Fiber Deflection Probe for Small Hole Measurements

B. Muralikrishnan[1], J. A. Stone[2], S. C. Vemuri [3], C. Sahay[3], A. Potluri[3], J. R. Stoup[2]

[1]Department of Mechanical Engineering & Engineering Science, UNC Charlotte, Charlotte NC
[2]Precision Engineering Division, National Institute of Standards and Technology, Gaithersburg, MD
[3]Mechanical Engineering Department, University of Hartford, West Hartford, CT

1. Introduction

Measurement of diameter and form of small holes is of great importance in applications such as fuel injector nozzles, fiber optic ferrules, wire drawing dies, holes in printed circuit boards and medical apparatus such as syringes, etc. A variety of technologies that address the problem of small hole measurement are reported in the literature [1-4]. In this paper we describe a probing method, referred to as Fiber Deflection Probing (FDP), for use on Coordinate Measuring Machines (CMM). The technique is simple and yields expanded uncertainty on diameter of 0.11 μm (k = 2). The principle of this technique, characterization and measurement results are presented here.

2. Measurement principle

A thin glass fiber (20 mm long, 50 μm in diameter), fixed at one end and with a ball (85 μm diameter) mounted on the other serves as the probe. A small segment of this fiber is illuminated by a light emitting diode 5 mm below the ball as shown in Fig. 1. The shadow of the fiber is magnified and imaged using a camera. When the probe contacts a surface, it is deflected by a small amount. The magnitude of this deflection is determined by recording the position of the shadow in free state and in deflected state. The deflection of the fiber in pixels can be related to the deflection of the probe tip in micrometers using a calibration procedure that is described later. The deflection of the probe tip is then added to the machine scale reading to obtain coordinates on the surface.

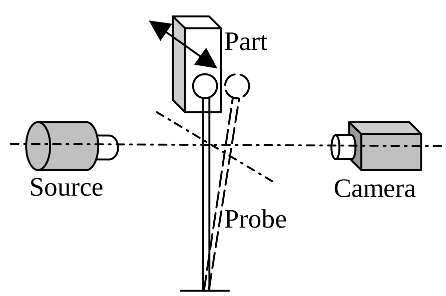


Fig. 1 Measurement principle

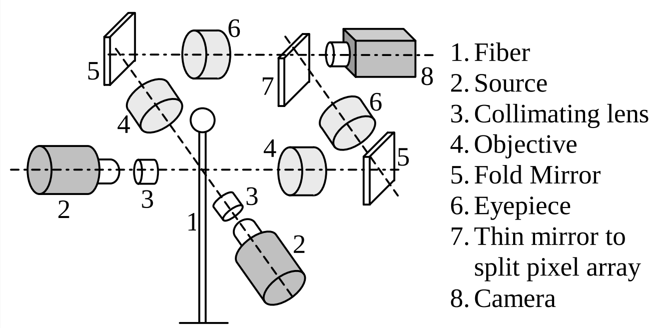


Fig. 2 Optical setup for fiber deflection measurement

In order to obtain deflections in both X and Y, two orthogonal sources are used. The shadows of the stem are magnified using 7X objectives placed 12 mm from the fiber. The resulting images are further magnified using 5X eyepieces and imaged using a CCD camera. Overall magnification is about 35. The optical setup is illustrated in Fig. 2. The mirror in front of the camera (7) extends half way across the pixel array, so that light from one axis illuminates half of the array and light from the second axis falls on the other half of the array.

The shadows of the fiber stem, as projected onto the camera, appear as a dark region with a bright band down the center. As shown in Fig 3(a), two bright bands are seen, one for each direction X and Y. An automatically determined threshold is applied to this image to convert it to a binary image. This is followed by a software routine for particle removal to suppress the influence of any dirt particles. The resulting image is shown in Fig. 3(b). Subsequently, the leading and trailing edge coordinates for both bright bands are determined for each horizontal pixel row. This information is used (through least squares fitting and averaging) to determine the center pixel of each of the bands at the center row.

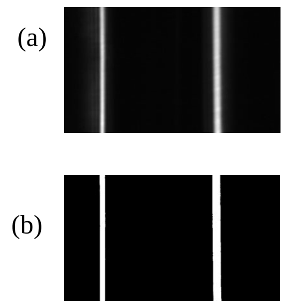
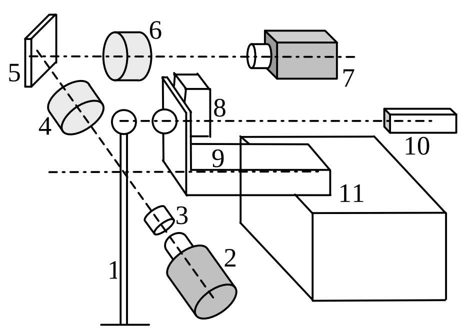


Fig 3 (a) Image as recorded by the camera (b) Binary image after processing

3. Probe characterization in 1D

Before the system is mounted on a CMM for rigorous testing, 1D performance is evaluated using a piezo stage. A long arm is mounted on the piezo stage and is aligned parallel to one optical axis of the deflection system. A retro reflector is held at the end of this arm and a 5 mm steel ball is glued to the backside of the retro reflector. The ball serves the function of a test surface and is centered on the retro to essentially measure at zero Abbe offset. The ball is brought in contact with the fiber, which is deflected by moving the piezo stage. The actual distance traveled by the stage is monitored using a laser interferometer. A schematic of the setup is shown in Fig. 4.



