ROUNDNESS MEASUREMENTS USING THE NIST FIBER PROBE

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INTRODUCTION

We have previously described [1] a fiber probe for dimensional measurement of micro-holes on a Coordinate Measuring Machine (CMM). In this paper, we discuss the adaptation of this probe for measuring roundness in a configuration similar to that of a more traditional roundness measuring instrument with the part mounted on a precision spindle and the probe sensing radial deviations. We have measured roundness of knife-edge apertures using this method. These apertures are used as standards in radiometry and currently measured using optical techniques only [2, 3].

THE NIST FIBER PROBE

The fiber probe developed at the National Institute of Standards and Technology (NIST) was originally designed as a CMM probe to operate in point-to-point mode. The probe is capable of measuring holes as small as 125 μm diameter to depths of 10 mm, with an expanded uncertainty in diameter of 70 nm (k = 2). The probe is sensitive not only in *X* and *Y*, but also in *Z*; *Z* measurements are achieved by observing the magnitude of buckling of the fiber while measurements in the *XY* plane are achieved by observing the deflection (bending) of the fiber. Deflections and/or buckling are detected by optically measuring from two orthogonal directions, the stem position at a point about 10 mm from the tip of the fiber

SURFACE ADHESION

A primary limitation of slender fiber based probing systems is the adhesion of the fiber to the test surface due to water layers, contamination, etc. These adhesive forces can be significant, of the order of several micronewtons. In order to overcome these forces, the fiber has to be drawn away from the surface by several hundred micrometers before it can be located at the next sampling point. To eliminate this problem, we excite the fiber into resonance between measurements; vibrating the fiber provides necessary energy to break free from the adhesive bonds. We have demonstrated this method for profile measurement of gage blocks [4]. Here we describe the adaptation of this technique for roundness measurement of circular features.

ROUNDNESS MEASUREMENT SETUP

A schematic of the setup is shown in Fig. 1. The probe is brought in contact with the test artifact (for instance, along *X)*, and deflections along the sensitive direction of the stem are monitored while the spindle is rotated.

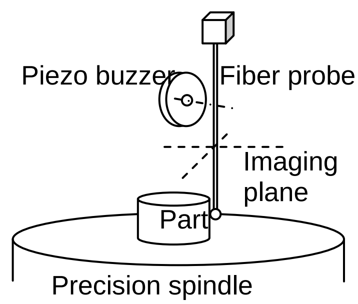

FIGURE 1. Schematic of the setup showing part mounted on a precision spindle, and the fiber excited acoustically. A piezo buzzer (which does not physically contact the fiber) generates the acoustic excitation.

The fiber is excited into resonance as the spindle is rotated to present the next sampling location on the part. However, because there is no available node on the stem, we are unable to image the stem when it is vibrating. Therefore, the spindle operates in a start-stop mode, where images are gathered when there is no spindle motion. Vibrating the fiber does not adversely impact repeatability if sufficient time is allowed (2 s) to damp out the vibrations prior to imaging.

While the technique is slower than traditional roundness instrumentation where the spindle is in constant motion, our technique does pose an advantage in that by being able to monitor the stem bending along the tangential direction in addition to the radial direction, we can quantitatively assess if the fiber displays any adhesion with the surface.

RESULTS

We have measured the roundness of precision spheres and knife-edge apertures using the above described technique. The measurements were performed using a 125 μm diameter fiber with the stem directly in contact with the test artifacts (not the ball on the end) to avoid any errors from a tilted knife-edge hole contacting the probe ball at different planes. Any variations in the stem diameter will contribute to errors; we discuss this in the later section on uncertainty.

Knife-edge aperture area is currently measured optically. However, an inter-comparison conducted by NIST [5] shows the disagreement between the different optical techniques is larger than the quoted uncertainties. A contact probe measurement of the same apertures is desirable. Traditional probes would damage the delicate knife edge but a fiber probe operating at forces ranging from about 10 nN up to several hundred nN should not damage the aperture. While we have not yet measured diameter (or area), we report on form measurements of these knife-edge apertures using a contact probe method. Poor form can be a large contributor to diameter (and area) uncertainty. The results reported here are probably the first roundness traces of such knife-edge artifacts using an ultra-low force touch probe.

