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The Modeling And Experiments of A PVDF Mirco-Force Sensor*

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***Abstract* - This paper aims at designing a kind of advanced micro-force sensor that can measure force in the range of sub-micro-Newton (μN). To accurately measure the micro interactive force (For example, adhesion, surface tension, friction, and assembly force) acting on micro devices during micromanipulation, the polyvinylidene fluoride (PVDF) is fabricated highly sensitive force sensors. This paper illustrates the modeling method of a PVDF sensor. The transformation between the micro interactive force and the output of the sensor is described. To calibrate the transformation, the model of the PVDF cantilever beam that shows the relationship between the interactive force and the deflection of the sensor probe tip is built first. Then, by given deflection, the interactive force can be calculated with the model. Finally, the transformation can be calibrated. Experiment results verify the effectiveness and accuracy of the transformation model, and the sub-μN sensitivity of the sensor. This micro force sensing technology will solve an important problem that restricts the development of micromanipulation and batch assembly of micro devices.**

***Index Terms* -** *sensor, micro-force, microassembly, PVDF.*

I. INTRODUCTION

Micromanipulation and microassembly provide brand-new methods of manufacture and experiments for physics, chemistry, and automation. However, at the micro scale, structures of micro devices are fragile and easily breakable, and they typically break at the micro Newton (μN) force range that can not be felt by a human operator, and can not be reliably measured by the existing force sensors during assembly [1]. At present, the measurement and feedback control of micro interactive force (For example, adhesion, surface tension, friction, and assembly force) can not be realized directly [2]. Therefore, it is extremely difficult to manipulate components for assembly at micro Newton scale.

For this reason, micro force sensing technology is urgently investigated. Currently, there exist some developing sensing methods. In [3], Carrozza *et al.* realized the force control with strained layer to complete assembly tasks for biomedical micro devices. Analogically, Thompson and Fearing developed a micro-force sensor with strained layer, which they used to position and manipulate micro devices [4]. In [5], Zesch *et al.* controlled the force during pushing a silicon block on a planar substrate by using an AFM probe equipped with a piezoresistive force sensor. Compared to piezoresistive sensors, capacitive sensors have a better long-term stability [6]. For example, Sun *et al.* developed a kind of capacitive sensor that can balance source force [7]. Based on magnetic effect, Boukallel *et al.* presented a micro-force sensor by using passive magnetic suspension mechanism [8]. Besides the above methods, optical techniques can be used to design force sensors, this kind of sensors can even offer high resolution in the range of nano Newton (*n*N). For example, Nelson *et al.* used an optical beam deflection method to measure the tip force status of the probe of an atomic force microscopy (AFM) during the assembly of MEMS devices [9].

Although the above micro-force sensing technologies have been developed for years, they are not able to be used to reliably measure the μN micro-force. The resolution of piezoresistive sensors, capacitive sensors and sensors with strained layers is in the range of sub-*m*N or *m*N. Theoretically speaking, although some magnetic effect-based sensors have high resolution in the range of nano Newton (*n*N) [8], this kind of sensing techniques is quite sensitive to electric magnetic environment. This feature makes the resolution of this kind of sensors decrease to the range of *m*N. Generally, optical techniques-based sensors have low depth of focus, small dynamics range, and bad flexibility. Furthermore, the optical techniques-based sensors are more expensive than other micro force sensing technique.

Compared with the above micro-force sensing technologies, the micro-force sensors based on the piezoelectric effect is able to reliably and accurately measure the micro-force in the range of μN generally. Therefore, piezoelectric material is adopted to fabricate the micro-force sensors in this paper. Among lots of piezoelectric material, lead zirconate-titanate piezoelectric ceramics (PZT) is in common use. With the respect to PZT, polyvinylidene fluoride (PVDF) has high sensitivity, compliance, and wide range of frequency response. The properties of two kinds of piezoelectric material are compared in table 1.

