-sensing of piezoelectric ceramics, such as voltage detection [25,32,33], charge detection [28,29,34–37], permittivity detection [38–40], and impedance detection [41,42]. In addition, it can be seen from previous studies that the resolution of piezoelectric ceramic self-sensing can also be sub-micron, comparable to that of external sensors. Therefore, the piezoelectric microgrippers with self-sensing can be better applied in practical production.

Piezoelectric micro-grippers have been used in various fields, but as existing work has focused on micron- or even nanometer-scale clamping targets, in the textile field, their application is not widespread [43]. The weft accumulator is used for temporary storage of weft yarns in rapier and piece-shuttle weaving machines, which creates good conditions for weft rewinding at high speed for the weft draw-in, and allows the rewinding of weft yarns to obtain a more uniform tension. The yarn gripper is one of the important components in the control unit of the weft accumulator due to its lifting and dropping of the pin to complete the weft of the fixed-length rewinding and control the rewind time. Its performance directly affects the weaving machine performance and yarn quality. Conventional yarn grippers are driven by an excitation coil. With the increase of working hours, the problem of insufficient end clamping force and poor cycle response consistency occurs, caused by the heat generation problem of the excitation coil. This can lead to inconsistent weft rewind lengths, which seriously degrade the performance of the weaving machine and the yarn quality. This problem can be solved by the use of piezoelectric yarn grippers. However, the diameters of yarn are generally between 130–280 μm , and the existing piezoelectric clamping devices cannot simultaneously satisfy such a large clamping range in a limited space. In the meantime, due to the specific needs of the yarn gripper, it is only necessary to have a gripping force that prevents the yarn from moving out of its gripping position.

Therefore, in order to solve the defects of the traditional yarn gripper and improve the productivity and technology level of the weaving machine, this paper uses the piezoelectric micro-gripper in place of the traditional yarn gripper. The target of this micro-gripper is shown in Table 1. It features a simple and easy-to-install structure, large clamping stroke, suitable clamping force, quick response time, and good response stability for high-speed yarn clamping operations. Theoretical modeling based on the cantilever structure and the design of the self-sensing method based on charge sensing were carried out to evaluate the working performance. The clamping stroke, clamping force, bending motion characteristics, and self-sensing ability of the micro-gripper were experimentally tested.

Table 1. The targets of the piezoelectric micro-gripper for yarn clamping.

Micro-Gripper	Size /mm	Clamping Stroke / μm	Clamping Force /mN	Response Speed /ms	Force Sensing Relative Error
Target	-	560	500	50	1%

2. Structure and Modeling of the Self-Sensing Micro-Gripper

2.1. The Structure of the Self-Sensing Micro-Gripper

In order to achieve the required clamping range and clamping force for yarn clamping, the self-sensing clamping device investigated in this paper is driven by a cantilever beam structure. In this paper, we chose the bimorph piezoelectric bending actuator (BPBA) composed of two layers of PZT-5H piezoceramics and one layer of carbon fiber substrate. The physical diagram of the BPBA is shown in Figure 1. The bimorph piezoelectric ceramic can improve its performance, while the substrate ensures that the actuator can meet the requirements of long-term high-intensity work and reduce the destruction rate. Two layers of piezoelectric ceramics are bonded to the upper and lower surfaces of the substrate, which alternately expand and contract under a certain period of varying voltage, generating a bending moment and then the free end of the reciprocating bending motion. The clamping scheme is shown in Figure 2. The specific dimensions of the piezoelectric cantilever and the performance parameters of the materials used are given in Tables 2 and 3.

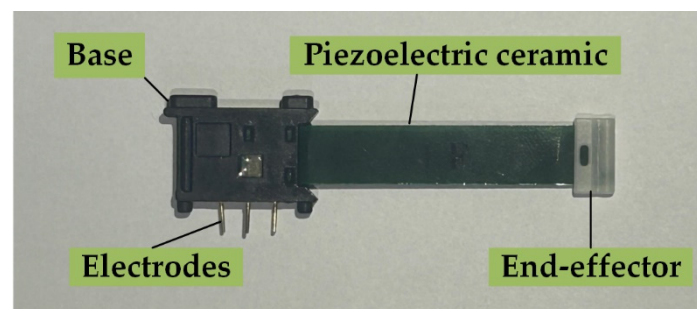


Figure 1. Photo of the BPBA. It consists of base, electrodes, actuator body, and end-effector.

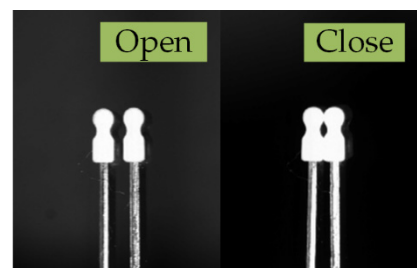


Figure 2. Diagram of opening and closing of the actuator.

Table 2. Structure parameters of piezoelectric cantilever beams.

Layers	Length/mm	Width/mm	Thickness/mm
Piezoelectric layer	41	7.2	0.245
Base layer	41	7.2	0.3

Table 3. Material parameters of piezoelectric cantilever beams.

