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Piezoelectric-ceramic-based microgrippers in micromanipulation

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1. Introduction

Microgrippers are widely applied in micromanipulation systems covering manufactural, biological and medical fields, and are especially important in microassembly process. There are several reasons. Firstly, as the size of microminiature parts is in millimetre or micron, the strength and stiffness compared to those of macro components is much smaller and thus microminiature parts are more easily damaged. Secondly, since geometric feature size for most of microminiature parts ranges between 0.01mm and 10mm, has not yet emerged a microgripper with which the scope to clipping all parts can be achieved. Thirdly, adhesion phenomena in microassembly process are a difficult problem that limits the development of microgrippers. At the beginning of the century, scholars have included the microgripper technology into research projects and made a lot of initial results. According to the driving force, microgrippers can be divided into piezoelectric-ceramic-based (Heyliger & Brooks, 1995), electrostatic-based (Majumder et al., 2001), electromagnetic-force-based (Quandt, 1997; Ashley, 1998), electric-based, vacuum, adhesive-material-based, shape-memory-alloy-based clampers, and so on. Li Q. and Li Y. (Li Q. & Li Y., 2004) summed up a detailed overview of microgripper profile and types.

Compared with other kinds of microgrippers, piezoelectric-ceramic-based microgripper is the most widely used one. Piezoelectric ceramics, owing to the unique properties such as direct and reverse piezoelectric effects, are utilized to generate controllable displacement in microgrippers far and wide.

2. Two categories of piezoelectric-ceramic-based microgrippers

Generally, one microgripper consists of two parts, clamper and actuator. A clamper usually contains two or more arms, and is driven by the actuator to grab tiny objects. Therefore, according to two different functions of piezoelectric ceramics, piezoelectric-ceramic-based microgrippers can be classified to two categories. The piezoelectric ceramic works as clamper or actuator. Although piezoelectric ceramics are adopted widely through both categories of microgrippers, the two mechanisms are constitutionally different.

When piezoelectric ceramic works as clamper, piezoelectric bimorph or heterogeneous bimorph is adopted in most cases. A piezoelectric bimorph consists of two piezoelectric elements stacked up. The heterogeneous bimorph consists of a piezoelectric element on the top of a non-piezoelectric element. Both elements of a piezoelectric bimorph serve two functions, electric and elastic, while in a heterogeneous bimorph one element serves only an elastic function, the other serves both functions. The microgrippers with piezoelectric bimorph or heterogeneous bimorph can achieve greater deflections and clamping force compared with those of the latter category. In addition, it is compatible with IC process. However, the driving voltage is high and cracking of the bimorph is severe. We developed a piezoelectric bimorph microgripper. The bimorph piezoelectric ceramics were chosen as the clampers. Theoretically, two pieces of piezoelectric ceramic were stuck together in order to form a laminated beam. Polarization of the two pieces was in the same direction, both along the thickness direction. However, during actual preparation, a substrate layer was added between the two piezoelectric layers. The structure is illustrated in Fig. 1. One end of the laminated beam was fixed up to form a cantilever. After electric field was applied, one piece of piezoelectric ceramics stretches while the other shrinks. Deformation direction can be changed by exchanging positive and negative connections. The free end of the laminated beam can be bent free to output force and displacement.

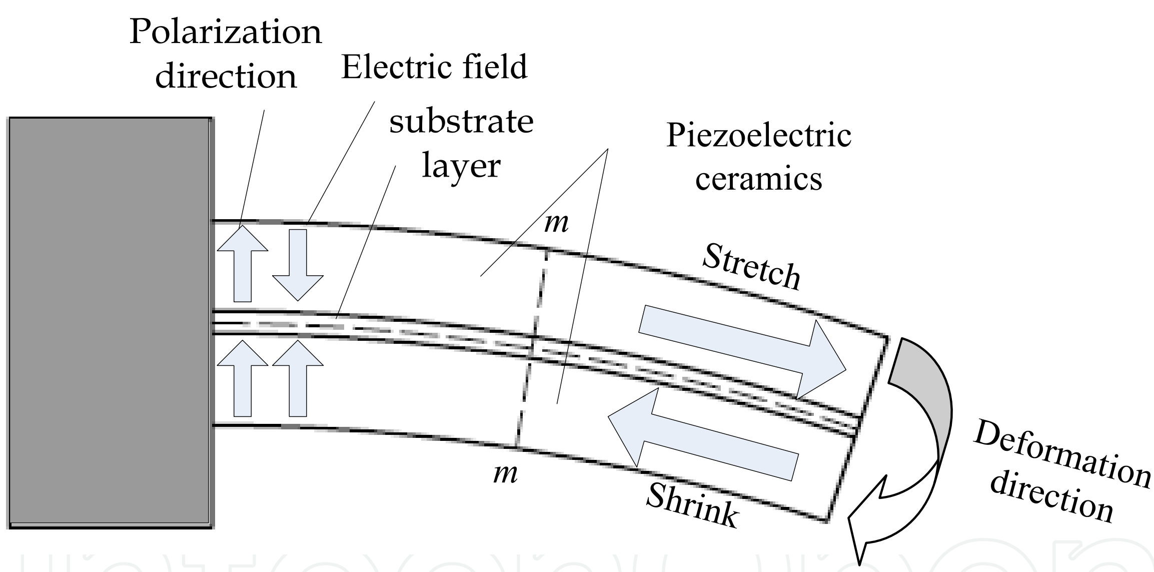


Fig. 1. The structure and working principle of parallel bimorph piezoelectric ceramic laminated beam.

