Concept design of a novel tactile probe tip for down scaled 3D CMMs

Ji, H.[a], Kong, L.X.[b], Hsu, H.Y.[c], Wedding, A.B[d]. and Lin, G.C.I[e]
[abce]Centre for Advanced Manufacturing Research, University of South Australia, Mawson Lakes, SA 5095, Australia
[d]School of Electrical and Information Engineering, University of South Australia, Mawson Lakes

Fan, K.C.[f]
[f]Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan, Republic of China

ABSTRACT

Although coordinate metrology has reached a very high state of development concerning versatility and accuracy for common engineering parts, a high precision capability with nano scale resolution and accuracy is often hard to achieve when it is required to measure very small parts and features. The limiting component is the bulky probing system of traditional CMMs (coordinate measuring machines). In order to satisfy increasing demand for highly accurate geometrical measurements on small parts and small structures, a new measuring probe of high sensitivity and small geometrical dimension with low contact forces needs to be developed. In this paper, a novel probing system, which combines a FBG (Fibre Bragg Grating) embedded optical fibre tactile probe with an optical sensing technique, has been proposed. With the sensor elements integrated into the probe tip directly, the system sensitivity can be increased significantly. A preliminary theoretical analysis of the sensitivity of the FBG fibre sensor under axial and lateral end point loading has been presented and the results show that this micro scale probe has great potential to realize a resolution of 1nanometer on geometrical measurement of small parts.

Key words: CMMs probe, FBG sensor, strain distribution

1. INTRODUCTION

In the last decade, there has been a miniaturization trend in manufacturing and industry. The traditional CMMs (coordinate measuring machines) with a bulky probing system can hardly perform high sensitive and high accuracy measurement for small parts and features. There is an increasing need to develop a high performance and downscaled dimension measuring tool. To meet these demands, concepts of miniaturized probe systems for contact CMMs have been continuously proposed[1-5]. Based on the principle of image sensors, optical levers, vibration resonant PZT sensors, optical fibre sensors and strain gauges instead of conventional mechanical electrical contact switch sensors. Most of these systems employ a ball tip probe consisting of a precise ball and a stem with a certain length, as shown in Figure1. In such systems, there is a certain distance between the sensors and the contact points. Besides the deflection of the stem during the measurement[6], the sensor should overcome the gravity of the stem and the ball to feel the contact of the ball with the parts and send out a triggering signal. Although the tip ball displacement sensor has the sensing element linked to the tip end and has an increased sensitivity and decreased pretravel errors, the accuracy is still limited by the assembly structure of the probe with the tip ball being attached to the stem.

Device and Process Technologies for Microelectronics, MEMS, and Photonics IV,
edited by Jung-Chih Chiao, Andrew S. Dzurak, Chennupati Jagadish, David V. Thiel,
Proc. of SPIE Vol. 6037, 60370Q, (2005) · 0277-786X/05/$15 · doi: 10.1117/12.638223

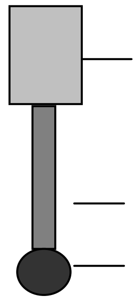


Figure 1. Schematic diagram of a traditional probe

In this paper, a novel miniaturized 3D probe, which combines an FBG (Fibre Bragg Grating) sensor embedded optical fibre tactile probe with an optical sensing technique, has been proposed. FBG sensor probe will measure the strain produced along the stem once the ball touches the surface of a part. As the sensor elements moved closer to the contact point and integrated into the probe tip directly, the system sensitivity can be increased significantly. A preliminary theoretical analysis of the sensitivity of the FBG fibre sensor under axial and lateral end point loading is presented. The analytical results show that this micro scale probe has great potential to realize 3-dimensional geometrical measurements on small parts with nanometres resolution.

2. CONCEPT DESIGN OF A MICRO SCALE FBG PROBE TIP

2.1 Structure of the Novel 3D Optical Fibre Probe Tip

Fibre Bragg gratings (FBGs) are made by producing permanent periodic index variation along a short section in the core of an optical fibre. Since Melz et al.[7] manufactured high reflectivity FBGs by a transverse holographic method, fibre Bragg gratings have been developed steadily and attracted wide attention. The intrinsic advantages over other sensors, such as the lightweight, electromagnetic interference immunity, wavelength-encoded operation and high sensitivity of FBG strain sensors make the FBG sensors employed in wide range applications, such as smart-structure monitor and quasi distributed sensing applications.

