Development of MEMS-based micro capacitive tactile probe*

Lei Li-Hua(雷李华)[a)b)], Li Yuan(李 源)[b)], Fan Guo-Fang(范国芳)[c)†], Wu Jun-Jie(吴俊杰)[b)], Jian Li(简 黎)[b)], Cai Xiao-Yu(蔡潇雨)[b)], and Li Tong-Bao(李同保)[a)]

[a)] *School of Physics Science and Engineering, Tongji University, Shanghai* 200092, *China*
[b)] *Shanghai Institute of Measurement and Testing Technology, National Center of Measurement and Testing for East China, National Center of Testing Technology, Shanghai* 201203, *China*
[c)] *Key Laboratory of Photochemical Conversion and Optoelectronic Materials, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing* 100190, *China*

(Received 25 April 2014; revised manuscript received 16 June 2014; published online 24 September 2014)

In this paper, a micro capacitive sensor with nanometer resolution is presented for ultra-precision measurement of micro components, which is fabricated by the MEMS (micro electromechanical systems) non-silicon technique. Based on the sensor, a micro capacitive tactile probe is constructed by stylus assembly and packaging design for dimension metrology on micro/nano scale, in which a data acquiring system is developed with AD7747. Some measurements of the micro capacitive tactile probe are performed on a nano positioning and measuring machine (NMM). The measurement results show good linearity and hysteresis with a range of 11.6 μm and resolution of better than 5 nm. Hence, the micro capacitive tactile probe can be integrated on NMM to realize measurement of micro structures with nanometer accuracy.

Keywords: micro tactile probe, micro capacitive sensor, MEMS, nano measuring machine

PACS: 87.85.Qr, 87.85.Rs, 85.85.+j, 87.85.Va **DOI:** 10.1088/1674-1056/23/11/118703

1. Introduction

With the development of nano technology,[1] the ultra-precision measurement and characterization of large-dimension micro-components with a high aspect ratio has become increasingly important.[2] For almost all industrial inspection purposes, optical methods (such as focus variation, confocal, and coherence scanning interferometry) are the preferred solution due to non-tactile operation, ease of use, speed of measurement, and easy integration into production lines. However, these optical systems are difficult to verify and calibrate due to sample surface properties and many adverse optical effects.[3,4]

Actually, coordinate measuring technology of integrated tactile probe has become an actual industry standard in the field of measurement technology.[5] However, existing tactile probing systems are not suitable for measurements of micro components due to their lack of sensitivity, damaging interactions, and difficulty of use.[6] A tactile probe system also lacks adequate standards for verification[7] (existing CMM standards, such as ISO 10360, are not applicable).

In this work, a micro capacitive sensor with nanometer resolution is fabricated using a MEMS non-silicon technique. A micro capacitive tactile probe is developed from the sensor for ultra-precision measurement of axial dimension and scanning measurement of surface topography. The performances of the probe are tested and calibrated on NMM.

2. Design of a tactile probe based on a MEMS-fabricated capacitive sensor

2.1. Probe detection modeling and structural analysis

A tactile probe based on a MEMS-fabricated capacitive sensor is composed of a glass substrate, a micro capacitive sensor, and a stylus. The bottom plate of micro capacitance and pillars are fixed by a glass substrate. A micro capacitive sensor is used for sensing the displacement, and then converts the displacements into measurable electrical signals, in which displacement is probed and transferred by a stylus. The sensitive element of the probe is set up based on parallel plate capacitive principle,[8] and the capacitance of the parallel plate capacitor, ignoring the capacitor edge effect, is

$$C = \frac{\varepsilon_{\mathrm{r}}\varepsilon_0 S}{d}, \tag{1}$$

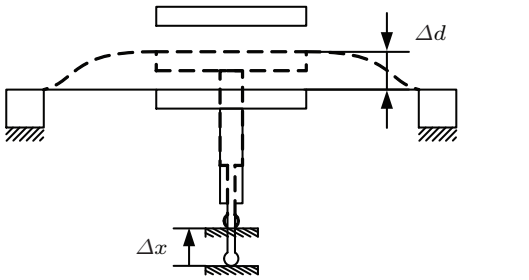
where C is the capacitance, ε_{r} is the vacuum permittivity, ε_0 is the relative permittivity, S is the relative area of plate, and d is the pole pitch.