When piezoelectric ceramic works as actuator, the clamper is usually a displacement amplification mechanism based on flexure hinges. This kind of microgripper has great advantages such as precise controllable output, zero friction, and zero clearance. However, this kind of microgrippers can not be made small enough for the minimum size is to a large extent limited by displacement amplification mechanisms and piezoelectric ceramics.

3. Microforce detection technology used in microgrippers

Since the manipulated objects are tiny and fragile, it is crucial important to detect the microforce during the micromanipulation process. Generally, microforce detection technology develops towards two directions, contact and non-contact detection styles. In the process of contact detection, hypersensitized force sensors are bonded with the clamper of microgrippers and utilized to obtain voltage information which is deduced to microforce after rectification, filtration, and amplification. During non-contact detection process, the clamping part's tiny deformation is detected by visual servo systems and then the microforce is deduced. In addition, forces are usually converted into light, sound, electricity, or heat. Accordingly, new experimental principle and technology, such as Optical Force Sensing method, are invented. Meanwhile, as human eyes cannot distinguish objects in micromanipulation clearly, scanning electron microscope (SEM), scanning tunneling microscope (STM), and atomic force microscopy (AFM) are utilized in the non-contact detection process.

3.1 Contact microforce detection

Strain gauge pressure sensor is one of the most important part in contact microforce detection devices. The main component is the resistance strain gauges. Resistance strain gauge is a piece of a sensitive device that an electrical signal can be converted into the measured strain. There are two categories of resistance strain gauges–metal strain gauges and semiconductor strain gauges (Smits & Choi, 1990).

The working principle of metal strain gauges is deformation after external force leads to changing resistance. Metal resistance strain gauge is divided into wire and foil strain gauges.

Semiconductor strain gauges work under external forces, apart from distortion takes places, its resistance will change. Horizontal effect, creep and hysteresis of the semiconductor strain gauge is quite small. And the frequency response range is wide for the information can be measured from the static response to high-frequency dynamic strain. With the development of integrated semiconductor manufacturing process, a variety of small and ultra-small semiconductor strain sensors can be made combining this technology with semiconductor strain gauges. Thus, the measurement system can be greatly simplified. The semiconductor strain gauge is more sensitive than the metal strain gauge, but its non-linear error is also bigger. Therefore, a semiconductor strain gauge with invariable electric current source has chosen as the main component in the micro force sensing system (Liu & Xu, 1990).

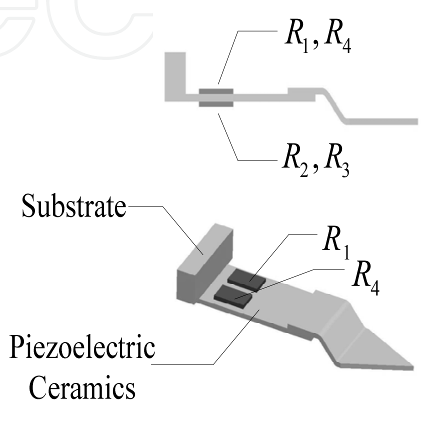


Fig. 2. Affixed position of semiconductor strain gages

Fix the parallel bimorph piezoelectric ceramic to the main body of the micro-gripper. Here, the piezoelectric ceramic can be used as a cantilever. Fig. 2 Shows the location of the semiconductor on the parallel bimorph piezoelectric ceramic.
The cantilever performs parallel bimorph bending purely when it's only effected by the moment $\boldsymbol{M}_e$, the relationship between the end displacement w and $\boldsymbol{M}_e$ is illustrated as follows.

$$w = \frac{M_e l^2}{2EI} \tag{1}$$

Here, E is the equivalent Young's modulus.
So,

$$M_e = \frac{2EIw}{l^2} \tag{2}$$

The relationship between the stress σ and the strain ε is shown as follows.

$$\sigma = \varepsilon E \tag{3}$$

The equation to calculate the stress on the pure bending cantilever is as follows.

$$\sigma = \frac{M_e y}{I} \tag{4}$$

Here, y is the coordinate of the thickness direction; $\boldsymbol{I}$ is the moment of inertia of the section of the cantilever. And, y equals half of the value of h, which is 0.3 mm. By integrating equations (2), (3) and (4), the following equation can be got.

$$\varepsilon = \frac{hw}{l^2} \tag{5}$$

A full-bridge circuit is applied to the invariable electric current source. The relationship between the input current of the circuit I_0 and the output voltage V_0 is shown as follows.

$$V_0 = R_0 K_0 I_0 e \tag{6}$$

By integrating the equations (5) and (6), the relationship between the displacement w and the output voltage of the full-bridge circuit V_0 can be illustrated as follows.

$$w = \frac{V_0 l^2}{R_0 K_0 I_0 h} \tag{7}$$

The output voltage of the full-bridge strain sensing circuit is given as follows.

$$U_0 = K \varepsilon U_i \tag{8}$$

Here, U_i is the sensitivity of the full-bridge strain sensing circuit, which stays at 3V all along the experiment; U_0 is the output voltage of the full-bridge circuit; K is the parameter of the strain sensitivity; ε is the strain.

According to the model of the force effected on the cantilever, the relationship between the gripping force and the moment is given as follows.

$$F_g = M_e / l_g \tag{9}$$

Here, l_g is the length of the strain gauge.