Radial Form of Known Spheres

Fig. 2 shows radial form data from a 3 mm nominal diameter, ruby sphere. 180 sampling points were acquired per trace, and 10 traces were measured. The repeatability (one standard deviation) over 10 runs is under 20 nm at any angular position. While the repeatability is excellent, a systematic form component of 80 nm amplitude is clearly identifiable in Fig. 2.

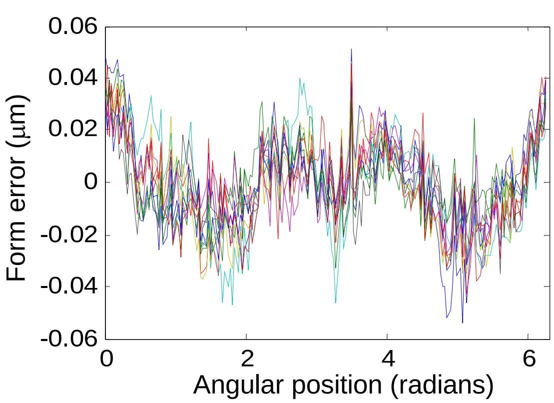

FIGURE 2 Radial form data from 3 mm sphere

Upon performing a full reversal (profiles after reversal shown in Fig.3), we were able to show that the observed form in Fig. 2 is in fact mostly due to the spindle and not the part, see Fig. 4 and 5. This was independently verified using a traditional roundness instrument available at NIST; the radial out-of-roundness of the ball was measured using this instrument as 15 nm (with an uncertainty of 6.4 nm, $k = 2$).

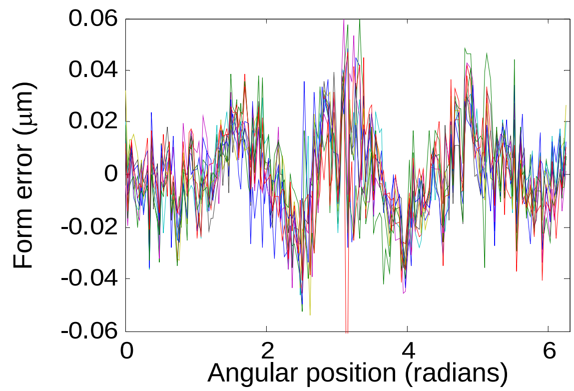

FIGURE 3 Radial form data from 3 mm sphere at the 180° position of a full Donaldson reversal, with 180 sampling points per trace and 10 traces

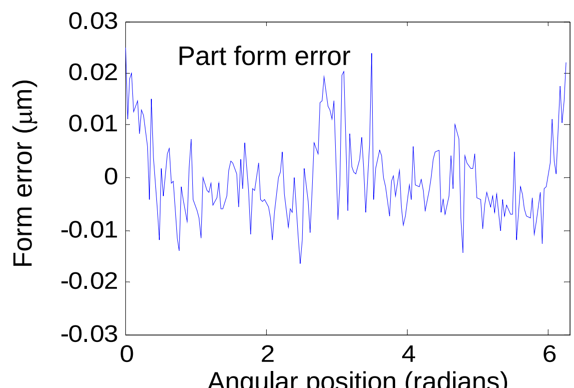

FIGURE 4 Part form error obtained as half the sum of the mean of 10 runs in Fig 2 and Fig. 3

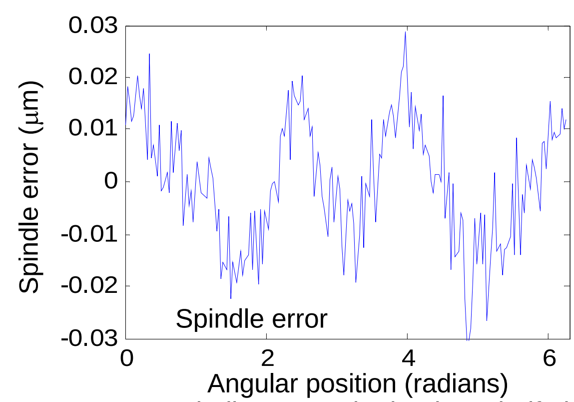

FIGURE 5 Spindle error obtained as half the difference of the mean of 10 runs in Fig 2 and Fig. 3

