Design of piezoelectric self-sensing microinjection device

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Abstract. With the development of biotechnology and injection technology, cell micro flow syringes have been widely used in many fields. In the meanwhile, the requirements of experimental equipment and experimental method are becoming higher and higher. In this paper, the author study on the theory and experiment of the first direct and secondary converse piezoelectric effects of piezoelectric ceramics by using the piezoelectric characteristics which can realize the integration of sensors and actuators. And the author design a self-sensing micro injection device which has the functions of localization, injection output and self-perception. The control precision and operation have been effectively improved by means of analyzing the relationship between the output and the input.

1. Introduction

With the continuous extension and development of nanotechnology, people begin to conduct a in-depth study of macroscopic and microscopic things. They not only explore some phenomena on the surface of things, but also make progress in further the development of miniaturization and precision. The scientific, medical and even government circles have put forward more and more high requirements to the MEMS system. A variety of piezoelectric sensors and actuators can be made by the single piezoelectric effect of piezoelectric materials. However, this separation sensor and actuator have been long existed and can not meet the needs of high technology. Therefore, a new type of micro sensor and micro actuator is extremely urgent by using the multiple piezoelectric effect theory[1, 2].

Because micro processing technology itself has many advantages, more and more industry begun to take advantage of the technology to develop all sorts of detection device, such as fluid monitoring, super precision machining, biological genetic engineering and so on. Microinjection device is one of them. In the piezoelectric applications, most of microinjection device use first converse piezoelectric effect of piezoelectric materials to complete the executive function, and does not apply multiple piezoelectric effects. The purpose of this study is using the first converse piezoelectric effect of actuator and the secondary direct piezoelectric effect of sensor in the same piezoelectric body to design an automatic microinjection device which can sense the actual liquid flow. While applying an external voltage on piezoelectric materials, it will output a small displacement. Use the secondary positive piezoelectric effect of our own to perform sensor functions. Use part of the output charge to sense the actual amount of microinjection produced by the inverse. In the case of the amount of
injection, the value of real injection can be realized. The control precision and operation efficiency of the microinjection device are improved effectively and the synchronism between the sensor and the actuator is reflected. Most microinjection devices will appear wear and deformation for a long period of time resulting in the output error between the theoretical value and the actual value. Self-sensing microscopic flow injection device can more accurately measure the actual output displacement using multiple piezoelectric effect, so that they can better control the dosage of micro syringe. The injection rate improve greatly. Therefore, it is great significance to study the principle and structure of the self-sensing microinjection device for the optimization of the original injection device[3-5].

2. The basic principle of piezoelectric self-sensing technology

2.1. Theoretical basis of piezoelectric self-sensing technology
Piezoelectric self-sensing technology refers to the use of piezoelectric ceramic materials of the direct piezoelectric effect and converse piezoelectric effect at the same time and piezoelectric ceramic output displacement or force for actuator to achieve self-sensing at the same time. The direct piezoelectric effect is that when the piezoelectric ceramic material is subjected to external forces in a certain direction, its surface will generate free charge, as shown in figure 1(a). The converse piezoelectric effect is that the surface of piezoelectric ceramic generates a free charge when an external force is applied in a particular direction, as shown in figure 1(b). For piezoelectric ceramic materials, the positive piezoelectric effect and inverse piezoelectric effect are generally simultaneous and reversible, as shown in figure 2. The primary inverse piezoelectric effect on the same piezoelectric ceramic material is used to realize the sensor function and the secondary positive piezoelectric effect is used to realize the actuator function. It can be regarded as the realization process of piezoelectric self-perception[6].

![Piezoelectric effect](image1)

**Figure 1.** Piezoelectric effect.

![Principle of piezoelectric self-sensing](image2)

**Figure 2.** Principle of piezoelectric self-sensing.

The electrical and mechanical states of piezoelectric materials are determined according to the form of boundary conditions. Therefore, the boundary conditions of piezoelectric materials play an important role in the study of piezoelectric effects. From the angle of "machine-electrical" coupling,
piezoelectric body can be under the condition of electrical and mechanical boundary conditions. Electrical boundary conditions are divided into electrical open circuit and short circuit. And mechanical boundary conditions are divided into mechanical freedom and clamping. Four types of combined boundary conditions can be obtained by combining the electrical and mechanical boundary conditions, and four types of piezoelectric equations can be obtained under the combined boundary conditions. The specific expression method is shown in table 1[7].

