Infinite Dimension Modeling of A Novel Micro Force Sensor and The Application in Micromanipulation

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Abstract: To accurately measure the micro interactive force (For example, adhesion, surface tension, friction, and assembly force) acting on micro devices during micro/nano manipulation, a novel micro force sensor that can reliably measure force in the range of sub-micro-Newton (μN) is designed and developed in this paper. During the application of this micro force sensor in micro/nano manipulation, the accuracy of this sensor's model is quite important to the force control of the system. Therefore, the accurate infinite dimension model of the micro force sensor is modeling. Based on the infinite dimension model, the micro force control algorithm is designed. To verify the infinite dimension model and the control algorithm, a micromanipulation experiment is designed and realized. Experiment results verify the accuracy of the infinite dimension model of the sensor, and show the efficiency of the force control algorithm. The developed micro force sensor and the infinite dimension modeling provide a feasible and versatile solution in micro force sensing and feedback force control for micro/nano manipulation, and will promote the technology of automating the micro/nano manipulation.

Keywords: Micromanipulation, Micro force, Sensor, Infinite dimension

1. INTRODUCTION

In micro/nano manipulation, researches have faced an obstacle that restricts the development of micro/nano manipulation. The obstacle is that at the micro/nano scale, structures of micro devices are fragile and easily breakable at the micro Newton (μN) force range that cannot be felt by an operator, and is not reliably measurable by the existing force sensors during micro/nano manipulation.[1] At present, the measurement and feedback control of micro interactive force can not be realized directly.[2] Therefore, it is extremely difficult to accurately control the process of micro/nano manipulation.

Currently, there exist some developing sensing methods. For example, with strained layer, Thompson and Fearing developed a micro-force sensor, which they used to positioning and manipulate micro devices.[3] By using an AFM probe equipped with a piezoresistive force sensor, Zesch et al. explored the force control during pushing a silicon block on a planar substrate.[4] Compared to piezoresistive signal transformers, capacitive sensors can sense real-time, and have a better long-term stability.[5] For example, Sun et al. designed a kind of capacitive sensor that can balance source force.[6] Based on magnetic effect, Boukallel et al. presented a micro-force sensor by using passive magnetic suspension mechanism.[7, 8] Besides the above methods mentioned, optical techniques can even offer high resolution in the range of nano Newton (nN). For example, Nelson et al. adopted 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] Most commercially available AFM systems use this technique to detect micro force.

However, the resolution of piezoresistive sensors, capacitive sensors and sensors with strained layers is in the range of sub- mN or mN. Theoretically, although some magnetic effect-based sensors have high resolution in the range of nano Newton (nN),[7, 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 mN. 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. Here, more suitably, the resolution of the force sensor based on the piezoelectric effect is in the range of μN generally. Based on PVDF, Yiyang et al. designed a novel micro force sensor that can reliably measure the micro contact force in the range of sub-μN.[10] However, in the micro/nano scale, a sub-μN force is corresponding to deflection in the range of micron. Therefore, a little deflection will cause a force in the range of μN. In this scale, traditional modeling method of the micro force sensor is not able to be satisfied. Infinite dimension modeling method is needed to satisfy the resolution of feedback control.

Therefore, the objective of this paper is to model the novel micro force sensor based on infinite dimension system method, to design a suitable feedback control algorithm, and to verify the accuracy of the model and the efficiency of the control algorithm according to an application experiment in micromanipulation.

2. INFINITE DIMENSION MODELING OF THE MICRO FORCE SENSOR

The structure of the micro force sensor/micro manipulator is shown in Figure 1, and the sketch diagram of micro mirror's microassembly with micro force sensor is shown in Figure 2.

