Theoretical research and application development of self-sensing micro-flow injection device

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Abstract: In this study, the main content is based on theory and application of piezoelectric ceramic digital micro-injection, analyzing the first inverse piezoelectric effect and secondary positive piezoelectric effect of piezoelectric ceramics through theory and experiments, and using its principle to design self-sensing digital micro-injection structure. This paper designs a kind of digital micro-injection device which is based on the first inverse and secondary positive piezoelectric effect by according to the theoretical research and experimental verification of piezoelectric ceramic's piezoelectric effect. Push the syringe plunger under the action of the piezoelectric ceramic's first reverse piezoelectric effect to achieve a fluid flowing. At the same time, secondary piezoelectric effect can sense the injection volume to achieve self-sensing microinjection. Designing the overall structure of the program and validate the feasibility of the program is reasonable and practicable through feasibility experiments.

1. Foreword
Thanks to the rapid development of nanotechnology, people are able to delve deep into macro world but also to the micro world as well. In the microscopic world, research objects continue to develop towards miniaturization, posing higher requirements for micro-electromechanical systems[1-3]. Microfluidic Control Technology are quite popular as accurate control of microfluidic substances are important in almost every industry [4]. However, most domestic scholars engaged in the application research of piezoelectric effect on micro injection are mainly focused on the theory of first inverse piezoelectric effect, with few dedicated into the profound research of the application of the secondary piezoelectric effect [5-6]. In this paper, by focusing on the research of the first inverse piezoelectric effect and secondary positive piezoelectric effect, it proposes the design scheme of self-sensed and controllable digital microinjection device and produces specific device to carry out field research.

2. The basic principle of the self-sensed microinjection device
In this paper, the micro-flow injection device is designed on the basis of the first inverse and secondary positive piezoelectric effect of the piezoelectric ceramic stack. It is featured by fast response, high control accuracy, high displacement resolution and large output force. The piezoelectric body starts from the inverse piezoelectric effect. The premise for the subsequent piezoelectric effect is that the piezoelectric body is in an electrical open circuit and mechanically Free State.

It analyzes the first inverse piezoelectric effect and secondary positive piezoelectric effect starting
from inverse piezoelectric effect. That is, when the condition of voltage drive and mechanical is free, only apply the external electric field $E_{wa}^{n}$, and the external stress is 0. The resulting piezoelectric effect process is as follows [7,8]:

The external electric field $E_{wa}^{n}$ → strain $S_{i}^{(1)}$: The first inverse piezoelectric effect.

strain $S_{i}^{(1)}$ → electric displacement $D_{m}^{(2)}$: Start of the first inverse piezoelectric effect and the secondary positive piezoelectric effect.

From the first inverse piezoelectric effect and the first type of piezoelectric equation, we can get

$$S_{i}^{(1)} = d_{ni}E_{wa}^{n}$$ (1)

Where, $d_{ni}$ is piezoelectric strain constant.

From the secondary positive piezoelectric effect and the piezoelectric equation, we can get

$$D_{m}^{(2)} = e_{mi}S_{i}^{(1)} = e_{mi}d_{ni}E_{wa}^{n}$$ (2)

Where, $e_{mi}$ piezoelectric stress constant.

From the above analysis, based on Equation (1) or the strain of the first inverse piezoelectric effect $S_{i}^{(1)}$ to control the travel and injection volume of the microinjection device; by using Equation (2) or the displacement created by the secondary positive piezoelectric effect $D_{m}^{(2)}$ to sense the displacement of this device.

3. Experimental research of piezoelectric ceramic stack in the microinjection device

3.1. Experiment Appliance

The main appliances for the experiment include XE-500/501 series piezoelectric ceramic controller, YE6232B data collector, LVDT micrometer, PZT-5 piezoelectric ceramics, etc. Major research objects-the basic parameters of piezoelectric ceramic stack as shown in Table 1 and Table 2.