TABLE 1. PROPERTIES OF PVDF AND PZT

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Properties	Units	PVDF	PZT
Density	10^3kg/m^3	1.78	7.5
Relative Permittivity	$\varepsilon/\varepsilon_0$	12	1200
Piezo Stress Constant	(10^{-3}) Vm/N	216	10
Acoustic Impedance	(10^6)kg/m^{2}sec	2.7	30

According to the above properties compare, it can be concluded that PVDF has better performance that PZT. For example, the piezoelectric constant of PVDF is ten times more than that of PZT. This means under the same force, PVDF sensor is able to generate ten times output voltage more than that of PZT.

Micro-force sensors must have high sensitivity, compliance, and wide range of frequency response. PVDF satisfies all these requirements, and has better properties than other piezoelectric material. Therefore PVDF is used to fabricate micro-force sensor in this paper.

This paper aims at pursuing the most feasible and versatile solution in micro force sensing for microassembly and micromanipulation. Based on the piezoelectric effect and the mechanics of material for PVDF cantilever beam, we have developed models of the 1-D PVDF force sensors with high sensitivity.

II. THE MODELING OF PVDF MICRO-FORCE SENSOR

The schematic diagram of the designed 1-D PVDF sensor is shown in figure 1. Its parameters are described as follows:

W : width of PVDF film; L : length of PVDF film; h : thickness of PVDF film; A : surface area of PVDF film ($L \times W$); a : cross sectional area of PVDF film ($W \times h$); L_0 : length of probe tip; d_{31} : piezoelectric constant of PVDF film.

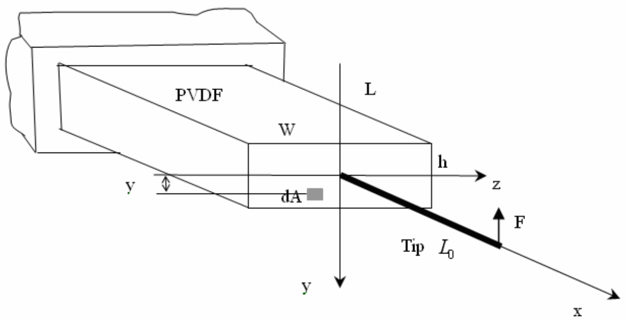

Fig. 1 The schematic diagram of the micro-force sensor.

Based on piezoelectric effect, the charge Q across the PVDF surfaces:

$$Q = \int d_{31}\sigma \mathrm{d}A \tag{1}$$

Where

$$\sigma = \frac{2}{Wh}\int_0^{\frac{h}{2}} \sigma_1 \mathrm{d}a \tag{2}$$

Where $\sigma_1 = \frac{M}{I_z}y$ (stress of one point in the cross sectional area of PVDF film), $I_z = \frac{Wh^3}{12}$ (inertia moment of PVDF film's cross sectional area), $M = F(L - x + L_0)$ (flexural moment of PVDF film's cross sectional area). Therefore equation (2) can be rewritten as:

$$\sigma = \frac{2}{Wh}\int_0^{\frac{h}{2}} \frac{M}{I_z} y \cdot W dy = \frac{1}{4}\frac{Mh}{I_z} = \frac{3M}{Wh^2} \tag{3}$$

Then equation (1) can be rewritten as:

$$Q = \frac{3d_{31}}{Wh^2}\int_0^L F(L - x + L_0)W dx = \frac{3d_{31}L(L+2L_0)}{2h^2}F \tag{4}$$

The equation (4) shows the relationship between the micro interactive force and the charge Q generated across the PVDF surfaces. However, the charge Q is difficult to directly measured and used in feedback control. If the model that describes the transformation between the micro interactive force and the output that can be easily detected is necessary, a signal processing circuit that can transform the charge Q into voltage must be designed and developed. The design of sensor signal processing circuit is as follows:

The diagram of PVDF sensor signal processing circuit is shown in figure 2.