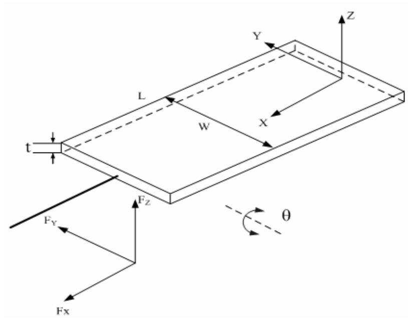

Fig. 1. Structure of PVDF Micro Force Sensor

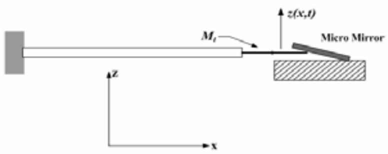

Fig. 2. Micro Assembly of Micro Mirrors With Micro Force Sensor

Based on Hamilton Principle, the micro force sensor can be described as

$$\delta\int_{t_0}^{t_1}(T(t)-V(t)+W_f(t))\,dt=0 \qquad (1)$$

Where $T(t)$ delegates the kinetic energy of the micro force sensor/micro manipulator; $V(t)$ delegates the potential energy of the micro force sensor/micro manipulator; $W_f(t)$ delegates the work of the micro contact force acting on the probe tip.

The kinetic energy of the micro force sensor/micro manipulator consists of two parts, kinetic energy of the cantilever beam and kinetic energy of the probe. The kinetic energy of the micro force sensor/micro manipulator can be written as

$$T(t)=\frac{1}{2}\int_0^L \rho A\left(\frac{\partial z(x,t)}{\partial t}\right)^2 dx+\frac{1}{2}M_t\left(\frac{\partial\, z(L,t)}{\partial t}\right)^2 \qquad (2)$$

Where ρ delegates the density of the material(PVDF) of the micro force sensor; $A=Wt$ delegates the cross sectional area of the cantilever beam; M_t delegates the mass of the probe; L delegates the length of the cantilever beam; $z(x,t)$ delegates the deflection of a point on the cantilever beam whose coordinate along the length of cantilever beam is x.

The potential energy of the micro force sensor/micro manipulator also consists of two parts, contact potential energy of the probe tip and bending potential energy of the cantilever beam. Therefore, the potential energy can be written as

$$V(t)=\frac{1}{2}\int_0^L EI\left(\frac{\partial^2 z(x,t)}{\partial x^2}\right)^2 dx+\frac{1}{2}k^* z^2(L,t) \qquad (3)$$

Where E delegates Young's modulus of the PVDF film; I delegates inertia moment of PVDF film's cross sectional area; k^* delegates the elastic coefficient of the sample operated by the probe.

In this paper, the sample operated by the probe is rigid, so the elastic coefficient of the sample $k^*=0$. Based on equation (2), (3), and the boundary conditions, according to the property of variation and integral, the micro force sensor/micro manipulator can be described as

$$\rho A\frac{\partial z^2(x,t)}{\partial t^2}+EI\frac{\partial^4 z(x,t)}{\partial x^4}=f_c(t)\delta\left(x-L\right) \qquad (4)$$

Based on separation method of variables, assume $z(x,t)=\phi(x)q(t)$, the corresponding homogeneous equation of equation (4) can be written as

$$\rho A\phi(x)\ddot{q}(t)+EI\phi''''(x)q(t)=0 \qquad (5)$$

After solving the above equation, according Laplace transform, equation (4) is changed into:

$$q_i\left(s\right)=\frac{f_c(t)\varphi_i(L)}{\rho A\left(s^2+\omega_i^2\right)} \qquad (6)$$

Where $\omega_i=\beta_i^2\sqrt{EI/\rho A}$; β is the eigen solution of equation (5).

Based on piezoelectric effect, the charge $Q(t)$ generated by micro contact force $f_c(t)$ across the PVDF surfaces is

$$Q\left(t\right)=\int_0^L d_{31}\sigma_s\left(x,t\right)Wdx=-cE_pd_{31}W\frac{\partial z\left(x,t\right)}{\partial x}\Big|_0^L \qquad (7)$$

Where $\sigma_s\left(x,t\right)=-cE_p\frac{\partial^2 z\left(x,t\right)}{\partial x^2}$ delegates the stress of one point in the cross sectional area of PVDF film; c delegates the distance between the neutral axis and one point in the PVDF film; E_p represents the Young's modulus of the PVDF film; d_{31} is the piezoelectric constant of PVDF film; W is the width of the PVDF film. The output voltage of PVDF film can be written as $V_{pvdf}\left(t\right)=-Q(t)/C_p$. Where C_p is the equivalent capacitance of the PVDF film. The relationship between output voltage of micro force sensor V_{out} and the output voltage of PVDF film V_{pvdf} is $V_{out}=KV_{pvdf}$. Based on Laplace transform, equation (6) and (7) can be rewritten as

$$\frac{V_{out}\left(s\right)}{f_c(s)}=-cE_pd_{31}WK\sum_{i=1}^{\infty}\left\{\frac{\varphi_i(L)}{\rho A\left(s^2+\omega_i^2\right)}\right\} \qquad (8)$$

Equation (8) is the transfer function of the micro force sensor/micro manipulator. Therefore, the model of infinite dimension system has been built up.