Equation (1) shows that the changes of ε_{r}, S, or d will cause different C. Hence, capacitive sensors can generally be divided into three types: variable pole pitch type, variable area type, and variable dielectric constant type. In this paper, a variable pole pitch type is adopted. The detection model of probe is shown in Fig. 1(a).

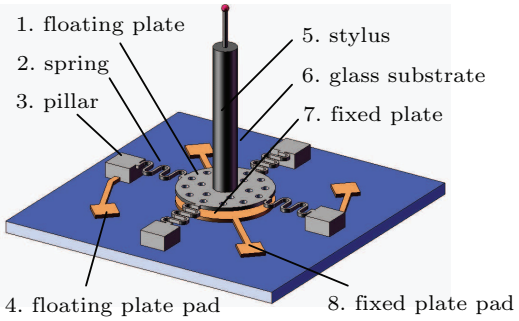
*Project supported by the Nano Special Projects of Shanghai Science and Technology Commission of China (Grant No. 11nm0560800) and the Young Scientists Fund of the National Natural Science Foundation of China (Grant No. 11104284).

†Corresponding author. E-mail: fanguofang@mail.ipc.ac.cn

© 2014 Chinese Physical Society and IOP Publishing Ltd



(a)



(b)

Fig. 1. (color online) (a) Detection model and (b) probe structure.

When a floating plate of capacitance moves Δd, the capacitance variation ΔC is given by

$$\begin{aligned}\Delta C &= \frac{\varepsilon S}{d_0 - \Delta d} - \frac{\varepsilon S}{d_0} \\ &= \frac{\varepsilon S}{d_0}\left(\frac{\Delta d}{d_0 - \Delta d}\right) \\ &= C_0 \frac{\Delta d}{d_0}\left(1 - \frac{\Delta d}{d_0}\right)^{-1}, \end{aligned} \tag{2}$$

where ε is the permittivity, Δd is the variation of pole pitch, d_0 is the initial pole pitch, and C_0 is the initial capacitance.

When $\Delta d << d_0$, Taylor series expansion of Eq. (2) is

$$\Delta C = C_0 \frac{\Delta d}{d_0}\left[1 + \frac{\Delta d}{d_0} + \left(\frac{\Delta d}{d_0}\right)^2 + \cdots\right]. \tag{3}$$

By ignoring higher order terms, we obtain

$$\Delta C \approx C_0 \frac{\Delta d}{d_0}. \tag{4}$$

Equation (4) shows that capacitive variation ΔC has a linear relationship with pole pitch variation Δd when the moving distance of capacitor floating plates is much smaller than the initial plate pole pitch.

As shown in Fig. 1, the stylus tip probe sphere is in contact with the measured object surface. We assume that a capacitive floating plate moves Δd when the displacement changes Δx. In our design, the distortion of the measured surface and stylus can be neglected due to the small contact force, and thus Δd can be considered equal to Δx. Hence, the static sensitivity of micro capacitive sensor k is

$$k = \frac{C_0}{d_0}\frac{\Delta d}{\Delta x} \approx \frac{C_0}{d_0}. \tag{5}$$

From Eq. (5), the static sensitivity of micro capacitive sensor k is proportional to the initial capacitance and inversely proportional to the initial pole pitch. Hence, the sensor sensitivity is effectively enhanced by reducing the initial pole pitch of the capacitor plate, but this contradicts with the measurement range of sensor. Moreover, the enhancement of sensitivity by increasing the plate area or using high dielectric constant requires better preparation technology.

Considering the above discussion and current technological conditions, in our design the plate diameter is 3.6 mm, the floating plate thickness and fixed plate thickness are 30 μm and 5 μm, respectively, and the plate distance is 10 μm. Hence, the initial capacitance value C_0 is 9 pF (based on Eq. (1)). Because the data acquiring system is developed with AD7747,[9] which detects the minimum capacitance ΔC as 20 aF and the plate distance d_0 as 10 μm, we can obtain the minimum displacement of the system; that is, 0.022 nm (based on Eq. (5)).[10]

2.2. Fabrication process of a micro capacitive sensor

In our design a low cost glass substrate is chosen as the processing substrate of the micro capacitance sensor. A high intensity, low internal stress plate material of micro capacitive sensor with certain flexibility and cohesion at the same time is required. Nickel and gold are selected as the structural material and the plate surface signal layer material, respectively. On account of the suspended structure of the sensor, positive photoresist material is selected as a sacrificial layer by using sacrificial layer technology. The sacrificial layer is fabricated by photoresist whirl coating, the technology is simple, and the thickness can be easily and precisely controlled. Meanwhile, it is soluble in acetone and alkaline solution, and is easy to remove without internal stress.