Materials	Density (kg/m ³)	Young's Modulus (GPa)	Poisson's Ratio
PZT-5H	7500	56	0.36
carbon fiber	1800	250	0.28

2.2. Model of the BPBA

2.2.1. Mechanical Modeling

Figure 3a,b illustrates the schematic view of the operating state of the gripper corresponding to Figure 2, where D is the tip distance. To better understand the structure and

operation of the BPBA, it was modelled and analyzed. As the fingers of the gripper are symmetrically distributed, only one of them needs to be studied. Figure 3c,d shows the three-view schematic diagrams of the actuator. The 1, 2, and 3 axes of the graph represent the X, Y, and Z axes, respectively, where L is the length of the actuator and W is the width of the driver. s_u , s_c and s_l are the thicknesses of the upper piezoceramic layer, the middle carbon fiber layer, and the lower piezoceramic layer, respectively, and $s_u = s_l = s_p$.

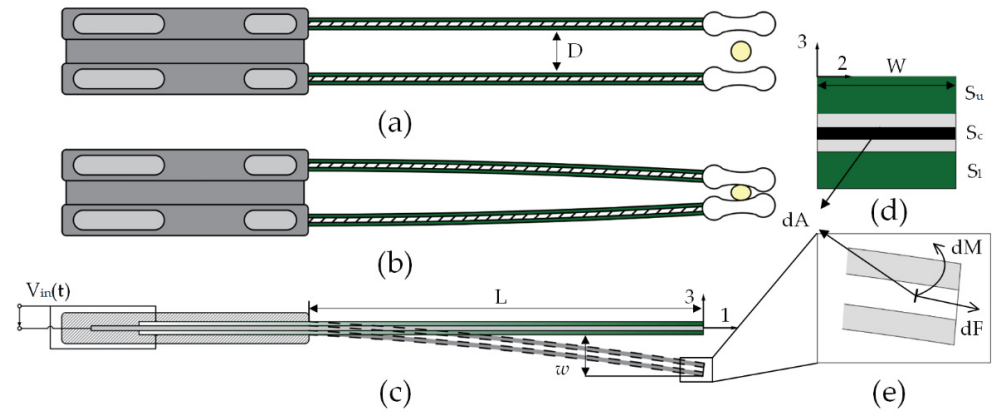


Figure 3. Schematic view of the gripper and the BPBA. (a) View of gripper (open), (b) view of gripper (closed), (c) view on the 13-plane, (d) view on the 23-plane, (e) detail of the end of the BPBA after bending.

A voltage is applied to the piezoelectric ceramic element and the driver is deformed by the inverse piezoelectric effect. According to the simplified piezoelectric equations of the first type:

$$\begin{cases} x_1 = s_{11}^E X_1 + d_{31} E_3 \\ D_3 = d_{31} X_1 + \epsilon_{11}^E E_3 \end{cases} \quad (1)$$

when piezoelectric ceramics are used as actuators, the strain x_1 of the piezoelectric crystal in the 1-axis direction under the action of stress X_1 and electric field E_3 is

$$\begin{cases} x_1^U = s_{11}^E X_1^U - d_{31} E_3^U \\ x_1^L = s_{11}^E X_1^L + d_{31} E_3^L \end{cases} \quad (2)$$

At the same time, there is no piezoelectric effect in the middle layer. Therefore, the strain–stress relationship for each layer of the three-layer structure of the driver is

$$\begin{cases} X_1^U = (s_{11}^E)^{-1} x_1^U + (s_{11}^E)^{-1} d_{31} E_3^U \\ X_1^C = (s_{11}^E)^{-1} x_1^C \\ X_1^L = (s_{11}^E)^{-1} x_1^L - (s_{11}^E)^{-1} d_{31} E_3^L \end{cases}, \quad (3)$$

where $(s_{11}^E)^{-1}$ and $(s_{11})^{-1}$ are the Young's modulus of the piezoelectric layer and the substrate, respectively, which can be written as E_p and E_c . Due to the symmetrical structure and opposite polarization directions of the upper and lower piezoelectric layers, pure bending of the mid-plane of the BPBA occurs at the driving voltage. Its bending curvature k can be expressed as

$$k = \frac{d^2 w}{dx^2}, \quad (4)$$

where w is the deformation of the piezoelectric cantilever in the 3-axis direction. Then, the tensile strain of the piezoelectric cantilever in the 1-axis direction is

$$x_1 = k z_1 \quad (5)$$

Substituting into Equations (3) and (5)

$$\begin{cases} X_1^U = E_p k z_1^U + E_p d_3 E_3^U \\ X_1^C = E_c k z_1^C \\ X_1^L = E_p k z_1^L - E_p d_3 E_3^L \end{cases}, \quad (6)$$

where, as shown in Figure 3d,e, dA is the area of width dz and length W on the 23-plane, and dF and dM are the tensile force and torque on the area of dA , respectively.

The torque at the end of the drive can be expressed as

$$\begin{aligned} M &= \int_0^s X_1 W z dz \\ &= \int_{\frac{s_c}{2}}^{\frac{s_c}{2} + s_p} (E_p k z_1^U + E_p d_3 E_3^U) W z dz + \int_{-\frac{s_c}{2}}^{\frac{s_c}{2}} (E_c k z_1^C) W z dz \end{aligned} \quad (7)$$

when the piezoelectric ceramic is subjected only to the electric field and no external force or moment is applied to the actuator, solving and simplifying the Equation (7),

$$k = \frac{12 E_p d_3 E_3 (s_p s_c + s_p^2)}{8 E_p s_p^3 + 12 E_p s_p^2 s_c + 6 E_p s_c^2 s_p + E_c s_c^3} \quad (8)$$

