Design of an Analogue Contact Probe for Nano-Coordinate Measurement Machines (CMM)

Rui-Jun Li*[a, c], Kuang-Chao Fan[a, b], Sheng Tao[a], Jian-Zhao Qian[a], Qiang-Xian Huang[a], Fang Cheng[d]
[a]School of Instrument Science and Opto-electric Engineering, Hefei University of Technology, Hefei , China, 230009; [b]Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan, 106; [c]Anhui Electrical Engineering Professional Technique College, Hefei, China, 230051; [d]School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, 639798

ABSTRACT

A new high precision analogue contact probe with long measurement range that is able to measure miniature components on a micro/nano-coordinate measuring machine (CMM) is proposed. This analogue probe is composed of a fiber stylus with a ball tip, a mechanism with a wire-suspended floating plate, a two-dimensional angle sensor and a miniature Michelson linear interferometer. The stylus is attached to the floating plate. The wires experience elastic deformation when a contact force is applied and then the mirrors mounted on the plate will be displaced, which displacements can be detected by two corresponding sensors. Each component of the probe is designed, fabricated and assembled in this research. Base on the design requirements and stiffness analysis of the probe, several constrained conditions are established, and optimal structure parameters of the probe are worked out. Simulation and experimental results show that the probe can achieve uniform stiffness, ±20μm measurement range and 1nm resolution in X, Y and Z directions. The contact force is less than 50μN when the ball tip is displaced by 20μm. It can be used as a contact and scanning probe on a Micro/Nano-CMM.

Keywords: Analogue probe, Floating plate, Stiffness, Micro/nano-coordinate measurement machine

1. INTRODUCTION

The increasing demands of industry for higher accuracy measurements of micro systems have led to the development of the field of micro- and nano dimensional metrology[1]. During the past decade, several micro- or nano-coordinate measuring machines (CMM) that can measure meso-to micro-scaled parts with nanometer resolution have been developed. They are equipped with noncontact probes[2-4] or contact probes[5-7]. Although noncontact probes feature fast surface scanning, for any CMM, however, the need for 3D contact probes is indispensable due to their capability to measure most fundamental geometries, such as line, plane, circle, sphere, cone, etc. A variety of contact probe systems have been designed for micro/nano-CMM, such as silicon-based [8], flexure structure-based[6, 7], fiber Bragg grating type[9], boss membrane structures[10, 11], suspension plate [12, 13], single fiber[14], etc. A summary of some probe systems was made by Weckenmann[15]. Some of them are only of touch trigger probes and some others possess a rather small analogue range, normally less than ±10 μm.

The authors' group developed an analogue tactile probe[13], which is composed of a monolithic fiber stylus with a ball tip, a wire-suspended floating plate as the main mechanism, and some focus sensors. The measurement range of this probe is only several micrometers and, due to embedding four focus sensors, its size is quite large.

A new contact probe having a large scanning range for micro/nano-coordinate measuring machine (CMM) is presented in this paper. Its working requirements include: (1) the scanning range is ±20μm in all axes, (2) the resolution is 1nm, (3) the stiffness is equal in three dimensions, (4) the contact force is less than 0.1mN, (5) the probe head diameter should be less than 40mm in order to fit the CMM dimension.

*liruijun001@126.com; phone +86 13856971653; fax +86 551 2903823

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2. DESIGN PRINCIPLE

This analogue probe is composed of a fiber stylus with a ball tip, a mechanism with a wire-suspended floating plate, a two-dimensional angle sensor (DVD pick-up head) [13, 16]and a novel miniature Michelson interferometer, Figure 1 presents its structure. The exchangeable ball tip stylus is inserted into a steel needle. The probe stylus is fabricated from an optical fiber by melting and solidification process. With proper selection of process parameters using the Taguchi method, this monolithic ball tip stylus can have very good sphericity[17], whose all errors (including diameter, roundness, center offset) of the tip at four different angles can be controlled to within 1μm.