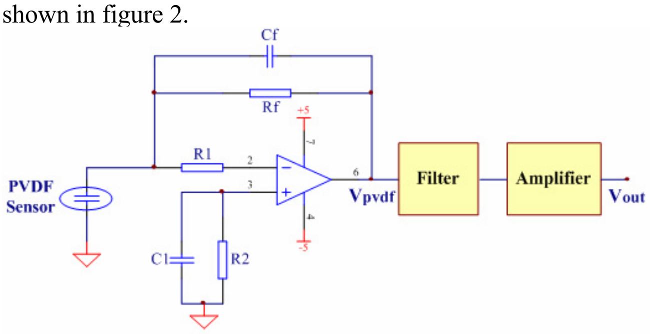

Fig. 2 The diagram of PVDF sensor signal processing circuit.

The feature of sensor's frequency response is decided by the feedback capacitance of charge amplifier C_f. Because the impedance of PVDF is quite high, the signal processing circuit must be designed with high input impedance and low output impedance. Generally, the input impedance should be more than $10^{12}\Omega$. The corresponding cut-off frequency is $f_c = 1/2\pi C_f R_f$. Commonly, the value of cut-off frequency is set in the range between 100 pF and 10 nF . To improve the stability of the processing circuit, the feedback capacitance C_f, is paralleled with high resistance R_f so as to supply direct current feedback.

As is shown in Figure 2, the relationship between the output of charge amplifier V_{pvdf} and the charge Q can be described as

$$V_{pvdf} = \frac{Q}{C_f} \tag{5}$$

After the output of charge amplifier V_{pvdf} is filtered and amplified, the signal output V_{out} can be presented as

$$V_{out} = KV_{pvdf} = \frac{K}{C_f} Q \tag{6}$$

Where K is the voltage amplification coefficient; C_f is the feedback capacitance of charge amplifier; V_{out} is the output voltage of signal processing circuit.

According to equation (4) (5), and (6), we can get the sensing device model that describes the transformation between the micro interactive force and the output of the sensor's signal processing circuit:

$$F = \frac{2h^2 C_f}{3Kd_{31}L(L + 2L_0)} V_{out} \tag{7}$$

The equation (7) shows the transformation between the micro interactive force and the output voltage of the signal processing circuit.

III. CALIBRATION OF THE PVDF SENSOR

Sensor's calibration is quite important for designing a sensor because the use of the device has to subject to the calibration curve. Its process is to confirm the relationship between the input and output with experiments. Here, the calibration results denote the relationship between the micro interactive force F and the output voltage V_{out}. V_{out} is the output of the signal processing circuit, and can be directly measured, while the micro interactive force F can not be directly gotten because the force is quite small (10^{-6}N). Therefore, a kind of indirect calibration method of the sensor is designed in this paper.

This indirect calibration method tries to find the relationship function between interactive force F and a transition variable that can be easily measured. In this paper, this transition variable is D, the deflection of PVDF sensor probe tip. Therefore the relationship function between the deflection of the PVDF sensor probe tip D and the micro interactive force F must be built up before the calibration.

Here, the PVDF film is seen as a cantilever beam. The schematic diagram of PVDF cantilever beam and probe's deflection is shown in figure 3.

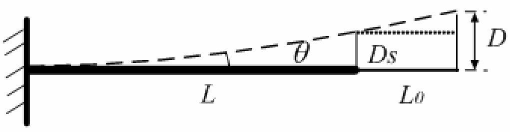

Fig. 3 The schematic diagram of PVDF film and probe tip's deflection.

Where L : length of PVDF cantilever beam; L_0 : length of contact tip; θ: deformation angle of PVDF cantilever beam; Ds : the deflection of PVDF cantilever beam's tip; D : the deflection of sensor's probe tip. (Here, Ds and D is sub- μm. Therefore, $\theta \approx 0^\circ$, and $\theta \approx \sin\theta$).