As the BPBA is a cantilever beam structure with a fixed end, its deflection profile can be expressed as

$$W(x) = \frac{k x^2}{2} \quad (9)$$

Substituting curvature k into the above equation, the maximum deflection at the end of the bimorph piezoelectric cantilever beam is obtained as

$$\delta_{zmax} = \frac{k l^2}{2} = \frac{12 E_p d_3 E_3 (s_p s_c + s_p^2) l^2}{8 E_p s_p^3 + 12 E_p s_p^2 s_c + 6 E_p s_c^2 s_p + E_c s_c^3} \quad (10)$$

By making $A = \frac{E_c}{E_p}$, $B = \frac{s_c}{2 s_p}$ and $s = s_c + 2 s_p$, the Equation (10) can be simplified as

$$\delta_z = \frac{3 L^2}{s} \cdot \frac{(1+B)(2B+1)}{(AB^3 + 3B^2 + 3B + 1)} \cdot d_{31} E_3 \quad (11)$$

When an electric field is applied to a piezoelectric layer, the bending moment generated by the electric field causes the actuator to bend. This bending deformation can be equated to an external force, which is caused by the tip output force F_z . From the beam theory in mechanics of materials,

$$F_z = \frac{3 W s^2 E_p}{4 L} \cdot \frac{2B+1}{(B+1)^2} \cdot d_{31} E_3 \quad (12)$$

2.2.2. Electrical Modeling of BPBA

When the piezoelectric element is subjected to an external voltage, the piezoelectric element is equivalent to a capacitor with piezoelectric material as the dielectric, and its capacitance is C_p . And when the piezoelectric element is subjected to an external force, the two surfaces generate equal amounts of positive and negative charges, which are also equivalent to a charge source Q_p . Therefore, as shown in Figure 4, the static electrical equivalent circuit diagram of one of piezoelectric layers of the BPBA consists of a capacitor, a leakage resistor, and a charge generator connected in parallel.

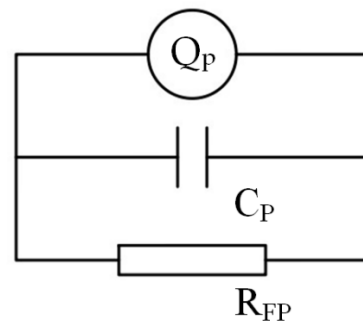


Figure 4. Equivalent electrical schematic of a piezoelectric actuator.

The charge accumulation on the surface of the BPBA is calculated by means of Gauss's law, which relates the potential shift D to the amount of free charge Q on a given surface. As the upper and lower piezoelectric layers are electrically parallel, their total system charge is the sum of the charges of the upper and lower piezoelectric ceramic layers:

$$Q = Q_U + Q_L = \iint_S (D_3^U + D_3^L) dA = 2WL\epsilon_{11}^E E_3 = \frac{2WL\epsilon_{11}^E}{S_p} V_{in} \quad (13)$$

Substituting the charge expressions into Equations (11) and (12), the relationship between the output displacement and the output force at the end of the BPBA and the charge on the piezoelectric ceramic layer can be obtained:

$$\begin{cases} \delta_z = \alpha Q \\ F_z = \beta Q \end{cases} \quad (14)$$

$$\text{where } \alpha = \frac{3L^2}{t} \frac{(1+B)(2B+1)}{(AB^3+3B^2+3B+1)} \frac{1}{4WL\epsilon_{11}^E} d_{31}, \beta = \frac{3Wl^2E_p}{4L} \frac{2B+1}{(B+1)^2} \frac{1}{4WL\epsilon_{11}^E} d_{31}.$$

2.3. Design and Modeling of Self-Sensing Circuits

2.3.1. Circuit Design and Modeling

Figure 5 shows the self-sensing circuit designed for the BPBA. The drive voltage V_{in} of the circuit is applied to the equivalent capacitance of the piezoelectric ceramic cantilever after being amplified by a signal amplifier circuit consisting of resistor R_1 , voltage amplifier U_1 , and resistor R_2 . A voltage divider circuit consisting of resistors R_3 and R_4 is required to prevent the operational amplifier chip from being damaged by excessive voltage and current. Voltage follower U_2 has a buffer, isolation, improved load carrying capacity, and other characteristics, while maintaining the original voltage to make the next level of amplification circuit operate more effectively. The self-sensing measurement circuit composed of resistors R_5 , R_6 , R_7 , feedback capacitor C_0 , and operational amplifier U_3 is the key to detect the sensing signals of the piezoelectric cantilever beam actuator, which is improved by the current integral amplifier circuit, which can integrate the current flowing through the feedback capacitor according to the change of external force and applied voltage. The output voltage V_{out} is the target quantity of the self-sensing circuit, and its expression is:

$$V_{out} = -\frac{R'_4}{(R_3 + R_4)} \cdot \frac{1}{C_0} \cdot \int_0^T i(t) dt = -\frac{R'_4}{(R_3 + R_4)} \cdot \frac{1}{C_0} \cdot Q \quad (15)$$

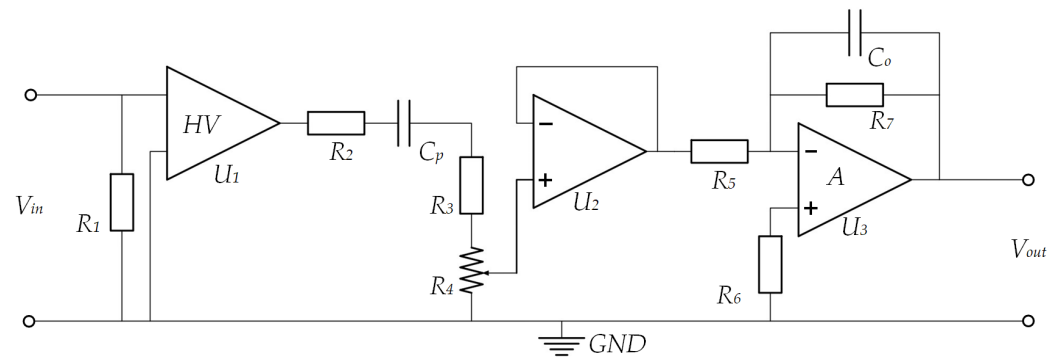


Figure 5. Electronic circuit schematic of self-sensing.