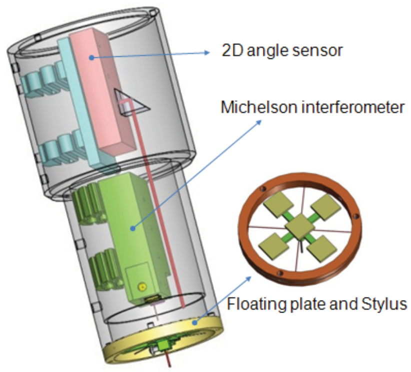


Figure 1. The structure of the probe

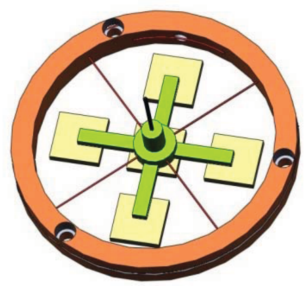


Figure 2. The structure of the floating mechanism

2.1 The floating mechanism

In designing any analogue probe, the suspension structure should have small contact force and equal stiffness in all measurement directions. The equal stiffness property is essential since it ensures a constant correlation between the probing force and the tip displacement regardless of the contacting angle. Figure 2 presents a schematic illustration of the stylus suspension structure developed in this study. The stylus is inserted to the floating plate, which is suspended by evenly distributed wires connected to the probe housing. The symmetrical design has the advantage of easy manufacturing and assembly, and therefore reduces risk of systematic error. The contact force causes the floating plate to tilt and move as a rigid body motion while the wires experience elastic deformations. Plate motion in horizontal plane is detected by the two-dimensional angle sensor on the top of mirrors mounted at proper positions of the floating plate. The vertical motion of the plate is detected by the novel miniature Michelson interferometer properly fixed in the probe.

2.2 Sensor design

2.2.1 Two-dimensional angle sensor

The schematic illustration of the two-dimensional angle sensor employed in this probing system is shown in Figure 3. In the present study, we used a two-dimensional angle sensor modified from a DVD pickup head, which is inexpensive but very accurate. This sensor is modified by removing the objective lens and VCM of a DVD pick-up head (Hitachi HOP-1000) so as to output with a collimated laser beam. The built-in four-quadrant photodiode (QPD) is used as the beam spot position detector. In this two-dimensional angle measurement system, the collimated laser beam is projected onto the plane mirror, and the reflected laser beam is then focused at the centre of the four-quadrant photodiode. A tilt in the angle of the plane mirror causes a corresponding shift in the position of the focused light spot across the center of the QPD. The photo detector transforms the incident energy of the focused light spot into electrical current signals. Deviations of the focused light spot from the centre of the photodiode result in a corresponding change in the magnitudes of the electrical signals output by the QPD. By applying an appropriate resistance to these electrical current signals, voltage signals can be obtained. Changes in the magnitudes of these signals can then be used to determine the *x*- and *y*-coordinates of the incident position of the focused light spot on the photodiode in accordance with the expressions[18]:

$$X = K\left[\left(V_{\mathrm{A}} + V_{\mathrm{B}}\right) - \left(V_{\mathrm{C}} + V_{\mathrm{D}}\right)\right] \tag{1}$$

$$Y = K\left[\left(V_{\mathrm{A}} + V_{\mathrm{D}}\right) - \left(V_{\mathrm{B}} + V_{\mathrm{C}}\right)\right] \tag{2}$$

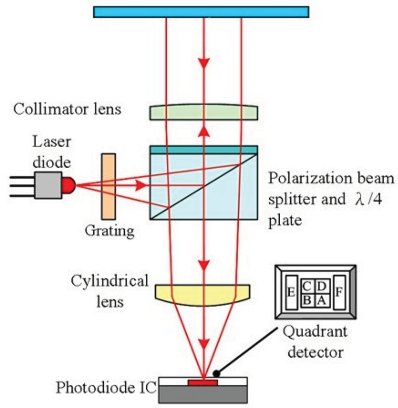


Figure 3 The schematic diagram of the two-dimensional angle sensor

2.2.2 Michelson interferometer

Figure 4 presents the schematic illustration of a miniature Michelson interferometer specially designed for this study. It is responsible for the sensing of the z motion of the ball tip. The laser beam is separated into S-beam and P-beam by the polarization beam splitter (PBS1) with equal intensity. Then the P-beam passes through PBS1and the S-beam is reflected to the reference mirror. The P-beam is changed into a right-circularly polarizing beam by the quarter wave plate (Q1) and reflected by the object mirror. When it passes through Q1 for the second time it is changed to an S-beam. Similarly the reflected S-beam is changed to a P-beam when it passes through Q2 twice. So the beams will not go back to the laser diode but propagate to Q3 after which the P-beam changes to a right-circularly polarizing beam and the S-beam changes to a left-circularly polarizing beam. The NPBS splits both beams into two beams to PBS2 and PBS3 with equal intensity separately. These four beams will be separated into 0-90-180-270 degrees by PBS2 and PBS3 (set fast axis to 45 degrees) and interfere with each other. Analyzed by the Jones vector, the intensity of each photo detector can be expressed as:

$$I_{PD1} = A[1 - \cos(2\Delta\omega \cdot t)] \tag{3}$$

$$I_{PD2} = A[1 + \cos(2\Delta\omega \cdot t)] \tag{4}$$

$$I_{PD3} = A[1 + \sin(2\Delta\omega \cdot t)] \tag{5}$$

$$I_{PD4} = A[1 - \sin(2\Delta\omega \cdot t)] \tag{6}$$

$$\Delta\omega = 4\pi \cdot \frac{\Delta x}{d} \tag{7}$$

where Δx is the optical path difference between reference beam and object beam, which is to detect the z movement of the central mirror of the floating plate in the probe.

Regarding the signal processing, with the operation of (I_{PD2}–I_{PD1}) and (I_{PD3}–I_{PD4}), two orthogonal sinusoidal signals with $\pi/2$ phases shift can be obtained, as shown in Fig. 5. With the pulse counting and the phase subdivision techniques, the optical path difference between the reference beam and the object beam can be resolved to nanometer resolution. Due to the allowable space of the probe head, the physical dimension of this interferometer is specially made to only about 4cm × 3cm, being a useful miniature Michelson interferometer.

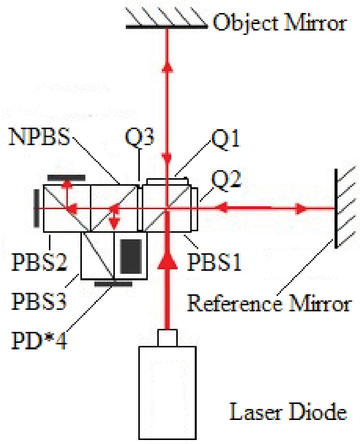


Figure 4 The schematic illustration of Michelson interferometer

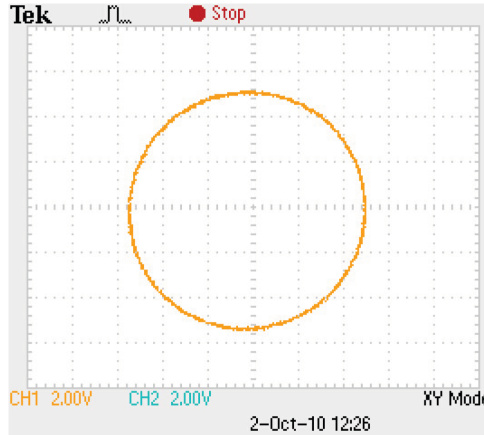


Figure 5 The normalized waveforms

3. OPTIMIZATION DESIGN OF THE STRUCTURE PARAMETERS

3.1 Contacting model of the probe

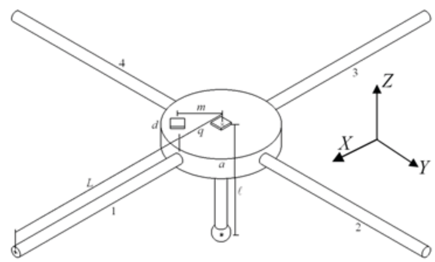
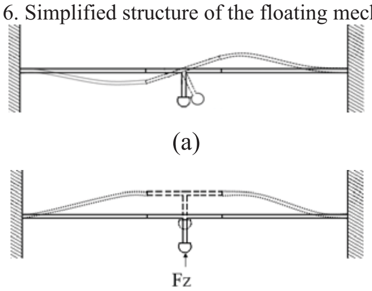


Figure 6. Simplified structure of the floating mechanism



(b)

Figure 7. Deflection mode under force, (a) horizontally and (b) vertically

In order to analyze the response of the displacement to the contact force, we have to find the stiffness model of the probe. Figure 6 illustrates the structure of the floating mechanism. The wires are deformed when a horizontal or vertical force is applied to the ball tip, as shown in Fig. 7. From elasticity theory the displacement-to-force relationship can be derived [19].