3.2 Non-contact microforce detection

As we don't involve any non-contact microforce detection technology, an optical force sensing system developed by (Yu & Bradley, 2000), illustrated in Fig. 3., is introduced. Contact force is detected by a protuberance on a cantilever tip. The displacement of the cantilever is obtained by that of orthogonal diode laser point. Thus, contact force can be deduced by the displacement multiplied by cantilever's elastic coefficient.

Microgripper with two fingers, illustrated in Fig. 4, is improved by the non-contact microforce detector. An improved cantilever without protuberance, used as one of the fingers, is connected with the other finger with protuberance by a piezoelectric actuator. The open-close action of the microgripper is realized by piezoelectric actuator extension and contraction. The contact force aroused by microgripper and gripping objects causes the displacement of cantilever. And as the elastic coefficient of the cantilever, contact force can be deduced by displacement detected by the optical force sensing system.

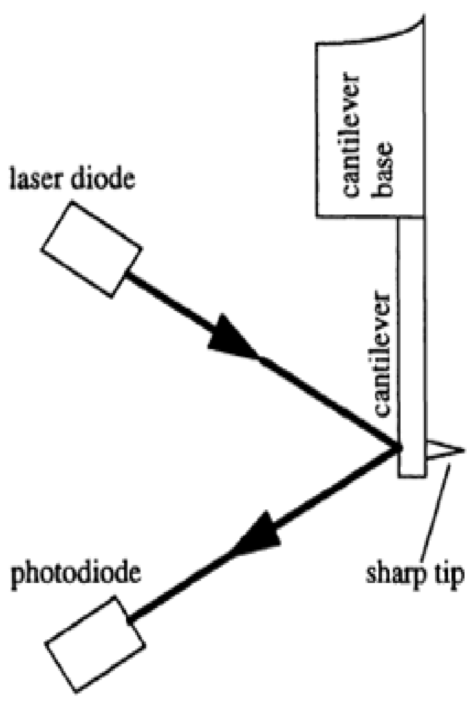


Fig. 3. Basic structure of optical force sensing system

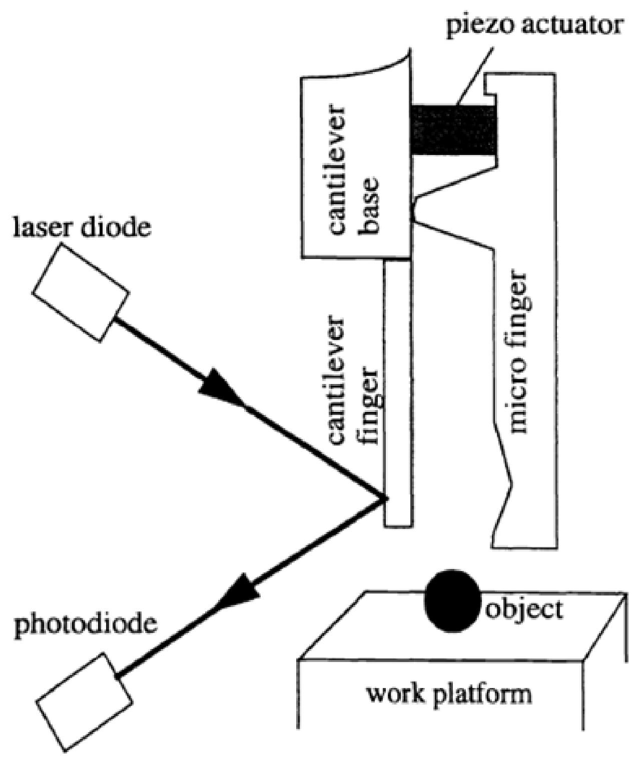


Fig. 4. Principle of microgripper with built-in optical force sensor

4. A bimorph piezoelectric ceramic microgripper integrating micro-force detecting and feedback

A combined micro-gripper offers new methods to settle the gripping and assembly problems of miniature structures and systems. Both of the large gripping extension and the gripping accuracy can be acquired by combining micro-gripper and a small linear motor with work distance of 15mm. However, two difficulties exist in combined micro-gripping technologies. First, though the gripping of some big structures in the demanded scales can be easily achieved by the combined micro-gripper, it's hard to avoid the shed of parts during the motion. Second, gripping forces range from micro-Newtons to Newtons, so it's difficult to ensure the precision of micro force sensing.

This chapter focuses on the gripping of miniature mechanical structures and systems, shows a combined two-chip piezoelectric ceramic microgripper integrated micro-force sensing and feedback function. This gripper uses the bend of two-chip piezoelectric ceramic and the motion of a linear electromotor to grip miniature structures and systems. A reinforcement machine is designed for the two-chip piezoelectric ceramic, which can avoid the shed of parts during the motion. The gripping stability and micro-force sensing and feedback are detailedly investigated theoretically and experimentally.

4.1 A combined two-chip piezoelectric ceramic micro-gripper

Abundant knowledge of the miniature parts to be gripped is required as preparation of the design and manufacturing of grippers. 3D miniature structures have peculiar demands for their grippers. First, the gripping extension of the micro-gripper must be large enough. Miniature structures can be as big as 10mm in geometry, so a larger gripping extension than generic micro-grippers is needed. Second, a high gripping precision is needed so that miniature structures as small as 0.01 mm in geometry can be successfully gripped. Third, a high gripping stability is requested to ensure a stable gripping of big parts during the motion.