Based on the above model of infinite dimension system, a switching controller is designed, and the control law is shown as below:

$$\begin{cases} If\;\; U=\left\{\left\{\dot{y}_c(t_{sw})>0\cap F_c=F_{sw}\right\}\cup F_c<F_{sw}\right\} \text{ Position Control} \\ If\;\; U=\left\{\left\{\dot{y}_c(t_{sw})\le 0\cap F_c=F_{sw}\right\}\cup F_c>F_{sw}\right\} \text{ Force Control} \end{cases} \qquad (9)$$

Where F_{sw} is the threshold of micro contact force; y_c is the position of probe tip; F_c is the micro contact force acting on the probe tip; t_{sw} is the time when the probe tip contacts the operated sample. According to the above control law, during the period $t < t_{sw}$, the system acts as position control, while during the period $t \geq t_{sw}$, the system acts as force control.

3. APPLICATION EXPERIMENTS IN MICROMANIPULATION

Based on the above infinite dimension system model and the switching controller, application experiments of micro force sensor are designed and realized as below. The experiment system consists of 3-D motor platform of New Focus Corporation in America (precision is 20nm), microscope and a computer.

3.1 Experiment of Force Control

This experiment is designed to test the accuracy of the infinite dimension system model and the efficiency of the switching controller. The program is shown as below. First, fix the micro force sensor/micro manipulator on the 3-D motor platform, and make the sensor downward 15 degrees relative to horizon; second, make the sensor move downward along Z axis towards the surface of the horizontal base; third, when the probe tip contacts the surface of the base, continue make the sensor move downward until the contact force reaches 1.5 μN; fourth, when the time of above process arrives at 0.6 seconds, make the sensor move along Y axis (shown in Figure 1) and keep the contact force 1.5 μN.

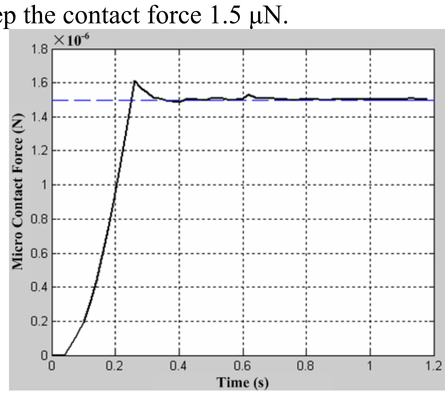

Fig. 3. Contact Force in Micro Force Control Experiment

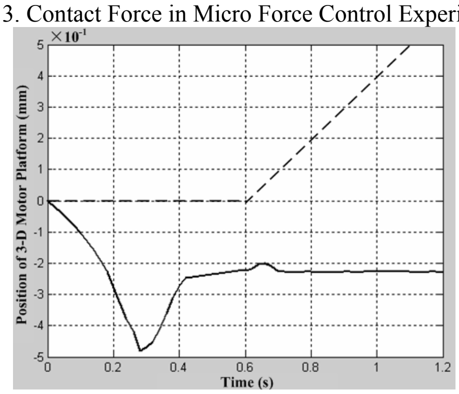

Fig. 4. Position of The 3-D Platform in Micro Force Control Experiment

The experiment results are shown in Figure 3 and Figure 4. According to Figure 3, the contact force quickly converged at 1.5 μN. After 0.6 seconds, because the sensor moved along Y axis, the contact force was disturbed, but the micro force quickly converged at 1.5 μN again.