In addition, an optical fibre with a diameter of 125 μm has micro scale size and good mechanical properties that make it possible to fabricate a micron scale probe tip. Many fusing techniques are available to fuse a spherical probe tip, such as laser-mechanical methods[8,9] and optical fibre splicer fusing[10]. These techniques help to make the light integrated micro scale spherical tip probe, which can help eliminate the errors brought by mechanical assembling processes in conventional probe fabrication. As the glass fibre can be drawn to thinner fibre, even smaller probe tip with tens of microns is possible. The small dimension of the fibre extends the application range to measure even smaller structures and features.

Here we propose to incoperate the FBG sensor element directly into the optical fibre with fused spherical ball tip to form an integrated 3D probe for a small CMM. The structure is shown below in Figure 2. In this compact structure, the fused spherical ball integrated with the stem helps to avoid the errors introduced by assembly process. Once the tip touches the surface of a part from axial or any lateral direction, or any other direction, a strain will be produced along the stem. As demonstrated in the fundamental of the FBG sensor, this FBG probe structure has two promising advantages over the traditional probe. It has higher sensitivity and has the potential to improve the performance. As the sensor is below the holder in the light fibre stem, the strain along the fibre can be detected by the Bragg grating element in the stem effectively. Another advantage is due to the circular cross section of the fibre grating. The circular structure leads to the generation of isotropic strain by lateral loading (X-Y) plane, which can help to decrease the lobbing effect lying in traditional three point electric mechanical switch. According to the analysis below, it shows the probe can perform 3 dimensional measurements with a high sensitivity.

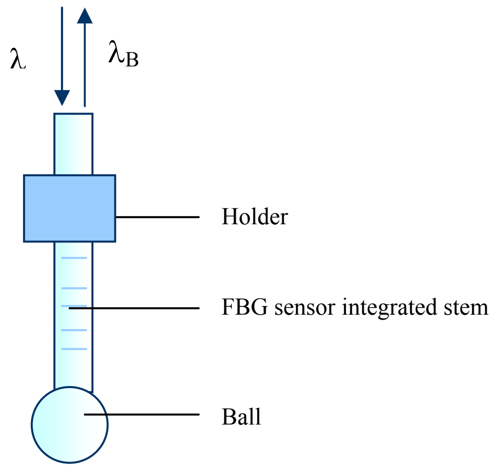


Figure 2. Schematic diagram of FBG integrated probe tip

2.2 Fundamental of the FBG probe

When light propagates in the core of an optical fibre containing a Bragg grating, a specific wavelength wave that satisfies the Bragg condition will be selected and reflected. This wavelength is called the Bragg wavelength of the grating and is given by[11]

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

where n_{eff} is the effective refractive index of the core and Λ is the periodicity of the refractive-index modulation or grating pitch. In this case the light with the Bragg wavelength is reflected by each perturbation in the grating, adds constructively and can be detected by a photo detector.

According to Eq. (1), any change in the refractive index or the index modulation pitch will result in a shift of the Bragg wavelength. While the refractive index and the grating pitch are sensitive to the strain of the fibre and the variation of the temperature, the shift in Bragg wavelength with the refractive index and the grating pitch can be expressed using

$$\Delta\lambda_B = 2\left(\Lambda\Delta n_{eff} + n_{eff} \bullet \Delta\Lambda\right) \quad (2)$$

When the probe tip touches the surface of a part, the strain produced along the fibre will result in a wavelength shift. There is a definite quantitive relation between the strain and the wavelength shift if the temperature effect can be neglected.

3. SENSITIVITY UNDER AXIAL LOADING AND LATERAL LOADING

3.1 Strain sensitivity under axial loading

Assuming the Ge doped SiO_2 fibre with Bragg grating is homogeneous and the stress distributed along the axis is uniform when under an axial compression load P, as shown in Figure 3., in an environment with a constant temperature. Then the strain produced in the grating is the same as that in the fibre, that is:

$$\frac{\partial\Lambda}{\Lambda} = \frac{\partial L}{L}$$

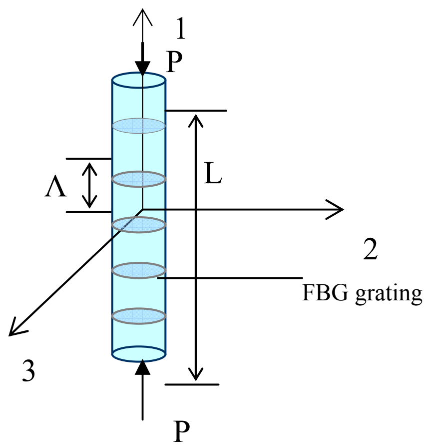


Figure 3. Schematic diagram of the optical Bragg grating fibre structure

According to the photo-elastic theory[12,13],

$$\frac{\Delta\lambda_B}{\lambda_B} = \{1 - p_e\}\varepsilon_z \quad (3)$$

where p_e is the effective photo-elastic constant that is approximately 0.22. Using this value in (3), the Bragg wavelength sensitivity can be expressed in a simple relationship:

$$\Delta\lambda_B/\lambda = 0.78\varepsilon. \quad (4)$$

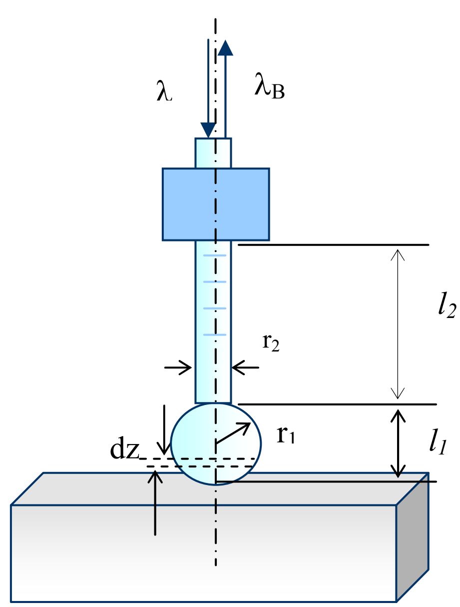


Figure 4. Schematic diagram for shperical probe tip under axial loading

For the integrated probe with a spherical tip, the sensitivity is decided by both of the fibre stem and the ball together. In this case, suppose that the fibre stem has a diameter of 125μm and the spherical ball has a diameter of 340μm. According to Hooke's law, the compression of a bar with a constant cross section area A and length of l under the axial load P is determined by

$$\Delta l = Pl/AE. \tag{5}$$

where E is the Young's Modulus of the silica fibre.

For a spherical ball, the cross section varies along the strain axis, but the same relationship still holds for a small element of length dz (as shown in Figure 4.). The compression Δdz of an element of original length dz is

$$\Delta dz = Pdz/AE. \tag{6}$$

Then the compression of the spherical ball is

$$\Delta l_1 = \frac{P}{E}\int_{r_1}^{0}\frac{1}{\pi(r_1^2 - x^2)}dx + \frac{P}{E}\int_{0}^{\sqrt{r_1^2 - r_2^2}}\frac{1}{\pi(r_1^2 - x^2)}dx$$
$$= \frac{P}{4Er_1^2} + \frac{P}{\pi E r_1^2}arctg(\sqrt{1-(\frac{r_2}{r_1})^2}\ ). \tag{7}$$

For the cylindrical stem section, the compression is

$$\Delta l_2 = \frac{Pl_2}{\pi E r_2^2}. \tag{8}$$

Then the total compression along the probe is

$$\Delta l = \Delta l_1 + \Delta l_2 = \frac{P}{\pi E}(\frac{l_2}{r_2^2} + \frac{\pi}{4r_1^2} + \frac{1}{r_1^2}arctg(\sqrt{1-(\frac{r_2}{r_1})^2})). \tag{9}$$

Assuming the stem has 0.1nm compression, E is 70GPa, l_2 is 5mm long, according to Eq. (8) and Eq. (9), the total compression is 4.25nm. The strain produced on the stem is 0.02-micro strain. Using an unbalanced interferometer as a wavelength demodulator techniques, a strain resolution of 0.6-nano strain has been achieved using the FBG strain sensor[14], which is much smaller than 20 nano-strain (0.02 micro-strain). There is a great potential to even achieve a higher resolution for the FBG probe.

3.2 Strain sensitivity under lateral loading

Assuming that the optical fibre is a fibre bar with one end clamped and has an external loading P_l applied to the other end, as shown in Figure 5 (a), a unit elongation and a unit compression are produced proportional to the distance from the xz plane containing the axis oo´ of the fibre bar, which is called the neutral plane that undergoes neither extension nor compression when bending occurs. Here the axis oo´ is the same as the axis z before bending occurs. From simple geometrical considerations, as shown in the Figure 5 (b), using the strength of materials theory, the compression strain of a thin layer DD' that is at a distance y' from the neutral plane is[15,16]