$$\begin{bmatrix} \delta_{X,ball} \\ \delta_{Y,ball} \\ \delta_{Z,ball} \end{bmatrix} = \begin{bmatrix} C_1 & 0 & 0 \\ 0 & C_1 & 0 \\ 0 & 0 & C_2 \end{bmatrix} \begin{bmatrix} F_{X,ball} \\ F_{Y,ball} \\ F_{Z,ball} \end{bmatrix} \tag{8}$$

Where , $C_1 = \dfrac{\ell^2 L^3}{8EI \cdot (3q^2 + 3qL + L^2)}$, $C_2 = \dfrac{L^3}{48EI}$ 。

The stiffness of the probe mechanism is the inverse of C in the corresponding direction. The parameters affecting the stiffness are the wire length L, the stylus length *l*, the plate radius *q*, the moment of inertia of the wire *I* and Young's modulus of the wire material *E*.

3.2 The constrained conditions

According to the design requirement for the probe, five constrained conditions that the probe needs to conform have been established as follows:

1) Uniform stiffness: $C_1 = C_2$, so that $6l^2 = 3q^2 + 3ql + L^2$ (9)

2) Maximum contacting force [19]: $F \le 0.1mN$ (10)

3) Measurement range:

$$\delta_{X,\ ball} = C_1 \cdot 0.1mN \geqslant 20\mu m$$

or

$$\delta_{Z,\ ball} = C_2 \cdot 0.1mN \geqslant 20\mu m \tag{11}$$

4) 1nm Resolution:

$$l \le \sin\left(\frac{\varphi \cdot R_U}{U}\right)^{-1} \cdot 10^{-9} \tag{12}$$

where, φ is the angle measurement range of the angle sensor, U is the maximum output voltage of the angle sensor, R_U is the resolution of the voltage.

5) Horizontal size： $q + L \le 17mm$ (13)

3.3 Parameter optimization

The optimization parameters could be calculated by the optimization method based on the above five constrained conditions, as given in Table 1.

Table 1. The components of the floating mechanism.

Item	Specifications
Elastic wire	Material: nylon, $E = 2.83 \times 10^9 Pa$,diameter:0.16mm,length:13mm
Floating plate	Material: aluminum alloy, $E = 7.1 \times 10^{10} Pa$,base diameter: 14mm , thickness:2mm;arm length:10mm,arm thickness:2mm; weight:1.3g
Stylus	Material: glass fiber inserted into a steel needle , $E = 1.93 \times 10^{11} Pa$, length:10mm,diameter 0.5mm

From table 1, we can see that the probe's diameter is 40mm. The manufactured and assembled probe conforms to these design parameters is shown in Figure 8.

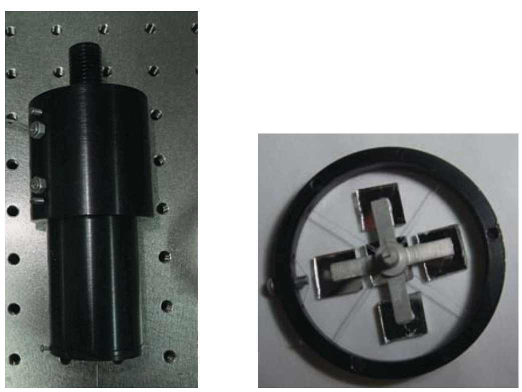
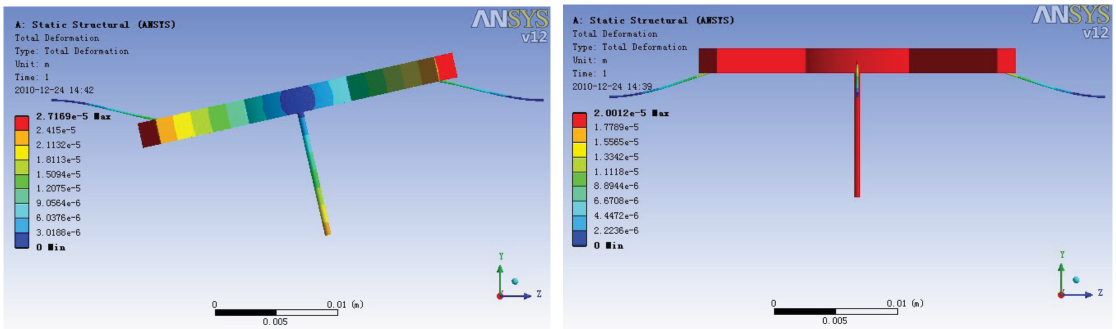


Figure 8. The picture of the probe and the floating mechanism

4. SIMULATION AND EXPERIMENT

4.1 Simulation

In order to validate the correctness the designed probe has been simulated and analyzed by ANSYS. The tip's displacement is shown in Figure 9 when it is applied a 40μN force in horizontal (a) and vertical (b) direction. The calculated linearity of the probe in measurement range is show in Figure 10.