Considering the bias current of the operational amplifier and the effect of the internal leakage resistance of the piezoelectric ceramic [29], the output voltage of the free cantilever is given by the following equation:

$$\begin{aligned} V_{out} &= -\frac{R'_4}{C_o(R_3+R_4)} \cdot \left(\frac{1}{\alpha} \cdot \delta_z + \int \frac{V_{in}}{R_{FP}} dt + \int i_{BIAS} dt \right) \\ &= -\frac{R'_4}{C_o(R_3+R_4)} \cdot \left(\frac{1}{\beta} \cdot F_z + \int \frac{V_{in}}{R_{FP}} dt + \int i_{BIAS} dt \right) \end{aligned} \quad (16)$$

The resulting estimates of output displacement and output force are given as

$$\delta_z = -\frac{C_o(R_3+R_4)}{R'_4} \cdot \alpha \cdot V_{out} - \alpha \cdot \int \frac{V_{in}}{R_{FP}} dt - \alpha \cdot \int i_{BIAS} dt \quad (17)$$

$$F_z = -\frac{C_o(R_3+R_4)}{R'_4} \cdot \beta \cdot V_{out} - \beta \cdot \int \frac{V_{in}}{R_{FP}} dt - \beta \cdot \int i_{BIAS} dt \quad (18)$$

2.3.2. Selection of Electronic Components

The voltage divider resistor consists of a fixed resistor R_3 (149 K) and a sliding varistor R_4 (1 k), where R'_4 is part of the resistor connected to the main circuit and the step-down voltage can be fine-tuned during commissioning. Improper selection of the charge amplifier will greatly reduce the accuracy of the sensing, so it is recommended to use a stable unit gain, otherwise oscillations will occur. Noise and bias current must be kept as low as possible. For this reason, the TPH2501-TR model has been chosen, which has a low bias current (0.3 μ A), low input offset voltage (500 μ V Max), and low temperature drift.

The feedback capacitor should have very high insulation resistance, low dissipation factor, and good temperature stability. We chose a polypropylene plastic film capacitor with a measured leakage resistance greater than 10 T Ω when the capacitance is equal to 1 μ F, which is sufficient to neglect its leakage effect in the circuit.

2.3.3. Self-Sensing Parameter Identification

For the circuit designed in this paper, the feedback capacitor $C_0 = 1$ μ F was chosen. The other parameters (i_{BIAS} , R_{FP}) of Equations (17) and (18) need to be further determined, and the following steps describe the identification process.

When the piezoelectric ceramic is not subjected to an external force and no external voltage is applied, no current passes through the piezoelectric material; the rise in output voltage at this point is caused by the bias current of the operational amplifier chip. Measuring the rate of change of V_{out} over a few tens of seconds gives $i_{BIAS} \approx 47$ pA.

From the electrical model of the BPBA, it can be seen that in the case of an external force $F = 0$ and a constant voltage $V_{in} \neq 0$, the electrical model of the piezoelectric ceramic can be simplified to a leakage resistance. An external resistor is connected in series with the piezoelectric ceramic. After a few hundred seconds, when the creep effect of the piezoelectric ceramic itself becomes negligible, the value of R_{FP} can be measured by the

voltage division method. The identification can be repeated and averaged for different values of the leakage resistance and the external resistance. For our actuator, we found $R_{FP} = 1.02 \text{ M}\Omega$.

3. Performance and Self-Sensing Testing of BPBA

3.1. Static Displacement Test

3.1.1. Test System Composition

In order to ensure that the designed clamping device can meet the requirements of the large clamping stroke range, it is necessary to design experiments to test the displacement of the cantilever beam under different driving voltages and, on this basis, to judge the relationship between its working stroke and the driving voltage to verify its adaptability to different working conditions.

The experimental setup for piezoelectric ceramic displacement sensing is shown in Figure 6. The drive signal is a 1 Hz step pulse signal generated by a signal generator (model: 2015 H, from Victor, Shenzhen, China) and amplified to 0–150 V by a voltage amplifier (model: ATA-2808, from Aigtek, Xi'an, China). The output displacement at the end of the piezoelectric cantilever beam is measured by a Laser Doppler Vibrometer (Model: LV-S01, from Sunny Instruments Singapore, Singapore), and the displacement data and displacement curve waveforms of the free end of the piezoelectric cantilever beam in the 3-axis direction are stored. The device is insensitive to interference and has a very high resolution and a very wide dynamic measurement range.

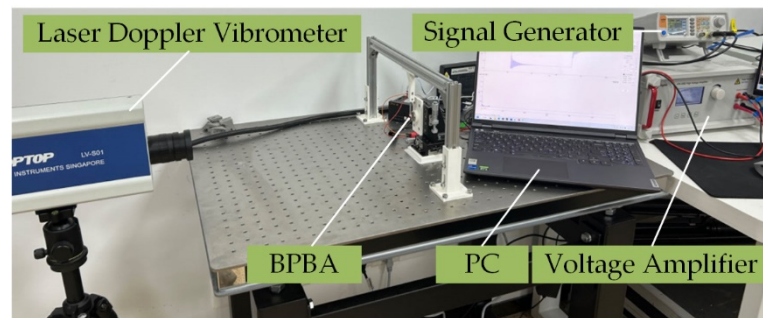


Figure 6. Photo of static displacement test experimental setup. Actuator is fixed in the middle and Laser Doppler Vibrometer is on the left side of the image.