$$\varepsilon_z = -\frac{y'}{\rho} \tag{10}$$

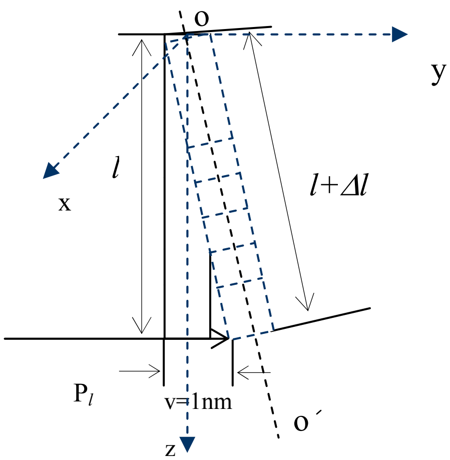
where ε_z is an axial strain along the fibre, y' is the layer distance from the neutral plane within the stem. ρ is the radius of curvature of the neutral axis of the stem bar and it is given by[16],

$$1/\rho = M / E I_x \quad (10a)$$

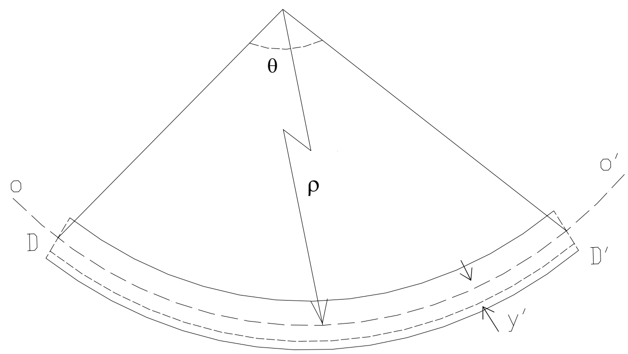
where M is the moment of the cross section of the bar, I_x is the moment of inertia of the cross section of the bar about the axis x. M and I_x is given by[17]

$$M = P_l (l - z) \quad (10b)$$

$$I_x = \pi R^4/4 \quad (10c)$$



(a)



(b)

Figure 5. (a) Schematic diagram of a fibre bar under lateral load; (b) Schematic diagram of a bending section on the fibre bar

Substitute Eq. (10a) in Eq. (10), then

$$\varepsilon_z = -\frac{My'}{EI_x} \quad (11)$$

$$\varepsilon_z = -\frac{P_l (l - z) y'}{EI_x} \quad (11a)$$

The displacement of the bar from the original neutral plane S is[17]

$$S = -\frac{P_l z^2}{6EI_x}(3l - z) \quad (12)$$

Then the displacement of the end of the optical fibre bar is

$$S = -\frac{P_l l^3}{3EI_x} \quad (13)$$

According to Eq. (11a) and (13), the strain can be a function of the displacement of the end that is given by

$$\varepsilon = \frac{3s}{l^3}(l - z)y' \tag{14}$$

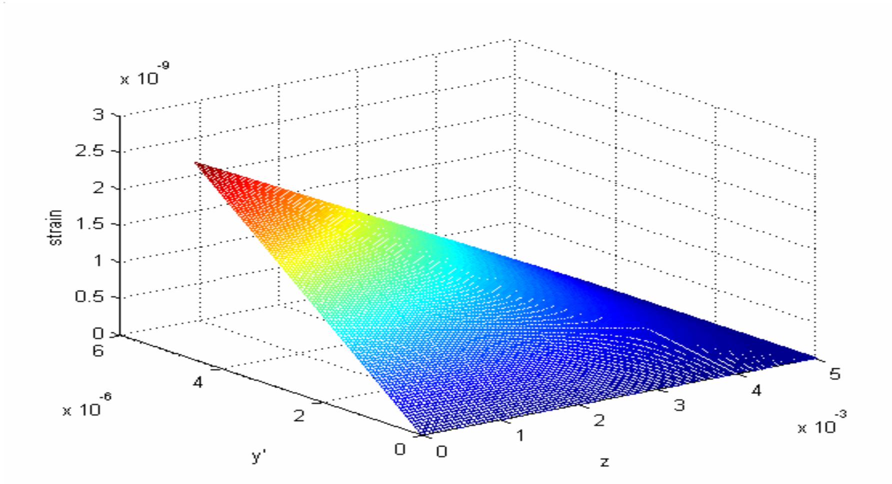


Figure 6. Strain distribution along the optical fibre core

Assuming that the end displacement is 5nm, E is 70×10^3N/mm^2, radius of the fibre R is 62.5μm, the length of the fibre bar l is 5mm, then I_x is 1.198×10^{-17}m^4. According to Eq. (13), P_l is only 0.1μN. As the Bragg grating sensor element is fabricated in the fibre core, the standard single mode fibre core diameter is of 9 μm. According to Eq. (14), the strain distribution along the optical fibre core is shown in Figure 6. The maximum strain is produced on the fibre top and proportional to the distance from the fibre axis. The strain approaches zero while z moves to the end of the tip and y' moves to the axis. So the maximum strain of the Bragg grating is 2.7 nano-strain with z is zero and y' of 4.5μm. This strain is 4 times bigger than that of the strain resolution of 0.6 nano-strain achieve by Kersey's group[14] that means there is a potential to achieve higher displacement resolution.