(a) Contacting in horizontal (b) Contacting in vertical

Figure 9. The tip's displacement when contacting force is 40μN

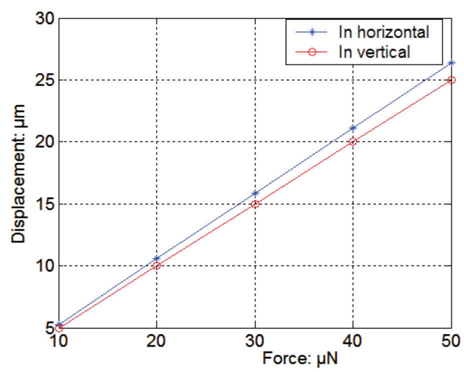


Figure 10. The linearity of the probe in measurement range

From Figures 9 and 10, we can see that the probe can have up to ±20μm measurement range, nearly equal stiffness and the contacting force is less than 50μN.

4.2 Experiments

The stability of the sensor's output signal determines the probe's resolution. The Michelson interferometer can have up to 1nm resolution. So it is only necessary for us to prove that the output signal of angle sensor (DVD pick-up head) is stable enough.

The voltage range of the angle sensor is about 15V, see the Figure 11. Compared with probe's measurement range (40μm), it is easy to calculate that the required voltage resolution is 0.37mV. The stability experiment has been carried out in a constant temperature chamber, and the result is shown in Figure 12. The signal drifted 30mV in nearly one hour, about 0.5mV per minute. The noise of the signal is less than 0.3mV by average filter. So it is stable enough for the angle sensor to accomplish 1nm resolution of the probe.

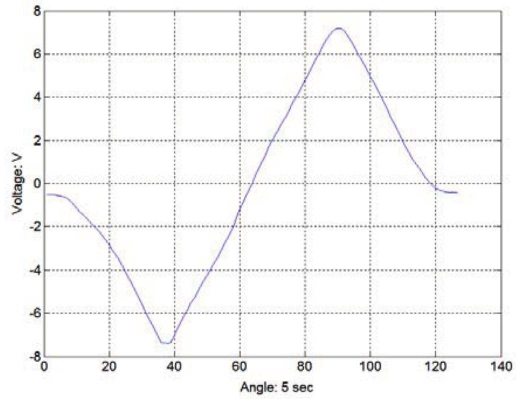


Figure 11. The S curve of the angle sensor

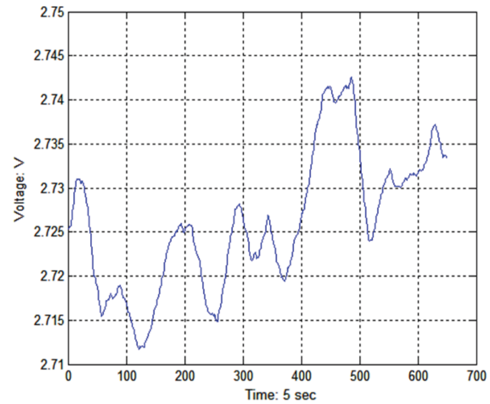


Figure 12. The stability of the focus sensor's outputting signal

5. CONCLUSIONS

This paper presents a new analogue probe for nano-CMM based on a floating mechanism and two high precision sensors. A special feature of this probe over other developed systems is that it can detect the analogue range up to ±20 μm in all directions. Two types of miniature sensors, namely the linear Michelson interferometer and the dual-axis angle sensor, are developed to fit into the probe head, every part of the probe is designed and assembled. Base on the design requirements and stiffness analysis for the probe, five constrained conditions are set and optimal structure parameters of the probe are obtained. Simulation and experimental results show that the probe can achieve equal stiffness, ±20μm measurement range and 1nm resolution in three dimensions; the contact force is less than 50μN when the ball tip is displaced to ±20μm.

ACKNOWLEDGMENT

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