3.1.2. Measurement Result

The test results are shown in Figure 7a. The output displacement of the BPBA can reach $834 \mu\text{m}$ at 150 V drive voltage. In addition, it shows the hysteresis effect of the gripper due to the piezoelectric drive. It causes a nonlinear relationship between output displacement and input voltage. Without considering the nonlinear hysteresis factor of piezoelectric ceramics, the simulation result should be a linear relationship. In order to be more consistent with the real situation, we used a polynomial hysteresis model to simulate it. Figure 7b illustrates the simulation output displacement at the input voltage of 150 V; it can go up to $827 \mu\text{m}$ and the error between this and the measured value is 0.83%. Apparently, the output displacement of this BPBA can reach the requirement of clamping stroke.

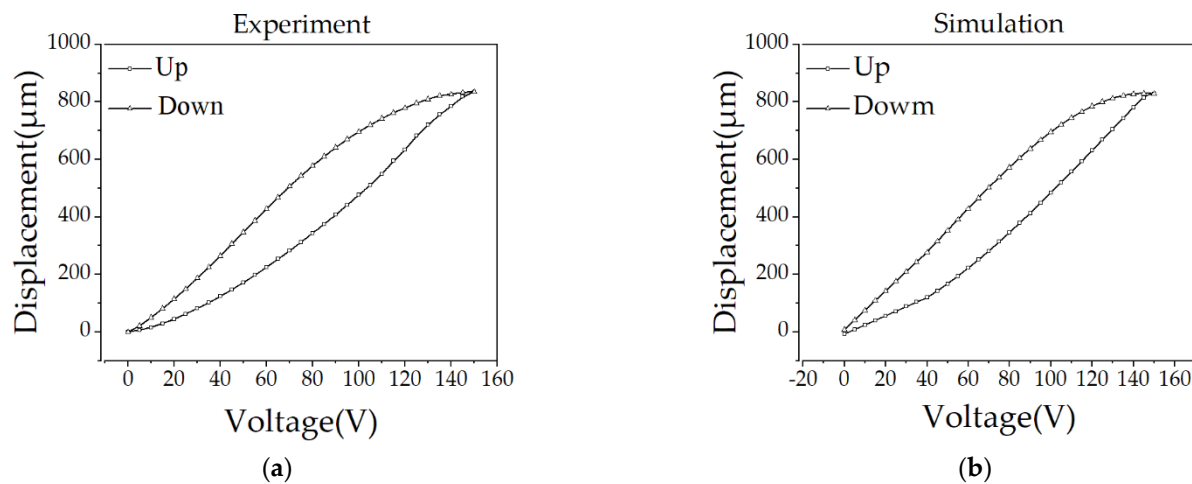


Figure 7. Test result of displacement experiment. (a) The measured value, (b) the simulation value.

3.2. Output Force Characteristic Test

3.2.1. Composition of the Experimental System

To ensure a large stroke, the output force at the end of the BPBA bending actuator also needs to be experimentally verified to ensure that it completes the clamping action. The experimental platform was designed and its mechanical properties tested using a high-precision pressure sensor. As the BPBA is affected by its own elastic deformation resistance during the bending process, its output force should be inversely proportional to the displacement. Therefore, the distance between the BPBA and the force sensor is 0 mm, the input voltage is increased from 0 V to 150 V in 5 V increments, and the experimental data from the force sensor are collected and processed by the PC software (V20.1). The actual experimental platform built is shown in Figure 8.

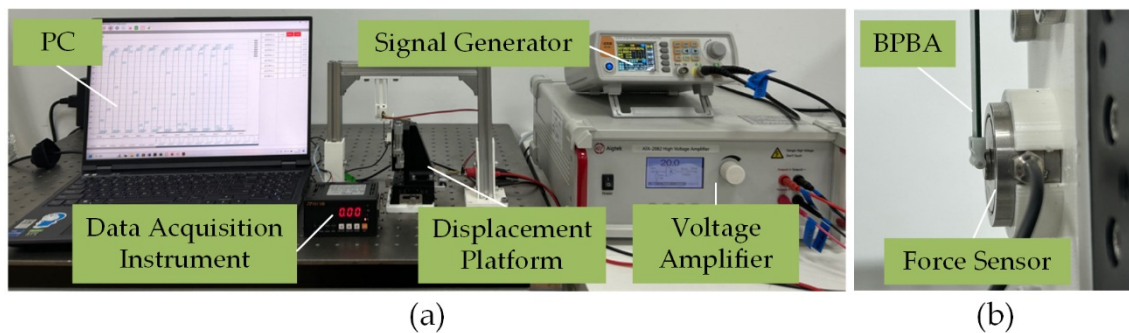


Figure 8. Photo of output force test experimental setup. (a) The overview of the setup, (b) actuator is fixed in the left and force sensor is in the right side of the image.

3.2.2. Measurement Result

Figure 9a shows that the magnitude of the static clamping force of the BPBA increases as the drive voltage increases. The largest force caused by the BPBA is up to 388 mN. From 40 V to 100 V, there is a strong linear relationship between the two. Figure 9b shows the result of clamping force F_z of the single BPBA obtained according to Equation (12) and the polynomial hysteresis model. At 150 V, it is up to 390.4 mN. The error between this and the measured value is 0.61%. Experiments on the output force of the BPBA have proved that it has a certain clamping force to prevent the yarn from falling out of its clamping range.

