DIAMETER AND FORM MEASUREMENT OF A MICRO-HOLE IN A FUEL INJECTOR NOZZLE WITH THE NIST FIBER PROBE

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INTRODUCTION

We discuss the measurement of diameter and form of micro-holes with reverse tapers in a fuel injector nozzle using an ultra-low force contact fiber probe on a Coordinate Measuring Machine (CMM). The fiber probe was designed and built at the National Institute of Standards and Technology (NIST) and has demonstrated extremely low uncertainties (under 100 nm, k = 2) on high-quality artifacts. We present diameter and form data, and detail an uncertainty budget for the diameter. The dominant terms in the uncertainty budget are related to the poor surface finish and form of the part. Our uncertainty budget indicates that the diameter of a suitably clean micro-hole in a fuel nozzle can be determined to an uncertainty of 196 nm (k = 2) with our probing technique. This uncertainty is primarily related to imperfections in the hole geometry. The measurement principle of the fiber probe and validation results is described in [1]. Fig. 1 shows a schematic of the fiber inside the hole and Fig. 2 shows a photograph of the same. Prior work in this area has been reported [2-6], but their uncertainties appear larger than that from our method.

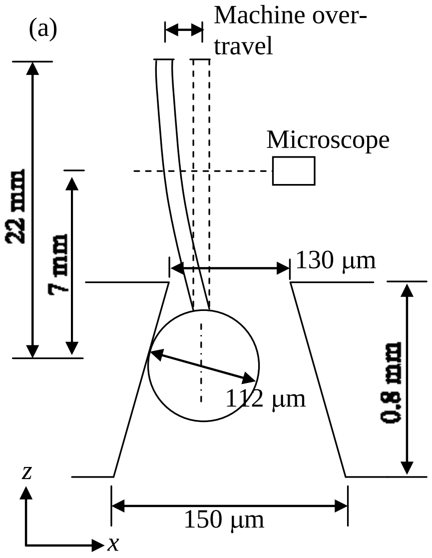


FIGURE 1 Schematic of the fiber probe in the hole

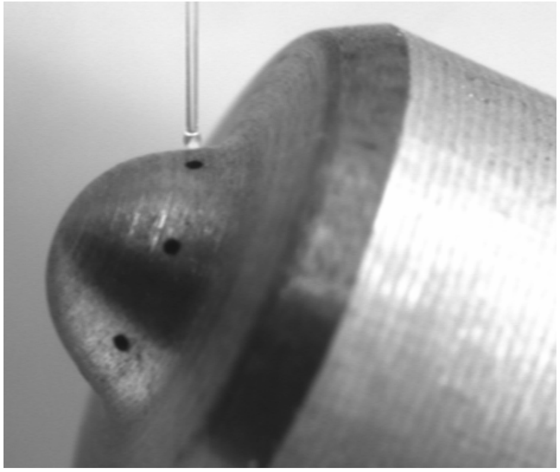


FIGURE 2 Photo of probe entering hole

DIAMETER AND FORM RESULTS

We measured circular traces at 16 different depths inside a hole, and sampled 48 equally spaced points (as 3 sets of 16 points to reduce drift effects) around the circumference at any given depth. We repeated the measurements 6 times and report the average of the 6 measurements as the diameter, see Fig. 3. A least-squares best-fit reference circle is used to compute diameter and radial form.

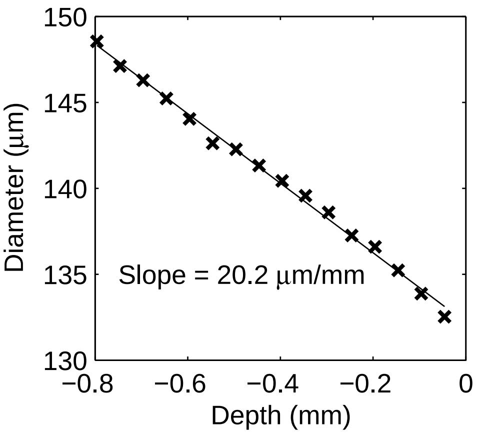
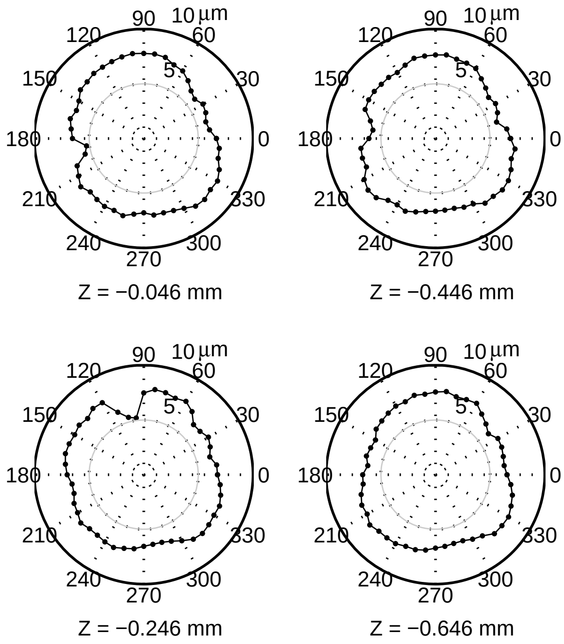