Table 1. Expressions and boundary conditions of four kinds of piezoelectric equation.

| Piezoelectric equations | Expression | Boundary conditions | Remarks |
|-------------------------|------------|---------------------|---------|
| The first \(d\)-type | \(S_i = s_{ij}^E T_j + d_{mj} E_n\) | Mechanical freedom | \(s_{ij}^E\): Short circuit elastic compliance constant matrix |
|                         | \(D_m = d_{mij} T_j + \varepsilon_{dn}^m E_n\) | Electrical short circuit | \(d_{mij}\): Transposed matrix of \(d\) |
| The second \(e\)-type | \(T_j = e_{mj}^E S_i + e_{ni}^E E_n\) | Mechanical clamping | \(e_{mj}^E\): Piezoelectric strain constant matrix |
|                         | \(D_m = e_{mni} s_{ij} - \varepsilon_{nmi}^E E_n\) | Electrical short circuit | \(e_{nmi}\): Dielectric constant matrix |
| The third \(g\)-type | \(S_i = s_{ij}^G T_j + g_{mj} D_m\) | Mechanical freedom | \(s_{ij}^G\): Short circuit elastic stiffness constant matrix |
|                         | \(E_n = -g_{nj} T_j + \beta_{nm}^T D_m\) | Electrical open circuit | \(g_{nj}\): Transposed matrix of \(g\) |
| The fourth \(h\)-type | \(T_j = c_{mj}^G S_i - h_{nj} D_m\) | Mechanical clamping | \(c_{mj}^G\): Piezoelectric strain constant matrix |
|                         | \(E_n = -h_{ni} S_i + \beta_{nm}^S D_m\) | Electrical open circuit | \(h_{ni}\): Transposed matrix of \(h\) |

Under mechanical freedom and only applied external electric field \(E_n^w\), the expression can be obtained according to the first converse piezoelectric effect and the first piezoelectric equation.

\[
S_i^{(1)} = d_{mj} E_n^w \tag{1}
\]

The simplified Eqs(2) is obtained by Eqs(1)[8].
\[ \delta^{(1)} = nd_{33}V \]  
(2)

Where, \( \delta \) is the first converse output displacement, \( n \) is the layer number of piezoelectric ceramic stack, \( d_{33} \) is the piezoelectric coefficient, \( V \) is the driving voltage.

The strain \( S^{(1)}_i \) generated in the first converse process will react on piezoelectric ceramics, the expression can be obtained according to the secondary direct piezoelectric effect and the second piezoelectric equation.

\[ D_m^{(2)} = e_{mi}S^{(1)}_i = e_{mi}d_{ni}E_n \]  
(3)

The simplified Eqs(4) is obtained by Eqs(3)[9].

\[ V^{(2)} = \frac{Q^{(2)}}{C} = \frac{AD^{(2)}}{C} = \frac{Ae_{33}d_{33}V_3}{Ct} = \frac{Ae_{33}}{Ct} \delta \]  
(4)

Where, \( V^{(2)} \) is the output voltage of the secondary direct piezoelectric effect, \( C \) is the equivalent capacitance of piezoelectric ceramics, \( A \) is the section area of piezoelectric ceramics, \( t \) is the thickness of a single piece ceramic. And \( e_{33} = d_{33}y_{33}, e_{33} \) is the piezoelectric stress constant, \( d_{33} \) is the piezoelectric coefficient, \( y_{33} \) is the elastic coefficient.

It can be seen from the above analysis that the displacement generated by Eqs(2) is used to control the stroke and injection amount of the microinjection device, and the voltage generated by Eqs(4) is used to perceive the actual output displacement.