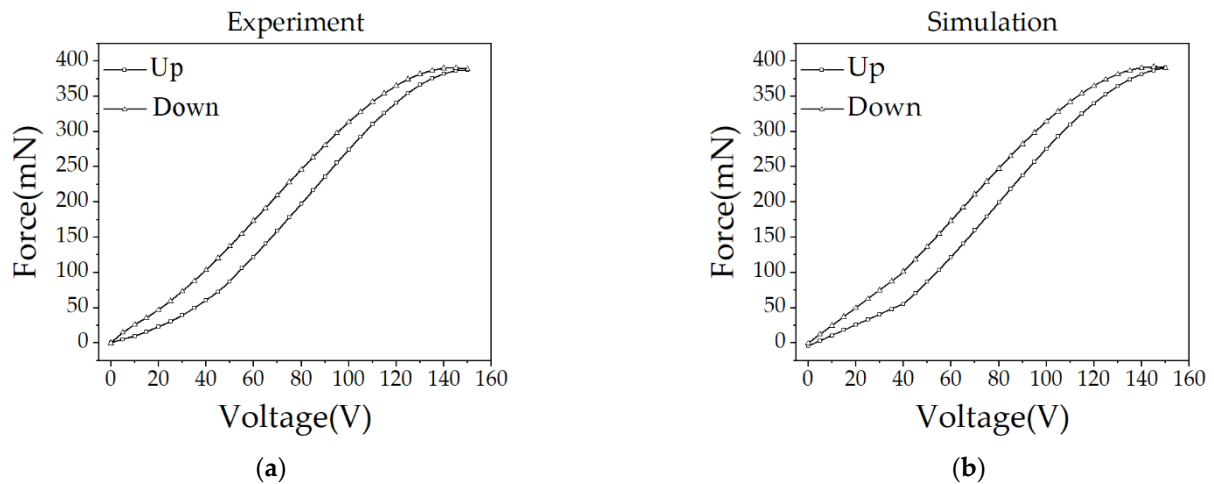


Figure 9. Test result of output force experiment. (a) The measured value, (b) the simulation value.

3.3. Clamping Distance Characteristic Test

3.3.1. Test System Composition

The performance of the BPBA is initially demonstrated after the investigation of the output displacement and output force characteristics. In order to adapt to different scales of clamping targets, it is also necessary to study the relationship between the output force and the clamping stroke. The force sensor is mounted on a high-precision three-axis translation stage to vary the distance between the BPBA and the force sensor, which is used to simulate the mechanical properties at different clamping ranges in real working conditions. The drive voltage was selected to be 125 V, which has good linearity. The clamping distance was increased in 0.01 mm increments to perform the measurement experiments. The experimental data were collected and processed by the host computer software.

3.3.2. Measurement Result

There is an inverse relationship between the output force of the actuator and the clamping stroke, as shown in Figure 10. For symmetrical grippers, the gripping stroke is defined as the sum of the maximum output displacements of both fingers. A large gripping stroke is more adaptable to targets of different sizes. However, the size of the target object is small, and a large clamping stroke may result in insufficient clamping force. Based on the linear relationship between the output force and the clamping stroke, the distance between the tips can be adjusted for more effective clamping in the face of different clamping targets.

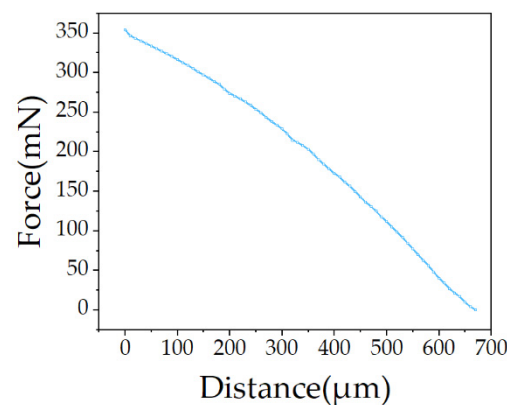


Figure 10. Test result of clamping distance experiment.

3.4. Study of Bending Motion Characteristics

3.4.1. Composition of the Experimental System

The main factors affecting the quality of yarn grippers are their consistency and stability. It was shown that the response speed of a conventional electromagnetic yarn gripper was measured by the on-time of the photosensitive tube at a driving voltage of 10 Hz. The relative response error of the conventional yarn gripper reaches 80% under continuous operation. In order to study the stability and consistency of the BPBA, it is also given a driving power of 10 Hz. However, due to the millimeter clamping range of the BPBA we studied, the opening and closing bending motion is short and fast, which makes it difficult to observe with the naked eye. And if the contact displacement sensor is used, it will lead to reverse elastic deformation at the moment of contact, which in turn affects the test results. Therefore, in this experiment, we used a high-speed camera (model: Dimax HD, from PCO, Germany) to photograph the bending motion of the BPBA and analyzed and processed it using TAME software (T2019a-64). A square wave excitation voltage of 100–150 V (10 Hz) was applied at 10 V intervals and photographed at a sampling rate of 1000 Hz. The actual bending motion experimental platform is shown in Figure 11.