The combined two-chip piezoelectric ceramic microgripper integrated micro-force sensing and feedback function is designed to meet the specific requirements of 3D miniature structures, which is shown in Fig. 5. The basic frame and function are as follows.

(a) The micro-gripper of the combined two-chip piezoelectric ceramic microgripper contains 5 portions — two-chip piezoelectric ceramic, fixed brace, reinforcement for the piezoelectric ceramic, linear fine-motion platform and pedestal. The linear fine-motion platform and the fixed brace are installed on the pedestal, while the two-chip piezoelectric ceramic and the reinforcement for the piezoelectric ceramic are installed on a folded plank which is connected onto the linear fine-motion platform.

(b) The implementing part of the micro-gripper is the two-finger mechanical gripper with one finger fixed and the other moving. The top end of the fixed brace is made of rigid alloy steel, and the top end of the moving finger is made up of less rigid two-chip piezoelectric ceramic. The tiny bending of the two-chip piezoelectric ceramic and the fixed brace work together to grip a complex 3D miniature structure.

(c) The linear fine-motion platform can produce large displacement, which can make up for the defect of small displacement produced by the tiny bending of two-chip piezoelectric ceramic. The two-chip piezoelectric ceramic's bending can only bring small displacement; what's more, the gripping force will counteract some displacement. So it's hard to meet the requirement of displacement during the assembly just by using two-chip piezoelectric ceramic. It's necessary to develop a linear coarse-motion module with large displacement output as a makeup for the fine-motion module.

(d) The reinforcement for the piezoelectric ceramic is made up of a lever machine with two reinforcing patches rotating around an axis, as shown in Fig. 6. The stretch and closing of the two reinforcing patches are controlled by an electromagnet installed on the top ends of them. When the electromagnet is cut, the spring releases so that the two reinforcing patches close. Here, the reinforcement for the piezoelectric ceramic can ensure that the two-chip piezoelectric ceramic's fixedness. When the electromagnet is switched on, the spring shrinks so that the two reinforcing patches stretch. Here, the two-chip piezoelectric ceramic can bend as long as the current is not cut. Through the stretch and closing of the electromagnet, the two patches of the reinforcement is able to clamp two sides of the piezoelectric ceramic. Therefore, the gripped part will not shed during the gripping and transfer for the reason of the inadequate stiffness.