The fabrication process steps are shown in Fig. 2: (i) clear and dry the substrate (Fig. 2(a)); (ii) 90-nm copper was sputtered as the seed layer based on glass substrate, then 5-μm positive photoresist whirl coating was carried out (Fig. 2(b)); (iii) rubber drying, exposure, development, and then the image of fixed plate and pillar were formed (Fig. 2(c)); (iv) 4.5-μm-thick nickel and 0.5-μm-thick gold were electroplated to form fixed plate and pillar (Fig. 2(d)); (v) 10-μm-thick positive photoresist whirl coating was carried out (Fig. 2(e)); (vi) rubber drying, exposure, development, and then the pillar image was formed (Fig. 2(f)); (vii) electroplating 10-μm-thick nickel to form pillar (Fig. 2(g)); (viii) 90-nm copper was sputtered as the second seed layer, then 5-μm positive photoresist

whirl coating was carried out (Fig. 2(h)); (ix) rubber drying, exposure, development, and then the shape of floating plate and S-shaped spring were formed (Fig. 2(i)); (x) electroplating 30-μm-thick nickel to form floating plate and S-shaped spring (Fig. 2(j)); and, (xi) remove photoresist and release capacitance structure (Fig. 2(k)).[11,12] The fabricated micro capacitive sensor is shown in Fig. 3. The scale length is 500 μm.

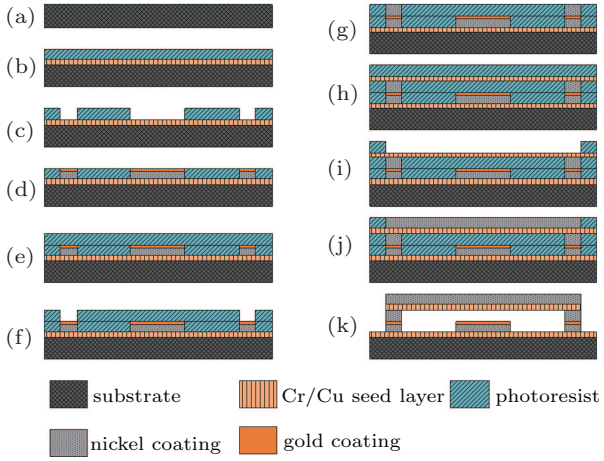


Fig. 2. (color online) Process flow diagram of sensor fabrication.

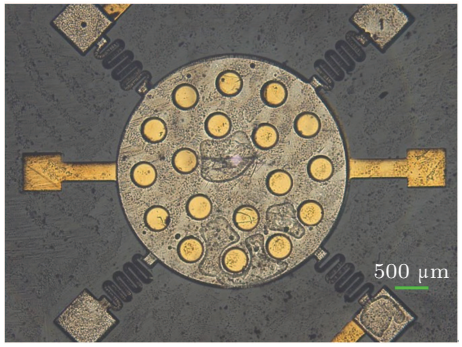


Fig. 3. (color online) Micrograph of micro capacitance sensor.

2.3. Packaging design of micro tactile probe

After preparation of the probe sensitive structure, probe packaging should be reasonably designed to realize electric connection with the signal conditioning circuit, which should be safe and reliable. In the design the stylus assembly is the main technical difficulty, whose accuracy directly affects the probe performance. Precise assembly of stylus and sensitive structure are achieved on the basis of self-alignment and self-locating technology on the micro scale.[13] A Renishaw A-5555-0108- type stylus is used as a micro capacitive tactile probe. A stylus length of 15.3 mm, diameter of 1 mm, and material of tungsten carbide are obtained. The diameter of probe sphere processed by ruby is 300 μm. The actual stylus is shown in Fig. 4.

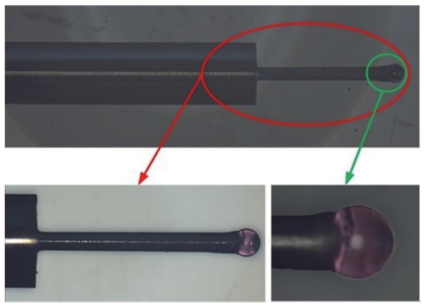


Fig. 4. (color online) A5555-0108 type stylus.