Table 1 The basic parameters of piezoelectric ceramic stack

| piezoelectric ceramic stack | Piezoelectric coefficient $(10^{-12} \text{C/N})$ | Piezoelectric voltage constant $(\text{m}^2/\text{C})$ | Piezoelectric stress constant $(\text{C/m}^3)$ | Elastic coefficient $(10^{10} \text{N/m}^2)$ | Piezoelectric stiffness $(10^7 \text{N/C})$ |
|-----------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| PZT-5                       | $d_{33} = 800$                  | $g_{33} = 0.019$                | $e_{33} = 34.4$                 | $c_{33} = 4.3$                  | $h_{33} = 2.15$                 |

Table 2 The basic parameters of two sizes piezoelectric ceramic stack

| Size | Number of slices | Thickness of single piece $(\text{mm})$ | Electric capacity $(\mu\text{F})$ | Maximum driving force $(\text{N})$ |
|------|-----------------|-----------------------------------|---------------------------------|---------------------------------|
| $10 \times 10 \times 30.4$ | 250              | 0.12                              | 1.75                            | 4000                            |
| $5 \times 5 \times 121.6$  | 1000             | 0.12                              | 1.75                            | 1000                            |

3.2. Test for the first inverse piezoelectric effect based on piezoelectric ceramic

Starting from inverse piezoelectric effect, it analyzes the first inverse piezoelectric effect and secondary positive piezoelectric effect. That is, when the condition of voltage drive and mechanical is free, only apply the external electric field $E_{wa}^{n}$, and the external stress is 0.

Two piezoelectric ceramics with the dimension of $10 \times 10$ and $5 \times 5$ are tested for micro displacement under the first inverse piezoelectric effect.

As shown in the figure, the first inverse piezoelectric effect has linear relations with the external drive voltage in general. The piezoelectric ceramics with the dimension of $10 \times 10$ and $5 \times 5$ are closer to
the theoretical value within the range of 50V~100V and 10 V~100V, with less errors.

Figure 1 The comparison picture of the theoretical and actual displacement produced in the first inverse piezoelectric effect

3.3. Test for the secondary positive piezoelectric effect based on piezoelectric ceramic

In the secondary piezoelectric effect experiment of piezoelectric ceramics, when the boundary conditions are mechanically free, the piezoelectric body can produce displacement through the primary inverse piezoelectric effect. In addition, the piezoelectric body can also generate an additional charge through the secondary positive pressure.

Under the boundary conditions of mechanical freedom free from external force applied, an external electric field $E_{ext}$ (0~100V) is applied to the piezoelectric ceramics with an increase interval of 10 V, the theoretical output voltage of the secondary positive piezoelectric effect is:

$$V^{(2)} = \frac{Q^{(2)}}{C} = \frac{AD^{(2)}}{C} = \frac{Ae_{33}d_{33}V_{3}}{Ct} = \frac{Ae_{33}d_{33}V_{3}}{Ct}$$

(3)

$$e_{33} = d_{33}V_{33}$$

(4)

Where, $V^{(2)}$ is secondary positive piezoelectric effect output voltage, $Q^{(2)}$ is secondary positive piezoelectric effect output charge.

Figure 2 The comparison picture of the displacement produced in the first inverse piezoelectric effect and the displacement sensed in the secondary positive piezoelectric effect

Figure 2 represents the comparison picture of the displacement produced in the first inverse piezoelectric effect and the displacement sensed in the secondary positive piezoelectric effect. Curve A1 and B1 represent the output displacement of piezoelectric ceramic with dimension 10*10 under the
first inverse piezoelectric effect while Curve A2 and B2 is its self-sensed displacement under the secondary positive piezoelectric effect; Curve C1 stands for the output displacement of piezoelectric ceramic with dimension 5*5 under the first inverse piezoelectric effect while Curve C2 is its self-sensed displacement under the secondary positive piezoelectric effect.

4. Microinjection Device Design
The micro displacement in this paper is generated under the first inverse piezoelectric effect with the adoption of piezoelectric ceramics. The microinjection method due to minor alteration of injection needles and injection capacity is based on the movement of the push needle in the liquid cavity to produce volume displacement, which acts on the fluid to achieve flow. The injection volume can also be sensed by the secondary positive piezoelectric effect of the piezoelectric ceramic. The assembly is shown in Figure 3.