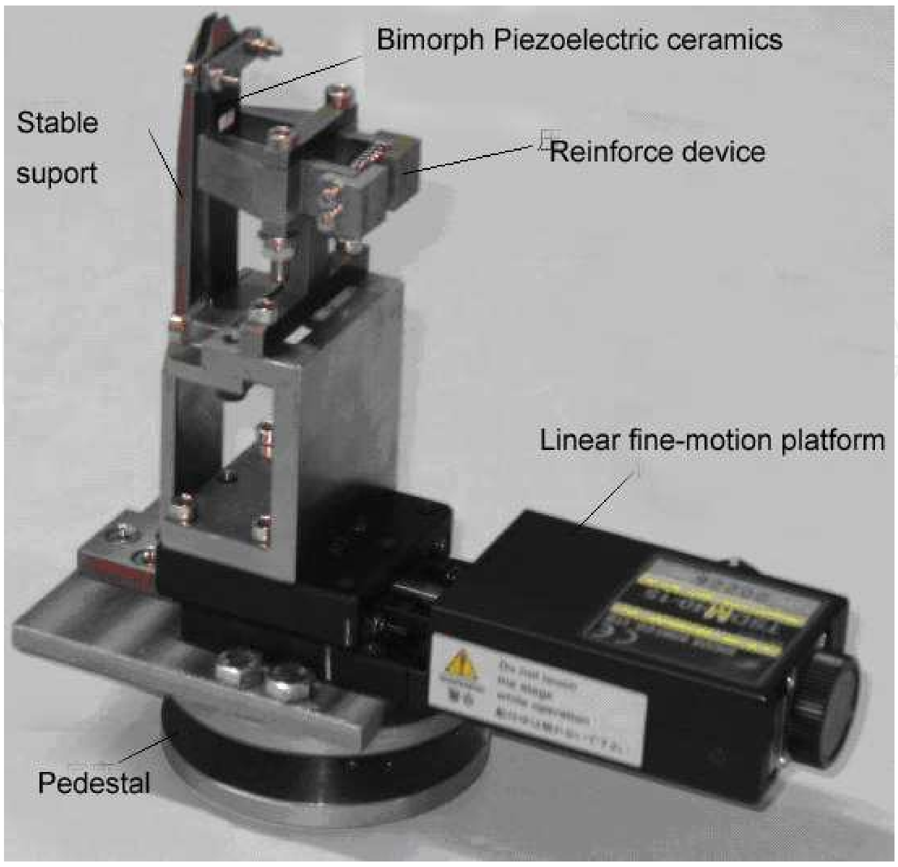


Fig. 5. Microgripper based on macle pizeelectric ceramics

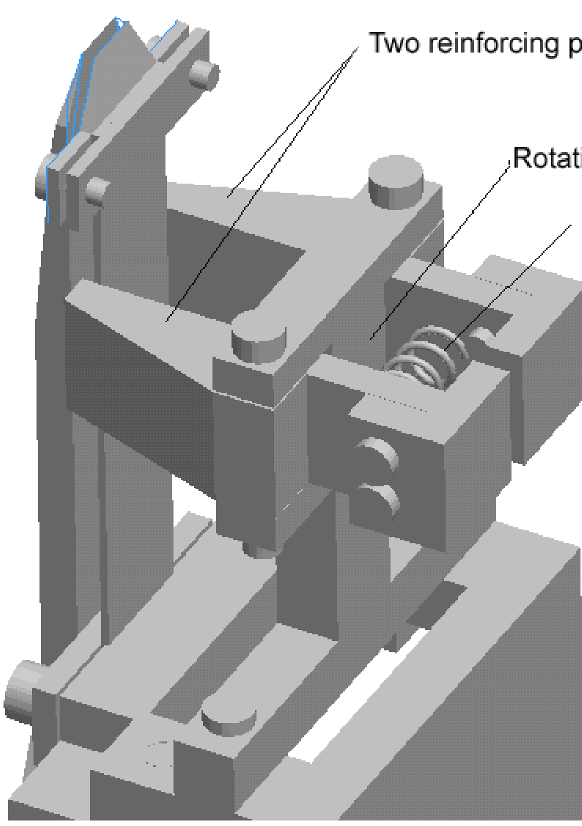


Fig. 6. Reinforcing device for piezoelectric ceramics

4.2 Micro force sensing and feedback

In this stage, researches mainly focus on two aspects–the strain sensing circuit as well as the amplifying and filter circuit. The function of the strain sensing circuit is to get the accurate voltage or current which can reflect the change in the resistance of the strain gauge. But because the parts to be gripped are very small, the bending of the two-chip piezoelectric ceramic is so tiny that the output of the strain sensing circuit is also tiny. It's necessary to apply an amplifying circuit to amplify to micro signal and a filter circuit to filter noises and other disturbing signals.

A full-bridge circuit with an invariable electric current source as its power supply is used in the strain sensing circuit. A reverse amplifier using negative feedback technology is adopted in the amplifying circuit, in which the gain is only decided by the resistance ratio. The filter circuit is designed into a twice Sallen-Key low-pass filter, shown as Fig. 7 (a) and (b).
An A/D acquisition card at the end of the sensing and filter circuits can gather the signals sensed and filtered by the previous circuits and change the analog data into digital data. Then the digital information is sent back to the control system, carrying out the feedback of the signal and providing the basis for the adjustment of the micro-gripper. This is the closed-loop control.

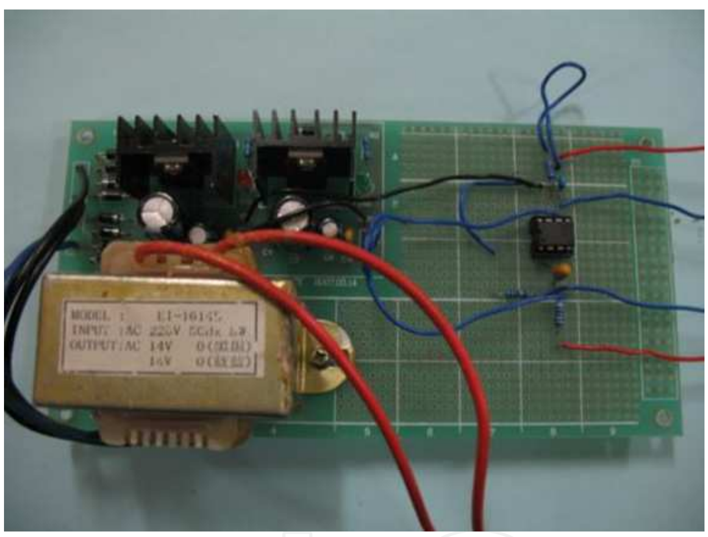


Fig. 7. (a) Amplification and filtering circuit

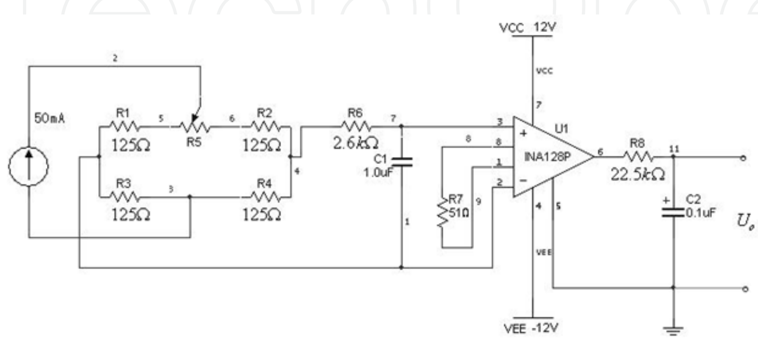


Fig. 7. (b) Amplification and filtering circuit diagram

4.3 Examples of the micro-gripping

The two-chip piezoelectric ceramic plays an important role in the combined two-chip piezoelectric ceramic micro-gripper integrated micro-force sensing and feedback function. The embodiment of its importance is shown as follows. (a) The shape of the two-chip piezoelectric ceramic is a flat cuboid, which is easy to stick the strain gauge on it. (b) The characteristic of the two-chip piezoelectric ceramic that it can bend when supplied with electricity provides a method to sensing the strain by the strain gauge.

When the two-chip piezoelectric ceramic is supplied with electricity and bending, the amplifying and filter circuits sense the output voltage of the strain sensing circuit, converse it into the corresponding end displacement, and test the capability of the two-chip piezoelectric ceramic and the relationship between the output voltage of the strain sensing circuit and the end displacement of the two-chip piezoelectric ceramic.

High precision optics displacement meter, as shown in Fig. 8, is applied to measure the true end displacement of the two-chip piezoelectric ceramic, which will be the benchmark of the end displacement.