The probe is attached to floating plate of micro capacitance sensor by using epoxy. Compared with ordinary glue, epoxy possesses greater stiffness and adhesive strength so as to satisfy needs of stylus assembly. The sensitive unit is also attached to the specific PCB board by using epoxy to realize the electrical connection between the sensor and data acquisition system. The packaged micro capacitive tactile probe is shown in Fig. 5.

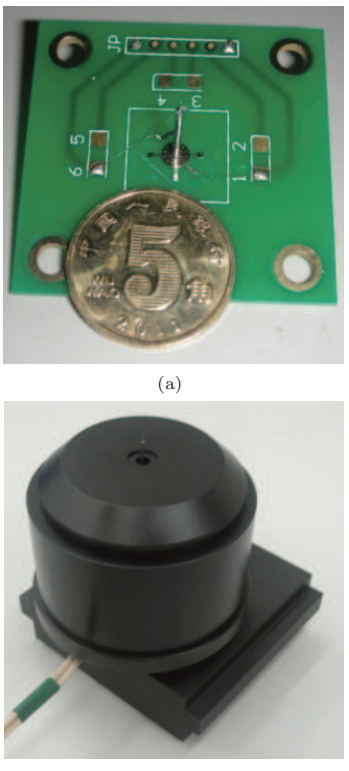


Fig. 5. (color online) Packaging photo. (a) Internal packaging; (b) fixed framework.

3. Characterizations of MEMS-based capacitive tactile probe

Here, the probe will be integrated into NMM through probe fixed unit and connector for the characterizations of the MEMS based capacitive tactile probe. As the core component of scanning measurement, calibrations of analog probe must be carried out. Real-time measurement of the positioning process is achieved by three laser interferometers of X, Y,

Z direction measuring axis of NMM, three-dimensional positioning with a resolution of 0.1 nm is realized in the range of 25 mm×25 mm×5 mm. During the installation of a micro tactile probe, the influence of temperature change on test is diminished by NMM using Zerodur as a supporting frame for the probe. The output signal of probe is collected by weak capacitive signal acquisition system based on AD7747 chip and C8051F410 microcontroller, and sent to upper-computer via serial port. LABVIEW is used to collect the capacitance data for further processing.

3.1. Measurement of the range and linearity

Movement controls for speed and step are provided by NMM using an electromagnetic driving system. In the experiment, the objective table moves in high-speed mode at first, the space between stylus and objective table is observed by CCD. When the space is close to touch, it switches to low-speed mode, it will then scan at 100 nm step and the output curve of the probe will be observed. When the probe is triggered, it will return back to the beginning point, and switches to a smaller step so as to find a more precise trigger point. The measurement range and linearity test of probe are carried out at 100 nm steps. The experimental results are shown in Fig. 6.

From Fig. 6, it can be observed that the measurement range is of 11.6 μm, which is slightly larger than the designed 10 μm, this may be caused by the increasing plate space due to the residual stress in the course of the capacitor structure releasing or the gravity of the stylus. The output capacitance is −8 pF when probing at 11.8 μm, which means that the upper plate is in touch with bottom plate and the probe has reached the measurement limitation. Line fitting is achieved using the data between trigger point and saturation point, a fitting degree R^2 of 0.98957 and residual square sum of 0.04106 are obtained.

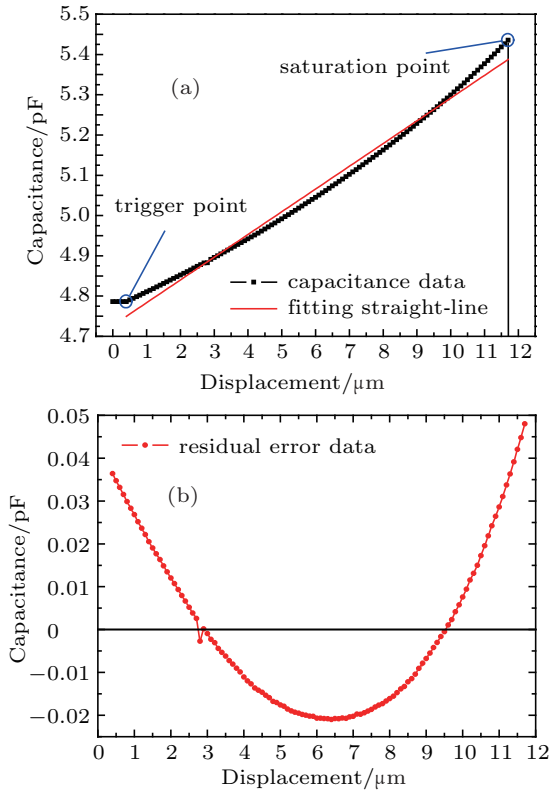


Fig. 6. (color online) Range and linearity tests. (a) Measurement range and linearity; (b) distribution of residual error.