1. Fiber
2. Source
3. Collimating lens
4. Objective
5. Fold Mirror
6. Eyepiece
7. Camera
8. Retro reflector with ball mounted behind
9. Long arm
10. Laser
11. Piezo stage

Fig. 4 1D Characterization Setup

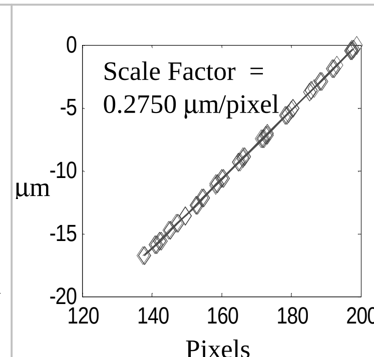
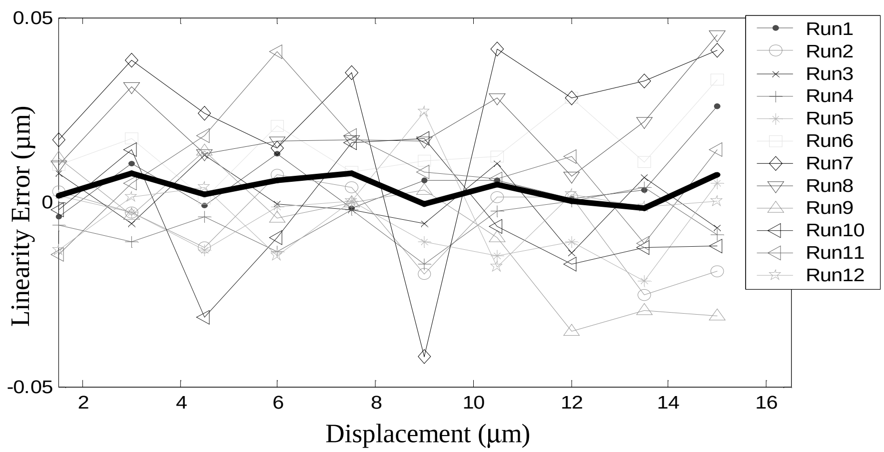


Fig 5. Calibration factor in µm/pixel

This setup is used for calibration (determining a scale factor that relates displacement of the probe stem in pixels to displacement of the tip in micrometers) in one axis (active axis) and also to evaluate linearity in that axis. A typical calibration run produces a plot shown in Fig. 5 and a scale factor in µm/pixel. Fig. 6 shows a linearity plot with 12 runs that was acquired over a 40 min period. In each run, the laser is zeroed (to correct for zero drift) at the start (zero displacement position) and the corresponding pixel reading is noted. For all subsequent deflections (from 1.5 µm to 15 µm in steps of 1.5 µm), the corrected laser position is computed (current laser reading – fiber deviation in pixels × scale factor in µm/pixels). This value should theoretically be identical to the laser reading at the start position, which in this case is zero. One standard deviation error in the graphs (arising from nonlinearity or noise) is between 10 nm and 25 nm for each run in this test. One standard deviation linearity/noise error is of the order of 17 nm over the entire duration, while it is much smaller for most runs individually. From Fig. 6, it is seen that there are no clear systematic effects in the linearity plot. The deviations shown in the diagram do not repeat well from one run to the next, indicating that the deviations arise primarily from random noise. The solid black line in Fig. 6, an average of the 12 runs, indicates that systematic deviations from linearity averaged over this period do not exceed 4 nm (one standard deviation).



Standard Deviation (nm)	
Run1	9
Run2	12
Run3	9
Run4	6
Run5	9
Run6	10
Run7	25
Run8	12
Run9	18
Run10	16
Run11	16
Run12	12

Fig 6. Long-term linearity results in 1D (Solid black line is average of the 12 runs at each position)

4. Probe characterization in 2D

After the probe is characterized in 1D, the system is moved from the piezo test bed to the CMM. Because the probing system with the camera and optics is heavy, it is mounted on the CMM table with the probe pointing upward. Test artifacts are mounted on the ram. The probe is calibrated in both X and Y directions. In general, it is observed that the scale factor is different in each direction because (1) the magnifications are not identical in both directions and (2) the point of observation on the fiber is not at exactly the same height for the two directions. After obtaining the scale factors, linearity tests are conducted to assess performance. Typically, a standard deviation of 35 nm in linearity error is observed in X and Y. The marginally better performance in the piezo test bed is probably due to better environmental control around the probe as the entire assembly can be shielded from air currents, a situation not feasible on the CMM. Also, a portion of the 35 nm linearity error on the CMM can be attributed to the machine's positioning repeatability (≈ 25 nm) itself.