The optics displacement meter can transform the actual displacement-the relative displacement of the certain point on the measured part-to the displacement of the reference point in a digital image, and the actual bending information will be processed by the digital image processing. The optics displacement meter won't do any harm to the measured part or import any added measuring error. Besides, its measuring precision is high. So the results got by the optics displacement meter can be considered as the ideal displacement of the two-chip piezoelectric ceramic. By comparing the end displacement got by the micro force sensing circuit and the ideal displacement got by the optics displacement meter, the measuring precision of the micro force sensing circuit can be tested.

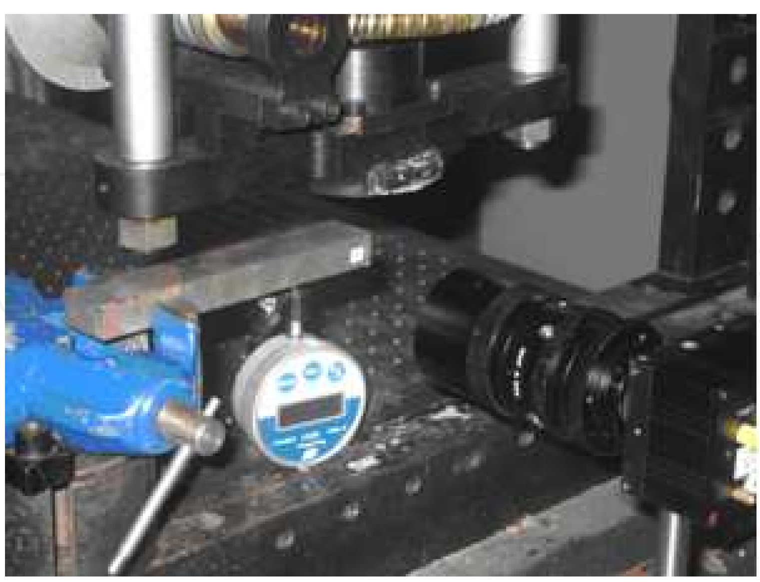


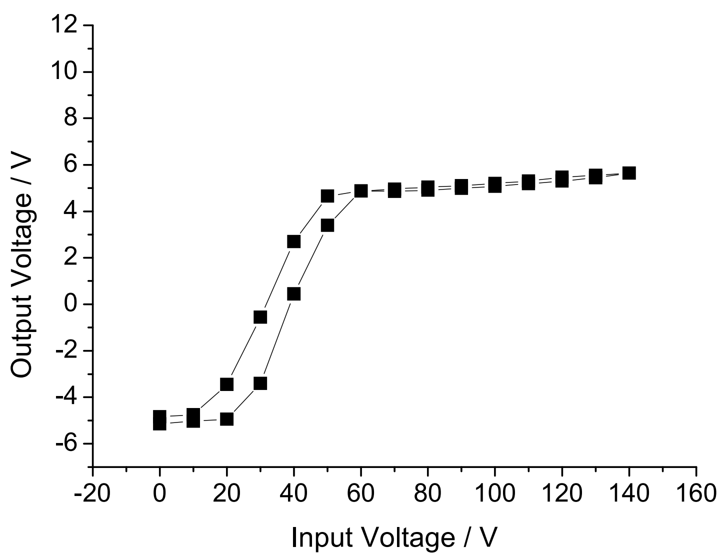
Fig. 8. Piezoelectric ceramics' displacement detected by optical displacement detection device

Fig. 9. Macle piezoelectric ceramics affixed with strain gages

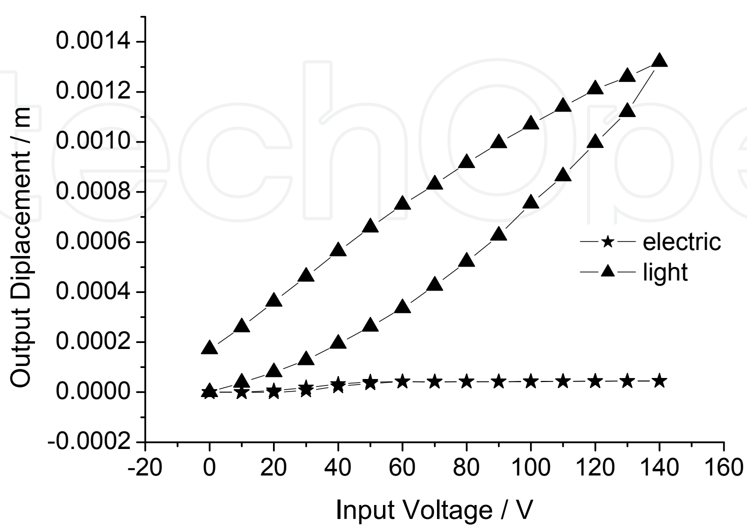
A full-bridge circuit is applied, with two of the total four strain gauges sticked on where the strain is the maximal positive and the other two on where the strain is the maximal negative. This arrangement can get the highest sensitivity. Switch on the driving circuit of the two-chip piezoelectric ceramic. The driving voltages are cataloged into a series, and the output voltages are recorded correspondingly to the driving voltage series, shown as: $U_1, U_2, \cdots, U_n$. These output voltages are the V_0 in the equation (6) and by putting them in equation (7) the displacement got by the measuring circuits $w_1, w_2, \cdots, w_n$ can be calculated.
A fine linear electrical source with invariable voltage and current is used as the driving power supply. The driving voltages range from 0 V to 150 V, with each one higher than the previous one by 10 V, which is 0, 10, 20, 30, …, 150 V, and then change degressively from 150 V to 0 V. Gather the output voltages of the amplifying and filter circuits and converse them into the end displacement information of the two-chip piezoelectric ceramic. Meanwhile, the actual displacements are recorded by the optics displacement meter. The results are shown as Fig. 10.