2.2. Experimental of piezoelectric self-sensing technology

The main equipment used in the experiment are PZT-5, YE6232B data acquisition, YE5850 charge amplifier, XE-500/501 piezoelectric controller, MDS amesdial, load cell and computer. The basic parameters of PZT are shown in table 2.

| Type       | Piezoelectric coefficient \( (10^{-12} \text{C/N}) \) | Piezoelectric voltage constant \( (\text{C/m}^2) \) | Piezoelectric stress constant \( (\text{C/m}^2) \) | Elastic coefficient \( (10^{10} \text{N/m}^2) \) | Piezoelectric stiffness constant \( (10^3 \text{N/C}) \) |
|------------|-----------------------------------------------------|--------------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| PZT-5      | \( d_{33} = 800 \)                                  | \( g_{33} = 0.019 \)                              | \( e_{33} = 34.4 \)                           | \( c_{33} = 4.3 \)                             | \( h_{33} = 2.15 \)                            |
| Number of pieces |                                      | Capacitance \( (\mu\text{F}) \)                     | Maximum driving force \( (\text{N}) \)        | Boundary dimension \( (\text{mm}) \)          |
| 250        | 0.12                                                | 1.75                                             | 4000                                          | \( 10 \times 10 \times 30.4 \)               |
| 1000       | 0.12                                                | 1.75                                             | 1000                                          | \( 5 \times 5 \times 121.6 \)                |

The experimental structure and physical connection of the first converse piezoelectric effect are shown in figure 3 and figure 4.
The piezoelectric ceramics are applied from 0V to 100V at a voltage interval of 10V, the experimental measurement and theoretical output values of the micro displacement generated by the first converse piezoelectric effect are shown in table 3.

| Driving voltage (V) | Theoretical value | Practical value | Theoretical value | Practical value |
|---------------------|-------------------|-----------------|-------------------|-----------------|
|                     | 10*10*30.4        | 5*5*121.6       |                   |                 |
| 0                   | 0                 | 0.013           | 0                 | 0.0267          |
| 10                  | 2                 | 1.477           | 8                 | 5.863           |
| 20                  | 4                 | 3.453           | 16                | 14.017          |
| 30                  | 6                 | 5.683           | 24                | 20.863          |
| 40                  | 8                 | 8.113           | 32                | 29.087          |
| 50                  | 10                | 10.333          | 40                | 37.040          |
| 60                  | 12                | 12.727          | 48                | 45.087          |
| 70                  | 14                | 15.247          | 56                | 52.963          |
| 80                  | 16                | 17.513          | 64                | 60.890          |
| 90                  | 18                | 18.310          | 72                | 72.747          |
| 100                 | 20                | 21.773          | 80                | 80.653          |

Figure 3. Experimental structure diagram.  
Figure 4. Physical connection diagram.  
Figure 5. Comparison diagram of theoretical and practical.
It can be seen from the figure that the applied driving voltage is basically in a linear relationship with the output micro displacement. The measured values of 10*10*30.4 stack and 5*5*121.6 stack between 0V~80V basically coincide with the theoretical values respectively. And the resulting error can be ignored. In practical application, the driving voltage of the two models should be controlled between 0V~80V to improve the system precision.

The experimental structure and physical connection of the secondary direct piezoelectric effect are shown in figure 6 and figure 7.

![Experimental structure diagram](image)

**Figure 6.** Experimental structure diagram.

![Physical connection diagram](image)

**Figure 7.** Physical connection diagram.

The experimental measurement and theoretical output values are shown in table 4.

| Driving voltage (V) | 10*10*30.4 | 5*5*121.6 |
|---------------------|------------|------------|
|                     | Theoretical value(mV) | Practical value(mV) | Theoretical value(mV) | Practical value(mV) |
| 0                   | 0          | 0          | 0                      | 0                      |
| 10                  | 32.76      | 10.88      | 32.76                  | 14.13                  |
| 20                  | 65.52      | 24.37      | 65.52                  | 27.67                  |
| 30                  | 98.28      | 36.58      | 98.28                  | 41.27                  |
| 40                  | 131.04     | 44.33      | 131.04                 | 54.69                  |
| 50                  | 163.8      | 57.78      | 163.8                  | 69.45                  |
| 60                  | 196.56     | 72.79      | 196.56                 | 82.76                  |
| 70                  | 229.32     | 85.08      | 229.32                 | 96.42                  |
| 80                  | 262.08     | 97.30      | 262.08                 | 110.27                 |
| 90                  | 294.84     | 113.48     | 294.84                 | 127.89                 |
| 100                 | 327.6      | 125.77     | 327.6                  | 141.39                 |