5. Probing system validation and results

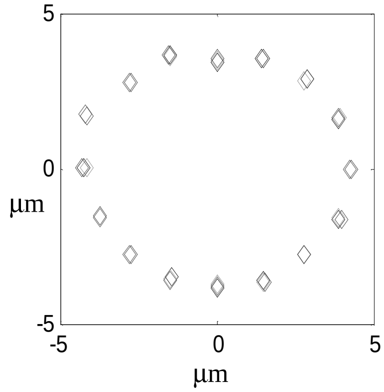
Three artifacts of known diameter and form are measured using FDP to validate the probing system. Prior to each of these measurements, the fiber probe diameter and form are calibrated by measuring a 3 mm ruby sphere of known diameter and form. The diameter of the 3 mm sphere is calibrated using the Universal Measuring Machine (Table 1) and the expanded uncertainty is 0.09 µm (k = 2). The master ball diameter uncertainty is thus a major contributor in the overall uncertainty budget, although a more careful measurement arrangement is expected to lower this significantly. Table 1 shows a comparison of diameters obtained using FDP and other techniques. The agreement in diameters is to within 60 nm, although the uncertainty in the difference is large because of large master ball diameter uncertainty.

Table 1 Comparison of diameters obtained using FDP and other sources

Artifact	Dia from other sources (µm)	Dia from FDP (µm)
5 mm Sphere 1	4999.98 (UMM[1]) ± 0.09	4999.92 ± 0.11
5 mm Sphere 2	5000.19 (UMM[1]) ± 0.09	5000.15 ± 0.11
1 mm Hole	999.53 (M48 CMM[2]) ± 0.15	999.48 ± 0.11

[1]UMM – Universal Measuring Machine at NIST. Two point diameters are measured at 10 locations and averaged. [2]Moore M48 [5] CMM at NIST is used to measure the hole. The number following the symbol ± is the expanded uncertainty (k = 2).

The FDP is then used to measure a 129 µm nominal diameter fiber optic ferrule. The hole is located by simply centering the fiber using the outer surface of the ferrule. Because the hole is concentric with the outer surface to within 2 µm, no special optics are needed to locate the hole. The fiber is inserted 80 µm inside the hole and a measurement is made. The diameter obtained is 129.58 µm. and the residual form error on the hole after removing fiber ball form is 1.04 µm radial out-of-roundness. These are shown in Fig. 7. These values have not yet been verfied using other techniques.



Probe calibration on 3mm Ball:
LS fit mean ϕ = 3088.12 µm
1σ on ϕ over 3 runs = 0.01 µm
Sphere ϕ from UMM = 3000.79 µm
⇒ Fiber Probe Ball ϕ = 87.33 ± 0.10 µm
Test Measurement on ferrule:
LS fit mean ϕ = 42.25 µm
1σ over 3 runs = 0.01 µm
Test Hole ϕ = 42.25+87.33 =
129.58 ± 0.11 µm
Test Hole OOR = 1.04± 0.11 µm

Figure 7 Form error on 129 µm fiber ferrule hole (radius suppressed). The number following ± is the expanded uncertainty (k = 2).

6. Conclusions

A novel technique for measurement of diameter and form of small holes is presented. The probe is first characterized in 1D using a piezo test-bed setup and linearity errors are of the order of 15 nm to 20 nm. Subsequently, when mounted on a CMM, it is observed that linearity errors are of the order of 35 nm or smaller. A number of test artifacts are measured using the FDP and diameter results agree to within 60 nm with those obtained using other techniques. And finally, the diameter of a 129 µm nominal diameter ferrule is measured. Although an uncertainty budget has not been presented here, analysis indicates expanded uncertainty of 0.11 µm on diameter (k = 2). Contributors include master ball diameter uncertainty, machine positioning repeatability, imaging uncertainty and axis out-of-squareness.

1. G. X. Zhang and S. M. Yang, Annals of the CIRP, 44/1/1995, 461-464
2. Masuzawa T., Hamasaki Y. and Fujino M., Annals of the CIRP, 42/1/1993, 589-592
3. T. Hashimoto, Y. Takaya, T. Miyoshi, R. Nakajima, Proc. of the ASPE, 2003, 83-86
4. H. Schwenke, F. Waldele, C. Weiskirch, H. Kunzmann, Annals of the CIRP 50/1/ 2001, 361-364
5. Commercial equipment and materials are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.