Fig. 10. (a) shows the relationship between the driving circuit of the two-chip piezoelectric ceramic and the input and output voltages of the measuring circuits. When the driving voltages change from 0 V to 150 V and then change backwards, the output voltages change from -6V to 6V and then go backwards to -6V. But when the input voltages curve declines, the output voltages curve declines too but its shape is not the same as the shape of the output voltages curve when the input voltages curve rises. A difference appears. Fig. 10. (b) shows the comparison of the actual displacement got by the optics displacement meter and the displacement got by the measuring circuit, where the actual displacement shows a typical hysteresis curve marked with ▲ which reflects the characteristic of the piezoelectric ceramic and the displacement got by the measuring circuits marked with □ is too small to be counted compared to the actual displacement. Fig. 10. (c) and (d) shows the displacement got by the measuring circuits and the actual displacement respectively in proper coordinates, where their shapes are almost the same although the displacement got by the

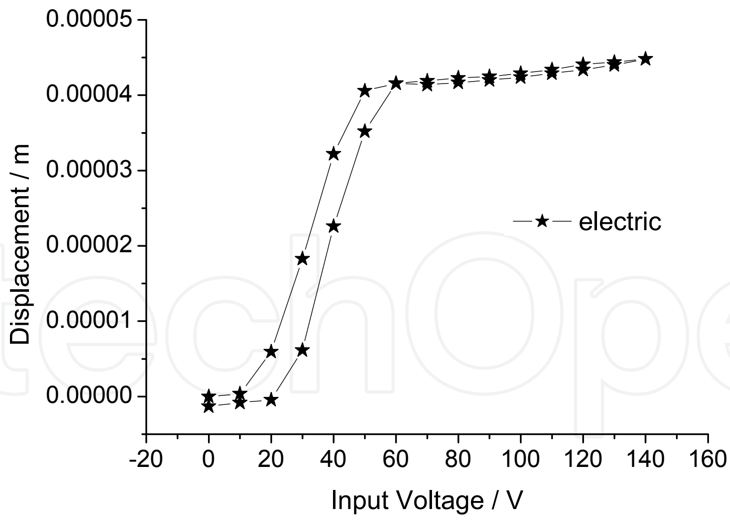
measuring circuit is two orders of magnitude smaller than the actual displacement. And then we can get the conclusions.
(a) The relationship between the end displacement of the two-chip piezoelectric ceramic and the driving voltage is not strictly linear, while the hysteresis is evident. (b) The displacement got by the measuring circuits shows the hysteresis, but its curve is S-shaped which is not accordant with the relationship between the end displacement of the two-chip piezoelectric ceramic and the driving voltage. This illuminates an aberrance of the signal. (c) The displacement got by the measuring circuits is two orders of magnitude smaller than the actual displacement got by the optics displacement meter, so it can almost be ignored. This illuminates that noises and other disturbing signals influence the measuring circuit largely, but the displacement got by the measuring circuits can already reflect the changing trend of the displacement.



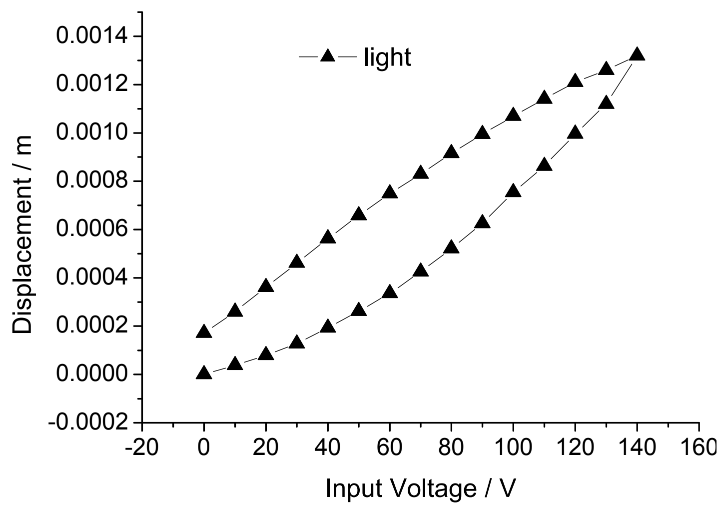
(a) Input and output voltage of detection circuit



(b) Comparison of displacement separately detected by optical displacement device and amplification filtering circuit



(c) Displacement obtained from amplification filtering circuit



(d) Displacement obtained from optical displacement device
Fig. 10. Detection result

4.4 Micro force sensing experiments

This experiment is based on the output voltage got by the amplifying and filter circuit when the two-chip piezoelectric ceramic is bending. By comparing the output voltages at the same driving voltage with a gripped part on the micro-gripper and without a gripped part, the critical driving voltage and the average output voltage when gripping a part can be found, and then they can be conversed into corresponding micro gripping force.