According to table 3 and table 4, the self-sensing displacement of piezoelectric ceramic stack is shown in table 5.
Table 5. Self-sensing displacement and first converse displacement.

| Driving voltage (V) | 10*10*30.4 | 5*5*121.6 |
|---------------------|-------------|-----------|
|                     | first converse displacement (μm) | Self-sensing displacement (μm) | first converse displacement (μm) | Self-sensing displacement (μm) |
| 0                   | 0.013       | 0         | 0.0276 | 0         |
| 10                  | 1.477       | 0.66      | 5.863  | 3.45      |
| 20                  | 3.453       | 1.49      | 14.017 | 6.76      |
| 30                  | 5.683       | 2.23      | 20.863 | 10.08     |
| 40                  | 8.113       | 2.71      | 29.087 | 13.35     |
| 50                  | 10.333      | 3.53      | 37.040 | 16.96     |
| 60                  | 12.727      | 4.44      | 45.087 | 20.21     |
| 70                  | 15.247      | 5.19      | 52.963 | 23.54     |
| 80                  | 17.513      | 5.94      | 60.890 | 26.93     |
| 90                  | 18.310      | 6.93      | 72.747 | 31.23     |
| 100                 | 21.773      | 7.68      | 80.653 | 34.53     |

Figure 8. Comparison diagram.

Although there is a large error between the self-sensing displacement and first converse displacement of piezoelectric ceramic stack, there is still a certain proportional relationship. The self-sensing displacement of 10*10*30.4 type ceramic stack is about 0.4 times of an inverse actual measurement of displacement. The self-sensing displacement of 5*5*121.6 type ceramic stack is about 0.5 times of an inverse actual measurement of displacement. According to the relationship between output and input, the input can be set between 0V–80V to ensure a linear relationship.

3. Model design and experimental verification

3.1. Model design

Based on the requirements of cell injection and the driving characteristics of different fluids, the multiple piezoelectric effect characteristics of piezoelectric ceramic stack were used to make small changes in the content of the syringe filled with medicine liquid for microinjection. Using the above theory and experiment, the microinjection device can complete the displacement and injection volume during the injection process. It can perceive the actual displacement and injection volume, and realize the positioning and quantitative control of microinjection to ensure the reliable and stable output of the liquid[10].
Through the analysis of functional structure and the process of microinjection, the corresponding structures are designed respectively. As shown in figure 8, it consists of four parts: 10*10*30.4 motion mechanism (positioning control), 5*5*121.6 motion mechanism (quantitative control), injection motion mechanism and peripheral detection circuit.

3.1.1. 5*5*121.6 series motion mechanism
This structure is used to push the syringe piston and inject the liquid into the object. In figure 10, base 1 is fixed on the platform with fixed screw 2, and slot 3 is open on base 1, and 5*5 stack is placed into straight slot to prevents the body from moving to right and left. The pretightening screw 4 is placed at the end of straight slot to secure one end of the stack and the other end is freely retractable.

3.1.2. 10*10*30.4 series motion mechanism
This structure is used to push the entire syringe to move the micro needle out of the cell, which is similar to the 5*5 motion mechanism in the structural design. In figure 11, two ceramic stacks are used to make the entire syringe move more accurately, base 5 is fixed on the platform, and there are two grooves 6, which are used to place the 10*10 stack, One end of the ceramic stack is fixed with pretightening screw 7, and the other end is connected with a u-shaped block 8. When the ceramic stack is energized, the u-shaped block is moved, and the u-shaped block is used to drive the syringe motion system connected in front.
3.1.3. Injection motion mechanism

This structure is mainly used to realize the movement and fixation:

1) Movement: U-shaped block 8, the needle tube 9, the suction plate 10, and the linear guide 11 are fixed together by fastening screws, and 11 and 12 constitute a frictionless track. When the 10*10 ceramic stack is energized, a telescopic deformation occurs, which causes the needle to move on the frictionless track to determine the position of the injection.