3.2 Micro Assembly of Micro Film

To simulate the assembly process of micro mirrors, a micro assembly experiment of micro films is designed. The film is made from PVDF, and the size of the film is 800μm×800μm×50μm. The density of the film is $1.78 g/cm^3$, and the gravity is approximately 0.57μN. The process of the experiment is, first, fix one side of the micro film on the surface of the horizontal base so that the film is able to rotate around this side and make the film horizontally lie on the base; second, horizontally insert the probe tip under the film; third, move the probe along Z axis and X axis to lift the film to vertical position and keep the contact force along Z axis 0.7 μN; stop the probe until the film is vertical.

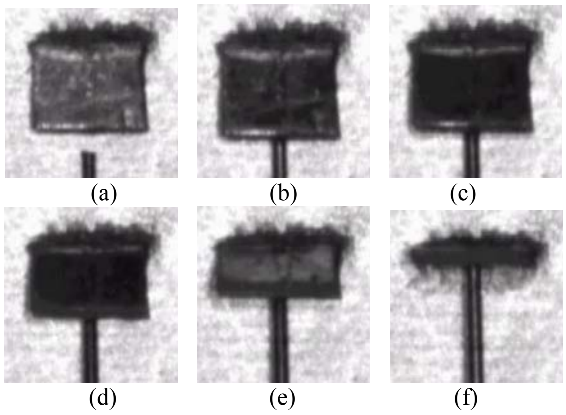

Fig. 5. Assembly of Micro Mirrors With Micro Force Sensor

The experiment process is shown in Figure 5, and the contact force along Z axis is shown in Figure 6. According to Figure 5, the contact force converged at 0.7 μN in short time before the film arrived at 45 degrees relative to horizon.

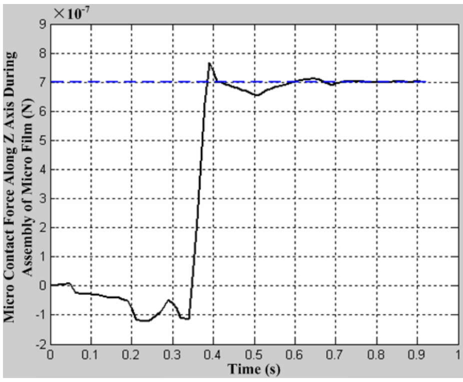

Fig. 6. Contact Force along Z Axis in Assembly of Micro Film

The results of above two experiments show that the infinite dimension system model is accurate and the switching controller is efficient.

4. CONCLUSIONS

In micro/nano scale, traditional modeling method is not able to satisfy the precision of sensor and controller. In this paper, the infinite dimension system model of micro force sensor/micro manipulator is built up, and a switching controller is designed based on the infinite dimension model. According to the results of experiments, it can be concluded that the sensor's resolution is sub- μN, the accuracy of the infinite dimension system model is good, and the switching controller is efficient.

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

Acknowledgements: This research work is supported by the National Natural Science Foundation of China (No. 60575050) and National High Technology Research and Development Program of China (No. 2009AA03Z316).

References:

1. S. Fatikow, J. Seyfried, ST. Fahlbusch, A. Buerkle and F. Schmoeckel, *Journal of Intelligent and Robotic Systems*. 27, 135 (2000).
2. K. F. Bhringer, Ronald S. Fearing, Ken Y. Goldberg, *The Handbook of Industrial Robotics (2nd edition)*. 1045 (1999).
3. J. Thompson and R. Fearing, *IROS 2001*. 295 (2001).
4. W. Zesch and R. Fearing, *SPIE Conference on Microrobotics and Micromanipulation.* 361 (1998).
5. R. Peters, *Reivew of Science Instrument*. 64, 2256 (1993).
6. Y. Sun, D. P. Potasek, D. Piyabongkarn, R. Rajamani, and B. J. Nelson, *ICRA 03*. 294 (2003).
7. M. Boukallel, E. Piat and J. Abadie, *IROS03*. 1062 (2003).
8. M. Boukallel, E. Piat and J. Abadie, *IROS03*. 529 (2003).
9. B. Nelson, Y. Zhou and B. Vikramaditya, *IEEE Control System Magazine*. 18, 35 (1998).
10. Liu Yiyang, Yu Peng, Wang Yuechao, Dong Zaili, and Xi Ning, *IEEE International Conference on Robiotics and Biomimetics*. 77 (2007).