Radial Form of Knife Edge Apertures

We measured radial form of several knife-edge apertures using the vibration assisted fiber probe technique. In Fig. 6, we plot the radial deviations of a knife-edge aperture (nominal diameter 6 mm). 180 sampling points were acquired around the circumference per trace, and this was repeated 10 times. The one standard deviation repeatability is only 62 nm at any radial location.

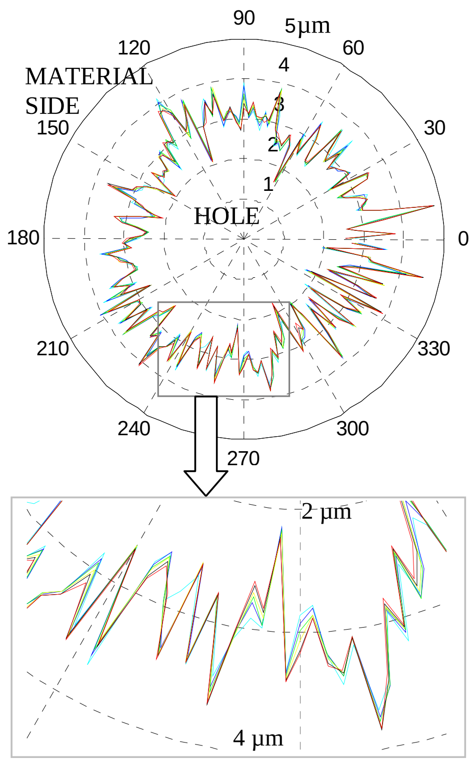

FIGURE 6 Radial form data from a knife-edge aperture. 180 sampling points per trace, 10 traces are shown. The repeatability at any location is only of the order of 62 nm*. The out-of-roundness of this artifact is approximately 2* μm*.*

In Fig. 7, we show the radial deviations of another knife-edge aperture (5 mm nominal diameter). This aperture was part of a round-robin comparison [5] conducted by NIST earlier. Again, we measured 180 sampling points per trace and acquired 10 traces; the average of the 10 traces is shown as the solid line in Fig. 7.

In addition to roundness measurements made using the vibration-assisted pseudo-scanning technique, we have also measured the form using our probe on a CMM in point-to-point mode. Two dimensional (2D) point coordinates were measured at each sampling location, and the residuals from the Least Squares best fit circle are plotted in Fig. 7. Form measurement on a CMM requires that the probe be retracted from the surface each time to overcome surface adhesion as described earlier. Therefore, fewer sampling points (16 points shown in Fig. 7) can only be acquired to reduce the effect of any drift in the system. Fig. 7 shows that there is good agreement in form data between the two configurations the probe can be used in: as a 1D roundness probe with the part on a precision spindle, and as a 2D CMM probe with the part on the CMM table.

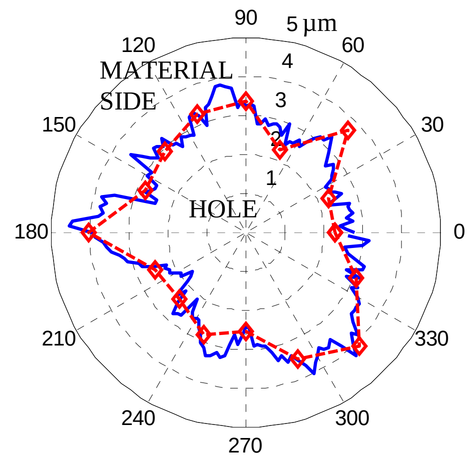

FIGURE 7 Radial form data from a knife-edge aperture used in NIST round robin comparison. 180 sampling points per trace, average of 10 traces shown in solid line. Additionally, the dashed-diamond line represents 16 sampling points measured with the probe on a CMM. 2D point coordinates were determined at each sampling location. The residuals from a Least Squares best fit circle are shown here.