Switch on the driving circuit of the two-chip piezoelectric ceramic and the amplifying and filter circuit, catalog the driving voltages in a series, and record output voltages of the measuring circuit respectively as follows: $U_1, U_2, \cdots, U_n$. When the gripper doesn't contact the part to be gripped, the output voltage increases as the driving voltage increases; when the gripper contacts the part, the bending of the two-chip piezoelectric ceramic can't be controlled by the driving voltage and stays invariable. Then the output voltage of the full-bridge circuit doesn't change either. So it's considered that the part has been gripped when the output voltage doesn't change. By using the voltage here to solve equation (5), (6), (8) and (9), the micro gripping force can be got.

Change the driving voltage from 0V to 140V with each 10V higher than the previous one-that is 0V, 10V, 20V, 30V…140V, gather the voltage information got by the amplifying and filter circuit, and converse the voltage into gripping force. The measuring result is shown as Fig. 11. Fig. 11. shows the output curve of the amplifying and filter circuits. The results data are divided into two groups–one is the data when no part is gripped, and the other one is the data when the micro-gripper is gripping a part.

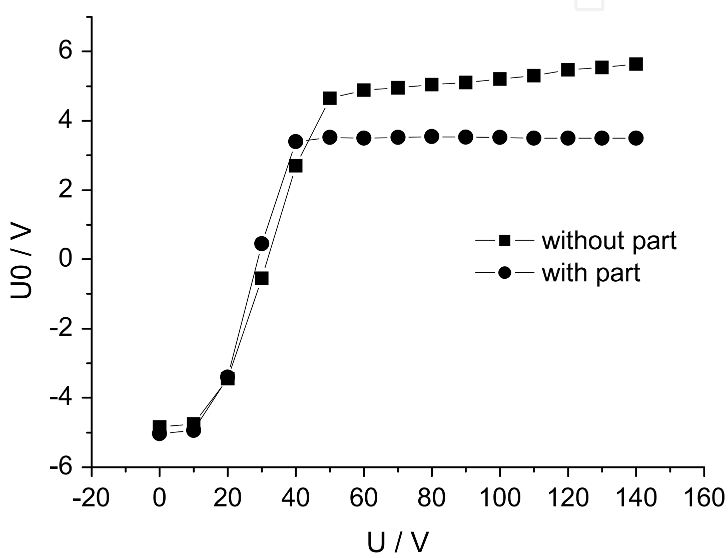


Fig. 11. Voltage result from micro force detection experiment

It can be concluded from Figure 8 that when no part is gripped the output voltage of the amplifying and filter circuit increases as the driving voltage increases and when the micro-gripper is gripping a part, the output voltage increases as the driving voltage increases from 0V to 40V, which is the same as when no part is gripped, but the output voltage stays invariable as the driving voltage continues to increase from 40V to 140V. So the 40V driving voltage is the critical voltage as the micro-gripper is gripping a part, which means that driving voltage upwards 40V will cause no more bending of the two-chip piezoelectric ceramic and no more changes of the measuring circuit. Here, the average output voltage is 5.213mV, and according to this the gripping force can be calculated to be 5.374mV.

5. Conclusion

In this chapter, we introduced the application of piezoelectric ceramics in microgrippers of micromanipulation area, especially microassembly. Two categories of piezoelectric-ceramic-based microgrippers were presented. The basic structures of bimorph piezoelectric ceramic clampers were established and the corresponding mathematical equations were deduced. After simply introducing the amplification mechanisms with flexure hinges, the reverse piezoelectric effect used by actuators of microgrippers were explained. Then, the microforce detection technology used in microgrippers was presented. The resistance strain gage was the essential and effectual constituent of contact detection style. The principles of metal resistance and semiconductor strain gauge were explained. Optical force sensing method, as a typical example of non-contact microforece detection method, was explained in detail. Finally, a practical example, a bimorph piezoelectric ceramic microgripper integrating microforce detecting and feedback, was developed. Experimental results indicated that the microgripper is possessed with not only clamping properties but also microforce detection function with milli-Newton scale accuracy.

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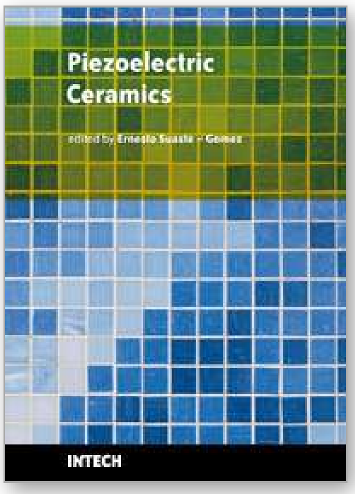

Piezoelectric Ceramics

Edited by Ernesto Suaste-Gomez

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This book reviews a big window of opportunity for piezoelectric ceramics, such as new materials, material combinations, structures, damages and porosity effects. In addition, applications of sensors, actuators, transducers for ultrasonic imaging, positioning systems, energy harvesting, biomedical and microelectronic devices are described. The book consists of fourteen chapters. The genetic algorithm is used for identification of RLC parameters in the equivalent electrical circuit of piezoelectric transducers. Concept and development perspectives for piezoelectric energy harvesting are described. The characterization of principal properties and advantages of a novel device called ceramic-controlled piezoelectric with a Pt wire implant is included. Bio-compatibility studies between piezoelectric ceramic material and biological cell suspension are exposed. Thus, piezoelectric ceramics have been a very favorable solution as a consequence of its high energy density and the variety of fabrication techniques to obtain bulk or thin films devices. Finally, the readers will perceive a trend analysis and examine recent developments in different fields of applications of piezoelectric ceramics.

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