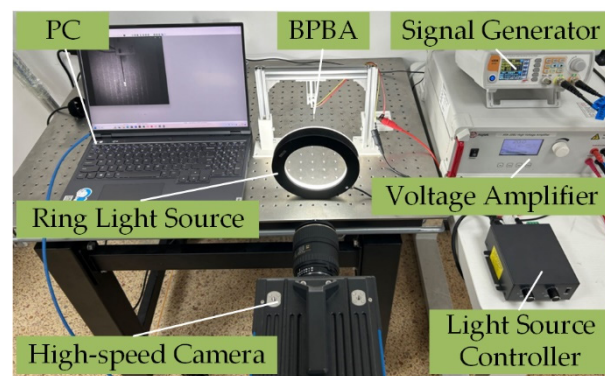


Figure 11. Photo of output force test experimental setup. The camera is at the bottom of the image.

3.4.2. Measurement Result

As shown in Figure 12a, the actuator end velocity profile is used to describe the motion process of the BPBA. By comparing the velocity profile graphs of two consecutive cycles, it was found that the end velocity profile of the actuator driven by different excitation voltages has the same periodicity. Also, we can see the response time of the BPBA is about 24 ms, which is shorter than our target. Meanwhile, the end velocity profile in each cycle is divided into two stages, which are divided into acceleration and deceleration in two directions, corresponding to each other with the direction of the applied square wave excitation voltage. The velocity at the end of the actuator increases during the deformation process, and when it reaches the bending equilibrium position for the first time, the internal stress generated by the excitation voltage is equal to the elastic force generated by the deformation, and the velocity reaches the maximum value. However, after the actuator passes the equilibrium position, the elastic force generated by deformation is greater than the internal stress generated by the excitation voltage, and the actuator begins to decelerate until the maximum swing position. The actuator then oscillates near the bending equilibrium position and finally stops at the equilibrium position. This is also true when a reverse excitation voltage is applied.

Figure 12b shows the end acceleration curve of the BPBA in one motion cycle with Figure 12a, which exhibits the acceleration change process corresponding to the velocity change process analyzed in the previous section. There is no obvious difference in the overall trend of the acceleration change process under different excitation voltages. We can see that the larger the excitation voltage, the faster the acceleration increases, the faster the piezoelectric actuator responds, and also the faster the acceleration change process ends.

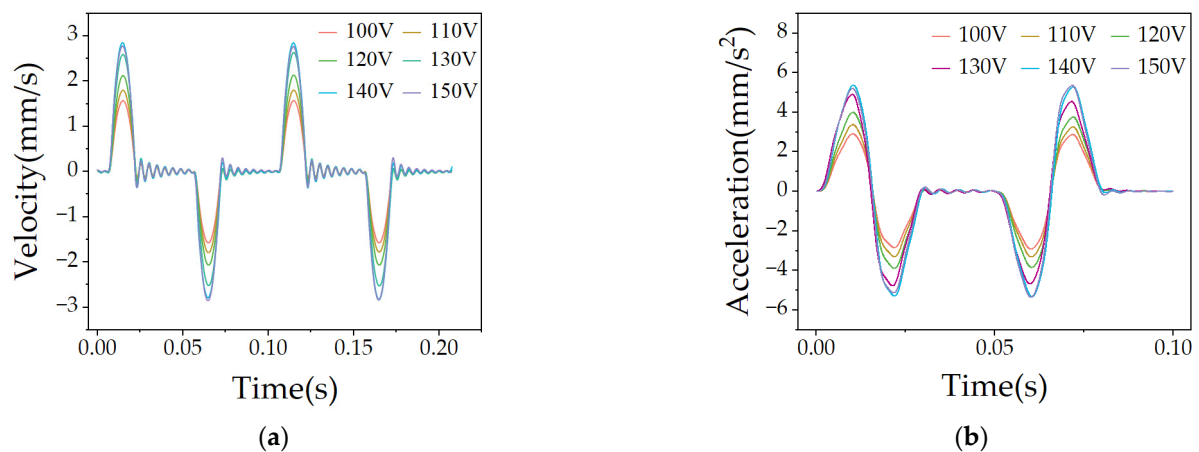


Figure 12. Test result of bending motion experiment. (a) The velocity of the end of the actuator, (b) the acceleration for the corresponding period.

3.5. Output Force Self-Sensing Test

3.5.1. Composition of the Experimental System

In order to verify the validity of the self-sensing method used in this paper, a self-sensing circuit was added to the platform of the end output force experiment and the output was connected to an oscilloscope. Since a reverse op-amp circuit is used in the self-sensing circuit, a step signal V_{in} , which decreases from 0 V to -100 V and then increases to 0 V at 10 V intervals, is input at zero external force, as shown in Figure 13a. The output voltage of the self-sensing circuit is detected by using an oscilloscope, while the end output force is measured and recorded by using an external pressure sensor. The estimated value F_{est} obtained from the self-sensing circuit is compared with the measured value F_{meas} obtained from the external force transducer to verify the validity of the self-sensing model.