2) Clamping: When the injection position is determined, the magnet in the base is energized, and the adsorption plate 10 is fixed by the generated suction. The position of the syringe does not change. When the 5*5 stack is energized, the deformation causes the piston to move forward, and then the liquid is squeezed out and injected into the cells to complete the microinjection.

3.2. Experimental verification

Figure 13 is the physical structure diagram of the self-sensing injection device. Firstly, 10*10 stack was preloaded, and then voltage was applied to the ceramics, resulting in micro displacement to drive the whole syringe movement, and there will be a gap between the 5*5 stack and the plunger of the syringe. After the ceramic is pre-tightened again through the screw, the liquid injected will reach the critical state at the needle. Finally, a voltage was applied to the 5*5 stack, and the resulting displacement pushed the piston to move slightly, injecting the liquid into the cells. In the whole process, the ceramic stack perceiving actual output displacement through secondary direct piezoelectric effect.
3.2.1. Microinjection flow generation experiment
Applying 0V~80V drive voltage to the 10*10 ceramic motion mechanism, the resulting micro displacement is shown in table 6.

| Driving voltage (V) | Experimental displacement 1(μm) | Experimental displacement 2(μm) | Average displacement (μm) |
|---------------------|----------------------------------|---------------------------------|---------------------------|
| 0                   | -0.15                            | -0.47                           | 0.31                      |
| 10                  | -1.17                            | -1.51                           | 1.34                      |
| 20                  | -2.13                            | -2.63                           | 2.38                      |
| 30                  | -3.46                            | -3.96                           | 3.71                      |
| 40                  | -4.92                            | -5.58                           | 5.25                      |
| 50                  | -6.64                            | -7.34                           | 6.99                      |
| 60                  | -8.39                            | -9.02                           | 8.705                     |
| 70                  | -10.13                           | -10.67                          | 10.4                      |
| 80                  | -11.91                           | -12.26                          | 12.085                    |

After positioning, electrify the magnet of the motion mechanism, fix the adsorption plate, and apply 0V~80V drive voltage to the 5*5 ceramic stack motion mechanism. In the experiment, the thinnest conventional injection needle was selected. When the drive voltage reached 40V, small droplets would appear in the tip, and the droplets would increase with the increasing voltage.

3.2.2. Microinjection flow measurement experiment
When the microinjection system is fixed, the voltage is applied from 40V. Under the same voltage, the same operation is repeated 5 times. The scale is used to measure the total liquid outflow for 5 times, and then the average value is obtained. Then, the drive voltage is transformed, 10V is a benchmark, and each drive voltage is measured 5 times until 80V, as shown in figure 14 and 15.
3.2.3. Microinjection flow perception experiment
The measurement results of microinjection flow perception are shown in table 7. According to the analysis of the table, the perceived displacement is 0.4 times of the actual displacement of the positioning mechanism, and the injection mechanism is 0.5 times, the output micro displacement has a good linear relationship with the applied voltage, which proves the correctness of the theoretical analysis and the rationality of the experimental setup.

| Driving voltage (V) | Self-sensing displacement of 10*10 (μm) | Self-sensing displacement of 5*5 (μm) |
|--------------------|--------------------------------------|--------------------------------------|
| 0                  | 0.075                                | 0                                    |
| 10                 | 0.385                                | 0.54                                 |
| 20                 | 1.5                                  | 1.53                                 |
| 30                 | 1.235                                | 2.56                                 |
| 40                 | 1.565                                | 3.63                                 |
| 50                 | 2.385                                | 4.62                                 |
| 60                 | 2.995                                | 5.64                                 |
| 70                 | 3.59                                 | 6.62                                 |
| 80                 | 4.1                                  | 7.61                                 |

The driving voltage can be applied to control the displacement and injection amount by the first converse piezoelectric effect, the actual displacement and injection amount are perceived by the secondary direct piezoelectric effect, and achieving the quantitative control of microinjection.

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