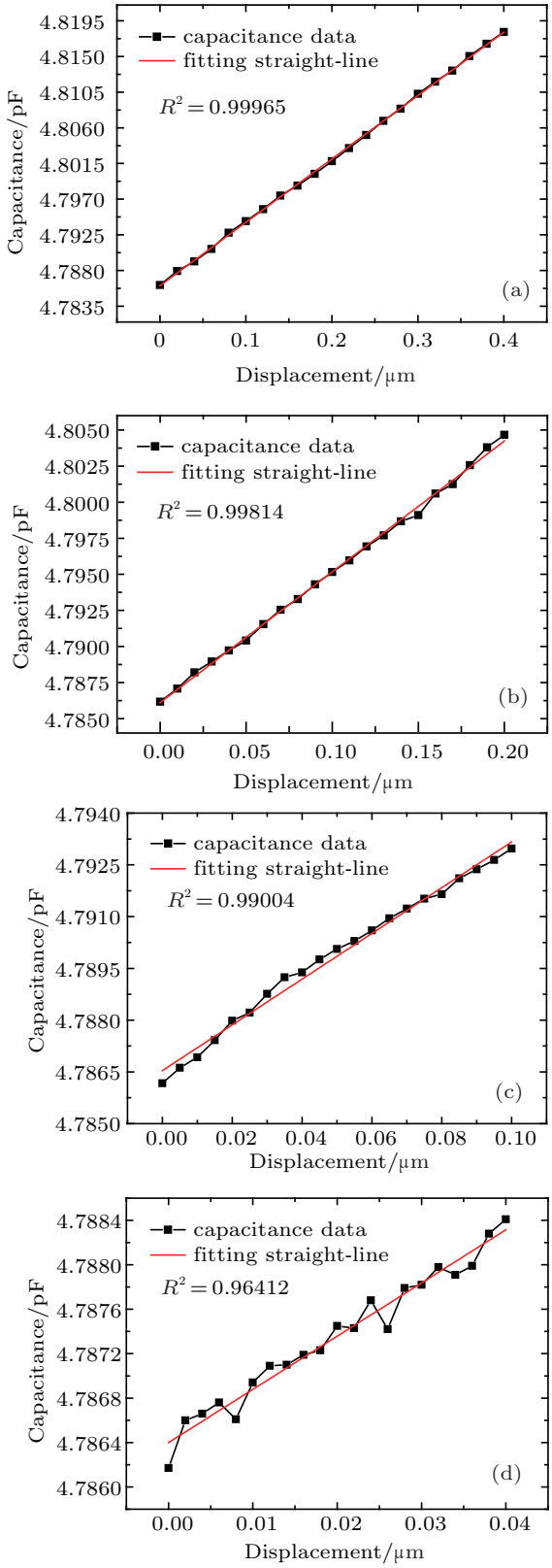


Fig. 7. (color online) Resolution measurement: (a) 20 nm step pitch; (b) 10 nm step pitch; (c) 5 nm step pitch; and, (d) 2 nm step pitch.

3.2. Measurement of resolution

Starting with the trigger point, experiments are performed at 20 nm, 10 nm, 5 nm, and 2 nm step, respectively, 20 points are collected for each step, then we fit a straight line and analyze the resolution according to linear degree of fitting line and degree of cross-tabs. The experimental results are shown in Fig. 7.

The analysis of Fig. 7 shows that degree of fitting is better than 0.99 when scanning at 20 nm, 10 nm, and 5 nm step without exception. When the step decreases to 2 nm, the degree of fitting reduces to 0.96 and the reduction of linearity is obvious. It can also be seen from Fig. 7(d) that the data points at 2 nm step is confused while the trend of data points at other steps are consistent, which means the resolution limitation of the probe has been reached. The above analysis demonstrates that resolution of the probe is better than 5 nm, which is more than the theoretical resolution of 0.022 nm because there exists some errors in the assembly and measurement.[14,15]

3.3. Measurement of the hysteresis

The hysteresis is an important parameter to evaluate the sensor, which will influence the accuracy of the probe. The tests of the hysteresis are performed by 1 μm step, which begins at the trigger point and ends at the displacement of 11 μm. The capacitance values of trace and retrace for different displacements are shown in Fig. 8. From this figure, one can obtain that the maximum probe hysteresis is 0.00561 pF.