![Figure 3](image)

4.1. Microinjection experiment based on the first inverse piezoelectric effect

4.1.1. Microinjection needle positioning experiment
The diagram of experimental system configuration is shown in Figure 4.

![Figure 4](image)

Table 3 The microinjection positioning based on the first inverse piezoelectric effect

| External voltage (V) | Experiment 1 displacement (μm) | Experiment 2 Displacement (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                    |
| 90                   | -13.57                         | -13.84                         | 13.705                    |
| 100                  | -15.31                         | -15.66                         | 15.485                    |
4.1.2, Microinjection experiment

Before the experiment, switch on the round magnetic power switch enabling absorption of the iron plate to fix the injection needle. Pre-load the 5*5 piezoelectric ceramic, and apply an external electric field to it through the driving power supply. The applied range is 0–100 V, and the increasing interval is 10 V.

A conventional injection needle is selected, and the volume is fixed at 0.5mL. It is observed in the experiment, when the driving voltage changes from 0 to 100 V, a droplet appears at the tip of the needle at 50 V, as shown in Figure 5. The droplet will expand with the increase of the applied voltage.

![Figure 5 The picture of drops in conventional needles](image)

Glass microneedles are used and glued to the conventional injection needles with a glue gun. When the driving voltage changes from 0 to 100 V, a droplet appears at the tip of the needle at 70 V, as shown in Figure 6. And the droplet will get bigger with the increase of the applied voltage.

![Figure 6 The picture of glass microneedles](image)

4.2. Self-sensed value experiment based on the secondary positive piezoelectric effect

The piezoelectric ceramic self-sensing displacement value measured by the circuit is shown in Table 4.

| External voltage (V) | Experiment 1 Self perceived displacement (μm) | Experiment 2 Self perceived displacement (μm) | Average displacement (μm) | piezoelectric ceramics of 5*5 Self perceived Displacement (μm) |
|---------------------|---------------------------------------------|---------------------------------------------|--------------------------|---------------------------------------------------------------|
| 0                   | 0.04                                        | 0.11                                        | 0.075                    | 0                                                             |
| 10                  | 0.35                                        | 0.42                                        | 0.385                    | 0.54                                                          |
| 20                  | 0.65                                        | 0.85                                        | 1.5                      | 1.53                                                          |
| 30                  | 1.19                                        | 1.28                                        | 1.235                    | 2.56                                                          |
| 40                  | 1.68                                        | 1.45                                        | 1.565                    | 3.63                                                          |
| 50                  | 2.31                                        | 2.46                                        | 2.385                    | 4.62                                                          |
| 60                  | 2.87                                        | 3.12                                        | 2.995                    | 5.64                                                          |
| 70                  | 3.51                                        | 3.67                                        | 3.59                     | 6.62                                                          |
| 80                  | 4.08                                        | 4.12                                        | 4.1                      | 7.61                                                          |
| 90                  | 4.66                                        | 4.72                                        | 4.69                     | 8.62                                                          |
| 100                 | 5.31                                        | 5.44                                        | 5.375                    | 9.61                                                          |
5. Conclusion
From the data in the paper, it can be concluded that the self-sensed value of piezoelectric ceramic with dimension of 10*10 is 1/3 of the actual value while self-sensed value of piezoelectric ceramic with dimension of 5*5 is 1/2 of the actual value. Therefore, from the self-sensed value of piezoelectric ceramic with dimension of 10*10, the displacement and injection volume of the injection needle can be worked out based on such ratio in real applications. The diameter of the cell is between 1~100μm, the diameter of animal cell is about 20μm, the diameter of cell nucleus is about 5μm, and the thickness of cell membrane is about 7nm. Based on the above experimental data, the injection needle can completely pierce the cell membrane. According to the experimental data of an inverse piezoelectric effect, the output displacement of the piezoelectric ceramic stack has a good linear relationship with the applied voltage. Therefore the injection amount can be well controlled through the control of the input voltage. According to the experimental data of the secondary positive piezoelectric effect, by measuring the voltage generated by the secondary positive piezoelectric effect, it can better sense the displacement of the primary inverse piezoelectric effect output, the movement of the device and the injection volume.

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