The bending moment of PVDF cantilever beam is

$$M(x) = F(L - x + L_0) \tag{8}$$

According to differential equation of deflection curve, the relationship between the deflection of PVDF cantilever beam's tip ds and micro interactive force F can be described as

$$\frac{d^2 Ds}{dx^2} = \frac{M(x)}{EI_z} = \frac{F(L + L_0 - x)}{EI_z} \tag{9}$$

Where $I_z = \frac{\mathrm{Wh}^3}{12}$. According to equation (8) and (9), Ds can be rewritten as

$$Ds = \iint \frac{F(L + L_0 - x)}{EI_z} dxdx = \frac{FL^2(2L + 3L_0)}{6EI_z} \tag{10}$$

Then, F can be described as

$$F = \frac{6EI_z}{L^2(2L + 3L_0)} Ds \tag{11}$$

Here, $\theta \approx 0^\circ$, so $Ds \approx D$. Therefore, the relationship between F and D can be presented as follows:

$$F = \frac{6EI_z}{L^2(2L + 3L_0)} D \tag{12}$$

Equation (12) denotes the relationship function between the deflection of PVDF sensor probe tip D and the interactive force F . The deflection of PVDF sensor probe tip can be measured easily. To calibrate the sensor and complete other experiments more accurately, an intelligent 3-D motor platform bought from New Focus Corporation is adopted. Taking advantage of the 3-D motor platform's high precision, accurate deflection of PVDF sensor probe tip D can be gotten. Then, the calibration experiment can be performed. We can set the PVDF sensor's probe tip on the edge of the 3-D motor platform, and use the 3-D motor platform to generate given deflection of sensor's probe tip D . Based on the equation (12), we can get the micro interactive force F . Then, we can use the value of micro interactive force F and the measured values of output voltage V_{out} to confirm the relationship between F and V_{out} so as to complete the calibration of micro-force sensor.

IV. CALIBRATION EXPERIMENTS OF THE PVDF SENSOR

Finally, to verify the effectiveness and accuracy of the sensor model, and the sensitivity of the sensor, the calibration is completed. Based on the relationship function between F and V_{out}, the calibration experiments are shown as follows:

A. Parameters of the PVDF sensor

The parameters of the PVDF sensor are: width of PVDF film $W = 1\times10^{-2}\text{m}$; length of PVDF film $L = 2.5\times10^{-2}\text{m}$; thickness of PVDF film $h = 2\times10^{-4}\text{m}$; Young's modulus of the PVDF film $E = 2.5\times10^{9}\text{Pa}$; length of sensor's probe tip $L_0 = 5\times10^{-3}\text{m}$. The errors of 3-D motor platform are $\pm 2\text{nm}$.

B. The procedures of the experiments

- Divide the measurement range of the PVDF sensor (0-3 μN) into 10 points;

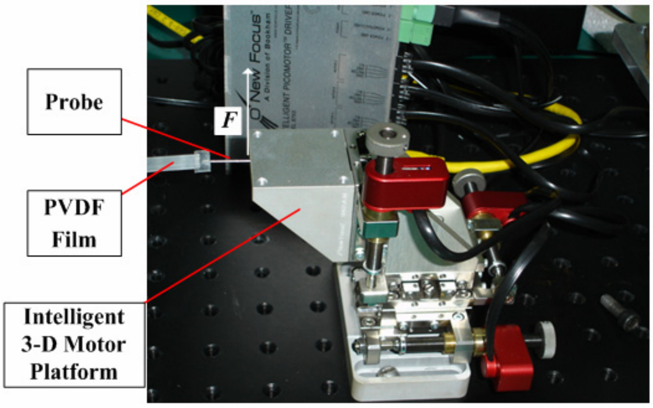

Fig. 4 The schematic diagram of calibration experiments.