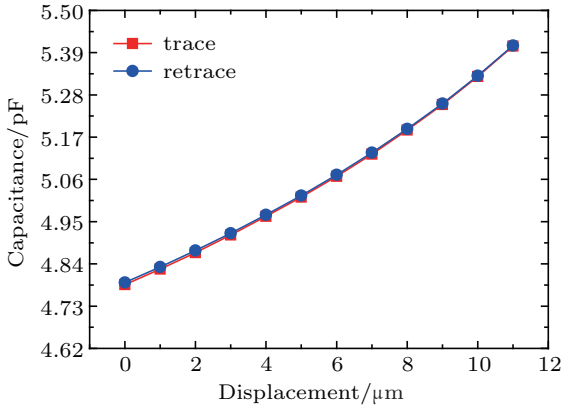


Fig. 8. (color online) Hysteresis test.

4. Conclusion

A micro capacitive sensor with nano resolution is fabricated using the MEMS non-silicon technique. Based on self-alignment and self-positioning technology on a micro scale, a 15.3 mm tungsten carbide-ruby stylus is attached to the floating plate of the capacitive sensors. Using the capacitive frequency measurement method, the output signal acquisition system is designed based on AD7747. The measurement range, linearity, resolution and hysteresis of probe are tested using NMM as a precision positioning platform. A measurement range of 11.6 μm, good linearity and hysteresis characteristics are obtained. The resolution is better than 5 nm.

The developed capacitive micro tactile probe can be used for ultra-precision measurement of a micro structure device in axial direction, surface topography of precision device and scanning measurement of roughness. The measuring force, repeatability, and drift of probe will be tested in subsequent experiments. Meanwhile, the integration technology of probe and NMM will be researched. By means of the development of corresponding interface driver and measuring software, the probe can be integrated to the NMM to expand its measurement capability.

References

[1] Lin X, He X B, Lu J L, Gao L, Huan Q, Shi D X and Gao H J 2005 *Chin. Phys.* **14** 1536

[2] Lei L H, Li Y, Fan G F and Li T B T 2013 *Sens. Actuators A* **203** 430

[3] Xu C K, Zhang P K, Li M and Chen X J 2014 *Chin. Phys. B* **23** 073402

[4] Meli F, Fracheboud M, Bottinelli S, Bieri M, Thalmann R, Breguet J M and Clavel R 2003 *Proc. EUSPEN* (Aachen, Germany)

[5] Manske E, Jäger G, Hausotte T and Füßl R 2012 *Meas. Sci. Technol.* **23** 074001

[6] Tiwana M, Redmond S J and Lovell N H 2012 *Sens. Actuators A* **179** 17

[7] Bütefisch S, Büttgenbach S, Kleine-Besten T and Brand U 2001 *Microsystem Technologies* **7** 171

[8] Peggs G N, Lewis A J and Oldfield S 1999 *CIRP Ann-Manuf. Techn.* **48** 417

[9] Ma J G, Zhang T H and Zhu L H 2008 *Transducer and Microsystem Technologies* **27** 65 (in Chinese)

[10] He M X, Liu R, Li Y, Wang H, Lu X, Ding G F, Wu J J, Zhang T and Zhao X L 2013 *Sens. Actuators. A* **194** 128

[11] Sui X H, Zhang R X, Pei W H and Chen H D 2007 *Chin. Phys.* **16** 2116

[12] Qin Z H 2013 *Chin. Phys. B* **22** 098108

[13] Wang X D, Dong P and Yi G Y 2006 *Acta Phys. Sin.* **55** 2092 (in Chinese)

[14] Zheng Y T 2010 *Design of Micro-displacement Detecting System Based on Parallel-Plate Capacitor* (MS Thesis) (Dalian: Dalian University of Technology) (in Chinese)

[15] Zhu Y Q 2008 *The Study of Capacitance Method for Precision Displacement and Vibration Measurement* (MS Thesis) (Beijing: Beijing Jiaotong University) (in Chinese)