4. CONCLUSIONS

With the development of the micro mechanical systems and nano technology, the challenges in CMM metrology are the development and the miniaturisation of high sensitive and accurate probing system. A novel compact micro FBG sensor integrated probe has been proposed in this work by using optical fibre technology to realize high sensitive and high-resolution measurement. As to the micro scale structure, the optical fibre is a good candidate for the tactile probe tip. According to the theoretical analysis, this compact FBG sensor integrated probe can perform 3Dimensional measurement with resolution of 5nm. With a high-resolution wavelength demodulation system, there is a great potential to realize resolution of 1nm or even sub-nanometre.

REFERENCES

1. Butler, C., *Probes for High Precision Demensional Measurement.* Sensor Review, 1994. **14**(1): p. 24-26.
2. Enami, K., et al. *Development of Nano-Probe System Using Optical Sensing*. in *IMEKO-XV World Congress*. 1999.
3. Kanda, T., Kurosawa, M.K., and Higuchi, T., *Sensitivity of a Miniaturized Touch Probe Sensor Using PZT Thin Film Vibrator.* Ultrasonics, 2002. **40**(1-8): p. 61-65.
4. Woody, S.C. and Smith, S.T., *Resonance-based Vector Touch Sensors.* Precision Engineering, 2003. **27**: p. 221-233.
5. Haitjema, H., Pril, W.O., and Schellekens, P.H.J., *Development of a Silicon-based Nano Probe System for 3-D Measurements.* Cirp Annals-Manufacturing Technology, 2001. **50**(1): p. 365-368.

6. Miguel, P.C., King, T., and Abackerli, A., *A Review on Methods for Probe Performance Verification.* Measurement, 1998. **23**(1): p. 15-33.
7. Meltz, G., Morey, W.W., and Glenn, W.H., *Formation of Bragg Gratings in Optical Fibres by a Transverse Holographic Method.* Optics Letters, 1989. **14**(15): p. 823-25.
8. Veiko, V.P., et al., *New Method of Fiber Optic Tool Fabrication Based on Laser Technologies.* Laser Applications Engineering (LAE-96), 1997. **3091**: p. 122-128.
9. Vaidya, A. and Harrington, J.A., *Sculpted Optical Silica Fiber Tips for Use in Nd:YAG Contact Tip Laser Surgery: Part1-Fabricaiton Techniques.* Optical Engineering, 1992. **31**(7): p. 1404-1409.
10. Fan, K.C., Hsu, H.Y., and Hong, P. *Feasibility Study of the Formation of Micro Spherical Probes with Optical Fibers*. in *The 9th International Conference on Mechatronics Technology*. 2005. Kuala Lumpur, Malaysia.
11. Kashyap, R., *Ch4. Theory of Fiber Bragg Grating*, in *Fiber Bragg Grating*. 1999, Academic Press.
12. Melle, S.M., Liu, K.X., and Measures, R.M., *Practical Fibre-optic Bragg Grating Strain Gauge System.* Appl. Opt., 1993. **32**(19): p. 3601-3609.
13. Kersey, A.D., et al., *Fiber Grating Sensors.* Lightwave Technology, Journal of, 1997. **15**(8): p. 1442-1463.
14. Kersey, A.D., Berkoff, T.A., and Morey, W.W., *High-resolution Fibre-grating Based Strain Sensor with Interferometric Wavelength-shift Detection.* Electronics Letters, 1992. **28**(3): p. 236-238.
15. Filonenko-Borodich, M., *Theory of Elasticity (translated from the Russian by M.Konayeva)*, ed. G. Ivanov-Mumjiev. 1964, Groningen, Netherlands: P. Noordhoff N.V., Scientific Publishers.
16. Stephenson, R.J., *Properties of Solids and Liquids*, in *Mechanics and Properties of Matter*. 1952, John Wiley & Sons, Inc.: New York. p. P275.
17. Landau, L.D. and Lifshitz, E.M., *Theory of Elasticity (translated from Russian by Sykes, J.B. and Reid, W.H.)*. Vol. 7. 1959, London: Pergamon Press. 94.