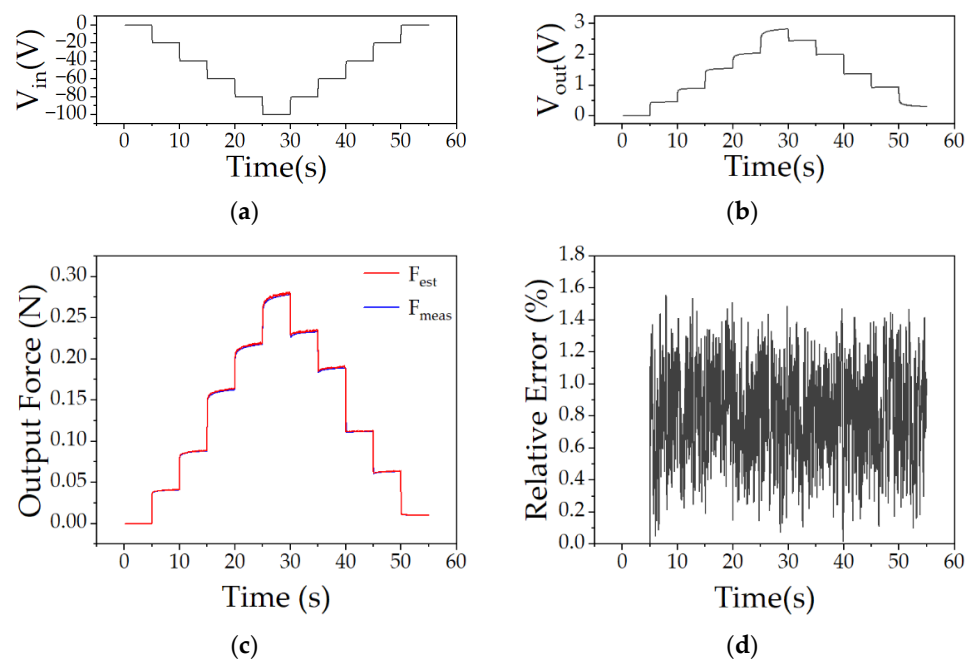


Figure 13. Test result of output force self-sensing experiment. (a) Input voltage, (b) output voltage, (c) comparison of estimated and measured output force, (d) the relative error of the two values.

3.5.2. Comparative Analysis

Figure 13b shows the output voltage V_{out} obtained from oscilloscope measurements. The output voltage value exhibits some offset due to the bias current of the op-amp chip.

This is due to the fact that charge loss and bias problems may occur when the device is used for a long period of time. In this case, periodic charge resets would be used to maintain sensing accuracy. This can also be ameliorated by applying a very low rate of increase/decrease of input voltage to the driver.

Figure 13c shows a plot comparing the estimated value F_{est} obtained from the self-sensing circuit with the measured value F_{meas} obtained from the external force sensor. The two force curves almost overlap and the relative error between the two is represented in Figure 13d, with a maximum relative error of 1.6% and an average relative error of 0.74%. In the meantime, the relation between input voltage and output force is not zero-order hold, and the higher the input voltage, the more obvious. This is caused by the creep behavior of piezoelectric ceramic materials. As the input voltage increases, the effect produced by the leakage resistance increases.

4. Conclusions

In this paper, we attempt to apply a piezoelectric yarn gripper with self-sensing instead of a conventional electromagnetic one to improve the performance of weaving machines. The comparison between experimental working capability and targets is shown in Table 4 and obtains the following conclusions:

- (1) The BPBA has a working length of 41 mm and a width of 7.2 mm. Mechanical and electrical modeling is performed according to the structure of the piezoelectric actuator, and the working range of the actuator can be estimated according to the theoretical values, which proves that the piezoelectric actuator of this structure meets the working requirements of yarn clamping. At the same time, the self-sensing circuits based on charge detection are carried out on the basis of the physical model, and the non-zero amplification bias current and driver leakage resistance are further compensated.
- (2) The maximum clamping stroke of the clamping device is about 1668 μm , and the maximum output force is about 776 mN, which meet the working requirements of yarn clamping. Compared with domestic and foreign micro-grippers, the clamping range and end clamping force are both improved.
- (3) By studying the negative correlation between the clamping distance and the end output force, the clamping distance can be decided according to the size of the target, so as to realize effective clamping for different targets.
- (4) The motion characteristics of the BPBA are analyzed by a high-speed camera, which shows a fast response speed and meets the requirements of a high-speed loom of 1000~1200 r/min. At the same time, its high response stability is greatly improved compared with the traditional electromagnetic-type yarn gripper.
- (5) The maximum relative error between the self-sensing output force and the force measured by the external sensor was found to be 1.6%, and the average relative error was found to be 0.74%. These values are the same as or better than previously reported displacement force self-sensing techniques using charge and voltage measurements.

Table 4. Structure parameters of piezoelectric cantilever beams.

Micro-Gripper	Size /mm	Clamping Stroke / μm	Clamping Force /mN	Response Speed /ms	Force Sensing Relative Error
Target	-	560	500	50	1%
BPBA in this paper	$41 \times 7.2 \times 0.79$	1668	776	24	0.74%

Future work will focus on the design optimization of this BPBA to obtain a better structure of smaller size. The gripper is well suited for any application scenario in which micron-sized objects are clamped, moved, and positioned during high-speed movement of the weaving machine. Thus, the potential for continued exploration of application

scenarios for grippers also exists. Combined with better sensing and detection strategies, the gripper can realize functions such as gripping, movement, and state detection of micron-scale objects.

Author Contributions: Conceptualization, Y.S., L.P. and Y.Q.; Methodology, Y.S.; Software, Y.S.; Validation, Y.S. and Y.Q.; Formal Analysis, Y.S.; Investigation, Y.Q.; Resources, L.P. and X.R.; Data Curation, X.R.; Writing—Original Draft Preparation, Y.S.; Writing—Review and Editing, X.R.; Visualization, Y.S.; Supervision, L.P.; Project Administration, L.P.; Funding Acquisition, L.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Key R&D Projects of the Science and Technology Department of Zhejiang Province [Grant No. 2024C01124].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors would like to thank Zhejiang Sci-Tech University for engaging in useful discussion on topics relevant to this work.

Conflicts of Interest: The authors declare no conflicts of interest.

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