The measurements we have performed indicate that these knife-edge apertures have poor form; the radial out-of-roundness is of the order of 2 μm. Therefore, part form error can be expected to have a substantial contribution to the overall uncertainty in diameter measurements and therefore the area of apertures used in radiometry.

ERROR SOURCES

Imaging errors, spindle errors, scale errors, fiber diameter non-uniformity and taper, part misalignment and surface finish contribute to uncertainty in radial form measurement.

Imaging errors (errors in determination of fiber position in camera coordinates) are extremely small (of the order of 5 nm [1]) primarily due to the large number of pixels that are available, and the result of averaging many images. Manufacturer specified spindle radial error is 25 nm. Our measurements indicate radial error of the order of 50 nm. Taking this more conservative value, and assuming a rectangular distribution, the contribution to radial form is 29 nm. The nominal scale factor is approximately 0.4 μm/pixel with an uncertainty of 0.001 μm/pixel [1]. Although the fiber may have a starting deflection of 50 pixels, we are only concerned about changes from one sampling point to the next. Assuming part form error of 4 μm (10 pixels) based on the apertures described previously, the uncertainty in radial form is about 10 nm. We have experimentally verified that vibration does not impact repeatability in any significant manner if sufficient time is allowed (about 2 s) for the vibrations to damp out before commencing the imaging process and is therefore not a major component in the uncertainty budget.

The tilt of the top face of knife-edge apertures is aligned to within a few micrometers using a dial indicator. Any residual tilt in the part will manifest itself as ovality in the form data. It is critical to align micro-holes to within a few micrometers. For the 5 mm and 6 mm diameter apertures we have measured, a 5 μm tilt across the aperture will have negligible impact on form, of the order of 1 nm. In addition, because we use the fiber stem for these measurements, and not the ball at the end of the fiber, any non-uniformity in the fiber coupled with tilt in the part will directly manifest itself as a radial form error. We have experimentally seen that over 5 μm along the stem axis, the fiber radius can change by 10 nm. We assign this value, 10 nm, as the contribution to radial form error due to this term assuming the part can be tilted/warped by as much 5 μm across the aperture. A similar effect is obtained when both the part and a uniform fiber are tilted. Assuming a fiber tilt of 0.1° (10 nm tilt over 5 μm), and a part tilt of 5 μm across the aperture, the radial form error is 5 nm.

The above mentioned terms contribute about 30 nm to radial form uncertainty when combined in root-sum-squared manner. Experimentally, we have determined repeatability of the order of 60 nm for apertures. We believe that surface finish could be a large contributor, accounting for most of this discrepancy. For a 6 mm diameter aperture, the spacing along the circumferential direction between sampling points (2°) is 105 μm. The spindle has 94,400 counts over 360°. Assuming an uncertainty of 10 counts in positioning (0.05°), the uncertainty in circumferential position is 2.5 μm. We have noticed a radial form of 2 μm for these apertures and assuming a worst case 2 μm radial height variation occurring between two consecutive sampling points spaced 105 μm apart, and interpolating this value for a spacing of 2.5 μm yields a radial variation of 50 nm. A denser sampling with a thin stem will provide better estimates of this term. It should be noted that both roughness of the surface we are measuring and our probe diameter are sufficiently large that tip convolution (mechanical filtering) is a distinct possibility. If there is a "V" shaped indentation in the knife edge artifact where the radius increases by 2 μm at one sampling point located between two points which are at the nominal radius, then the depth of the "V" would be underestimated by 11 nm. This error is small in comparison to our overall uncertainty.

The standard uncertainty in radial out-of-roundness based on two farthest points from the mean circle, each determined with a 62 nm uncertainty, is of the order of 88 nm.

CONCLUSIONS

We have described a technique for roundness measurement using the NIST fiber probe. With this technique, we have measured roundness of precision spheres and knife-edge apertures. The estimated expanded uncertainty in radial out-of-roundness is under 200 nm (k = 2) for knife-edge apertures and under 100 nm (k = 2) for precision spheres. We plan on measuring radial form of 100 μm diameter holes in the near future with our technique.

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