- As shown in figure 4, locate the PVDF cantilever beam horizontally, make the probe tip of the PVDF sensor just contact the edge of the 3-D motor platform, raise the motor platform upwards in sequence to deform the PVDF cantilever beam, according to the given deflection shown in the table 2, and record the output voltage values corresponding to the given deflection. The curve is shown in figure 5. In figure 5, blue circles represent a group of average values calculated with the data acquired in the calibration, and the blue line is the fitting curve of the above average values.;

TABLE 2. THE GIVEN DEFLECTION OF THE SENSOR PROBE TIP

Given Deflection (μm)				
0.105	0.175	0.245	0.350	0.455
0.595	0.700	0.805	0.945	1.050

- Repeat the above step five times to get five groups values of the output voltage;
- Calculate the average values of the five groups output voltage, take advantage of equation (12) to get the micro interactive force F;

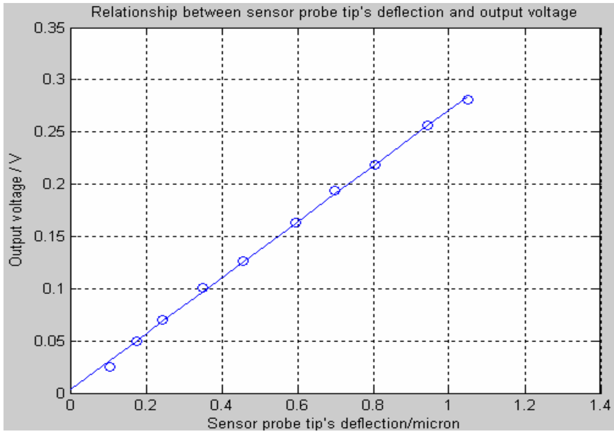

Fig. 5 The curve of relationship between the deflection and the output voltage of signal processing circuit.

- Take the deflection as a transition variable, then the values of F can be gotten;
- According to the values of F and V_{out}, the relationship curve of F and V_{out} is shown in figure 6. In this figure, blue circles represent a group of average force calculated with the equation (12) and the data acquired in the above step, and the blue line, $V_{out} = 0.1089F + 0.0033$, represents the fitting curve of the average force, and the red line, $V_{out} = 0.11198F$, denotes the theoretical function computed with equation (7).

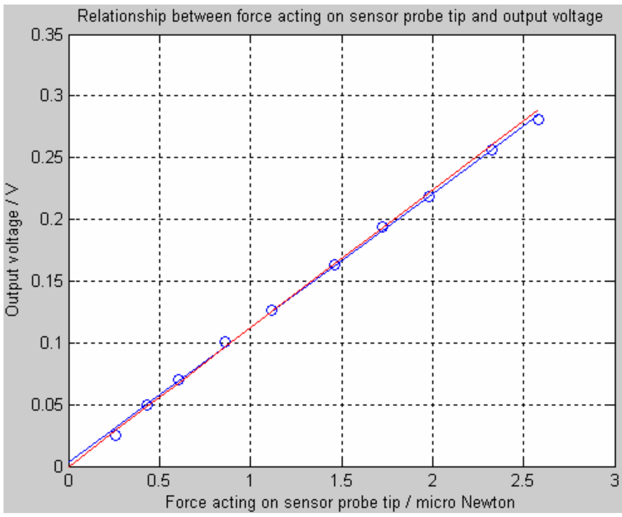

Fig. 6 The curve of relationship between the micro interactive force and output voltage of signal processing circuit.

V. CONCLUSIONS

This paper designed a kind of advanced micro-force sensor and illustrated the modeling method of a PVDF sensor. The transformation between the micro interactive force and the output of the sensor was described. To calibrate the transformation, the model of the PVDF cantilever beam that showed the relationship between the interactive force and the deflection of the sensor probe tip was built first. Then, by given deflection, the interactive force could be calculated with the model. Finally, the transformation was calibrated.

From the results of experiments, we can conclude that the sensor's resolution is sub- μN , and the curve drawn with the real data measured in the calibration experiments are quite compliant to the sensor model built by equation (7). The results verify the accuracy of the sensor's transformation model, and the effectiveness of the calibration method. The results also show the sub-μN sensitivity of the sensing device designed in this paper.

Taking the advantage of the micro-force sensor designed in this paper, micro interactive force (μN or sub-μN) can be reliably measured. This micro-force sensing device will provide a feasible solution of micro-force feedback control during micromanipulation and microassembly, promote the efficiency of the micro devices' manufacture, and decrease the cost of micromanipulation and microassembly.

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