FIGURE 3 Diameter as a function of depth



Z = −0.046 mm Z = −0.446 mm

Z = −0.246 mm Z = −0.646 mm

FIGURE 4 Radial form charts at some of the depths

The radial deviation chart is shown in Fig. 4 for some of the *z* positions. The radial out-of-roundness is between 1 µm and 3 µm for the traces. At several depths, the data shows some features that may possibly be particles of dirt or other machining residue, for example, between 90° and 120° at *z* = -0.246 mm.

UNCERTAINTY BUDGET FOR DIAMETER

The uncertainty budget for diameter measurements [7] is shown in Table 1, followed by a description of the components. The expanded (*k* = 2) uncertainty in diameter is 196 nm. This does not include the effect of dirt or machining debris that may be present. We discuss the effect of dirt on uncertainty in diameter at the end of the next section.

DESCRIPTION OF COMPONENTS

Machine Positioning and Imaging

There is an uncertainty in determining any coordinate in space due to machine positioning uncertainty and imaging uncertainty of the probing system. This uncertainty, 35 nm, impacts every measured coordinate and therefore the diameter of the measured artifact. For a 48 point measurement, the 35 nm uncertainty in a single point measurement results in a 4 nm uncertainty in the determination of diameter. This diameter uncertainty is present for both the master ball and test-hole measurements, and therefore the combined standard uncertainty is 6 nm on diameter.

TABLE 1 Uncertainty budget for diameter

Source	Standard uncertainty (nm)
Machine and probe related	
1. Machine positioning and imaging	6
2. Determining scale factor	14
3. Axis out-of-squareness	5
Part related	
4. Tilt of the hole	1
5. Taper of the hole and error in locating top surface	24
6. Part form and finite sampling	70
7. Surface finish and mechanical filtering	50
Measurement process related	
8. Determining equatorial plane of master ball	1
9. Master ball diameter uncertainty	5
10. Reproducibility of check sphere measurements	30
11. Repeatability of hole diameter measurements	20
Combined standard uncertainty (*k* = 1)	***98***

Determining Scale Factor

There is an uncertainty in determining the scale factor for the probe (the nominal scale factor is 0.1 µm per pixel with 0.0001 µm per pixel uncertainty). For typical operating parameters of the probe, we determine the error in diameter due to this source to be about 10 nm. Because we measure both the master ball and the hole, the combined standard uncertainty in diameter is 14 nm.

Axis Out-of-squareness

The axes of the probing system may be non-orthogonal and misaligned with the machine's axes, and this leads to an error in the measured diameter. The error is larger when the probe size is comparable to the hole size. The nominal misalignment angles of the probing system during the hole measurements were less than -2° (with x axis) and 3.0° (with y axis). Simulations indicate that the error in the diameter of a 130 µm hole measured using a probe of diameter 112 µm is of the order of 10 nm. We correct the measured data (software compensation) for the non-orthogonality and misalignment, and the residual standard uncertainty in diameter is determined to be less than 5 nm.

Tilt in the Hole Axis

The hole is aligned so that there is less than 2 µm tilt over 1 mm. This translates to less than 1 nm error in diameter of the hole at any given depth.

Taper of the Hole and Error in Locating Top Surface

The diameter of the hole changes at the rate of 20.2 µm/mm. Therefore, a 1 µm error in locating the reference point translates to an error of 20 nm in diameter at any given depth. Assuming a ±2 µm uncertainty in locating the z reference and a uniform distribution of errors within this range, the standard uncertainty in diameter is 24 nm. It should be noted that in the normal operation of our probe, we can measure z coordinate to well under 100 nm. But for the measurements reported here, we employed a coarse positioning method of determining z coordinate, and combined with the surface geometry and roughness of the nozzle, we can only detect z coordinate to about ±2 µm.

Part Form and Finite Sampling

A finite sampling strategy in combination with unknown part form leads to an uncertainty in the measured diameter. We have measured 48 sampling points for each circle. Shown in Fig. 5 is the Fourier transform of the part profile. It is apparent from the figure that the dominant harmonics are of low order and are captured by the 48-point sampling strategy.

We have measured the 48 sampling points as three sets of 16 points, and individually determined the least-squares best-fit diameter for each set of 16 points. The pooled standard deviation for an individual 16-point measurement is 120 nm. If this is modeled as a random error, then the uncertainty of a 48-point measurement (three 16-point measurements) will be $(120\ \text{nm})/\sqrt{3} = 70\ \text{nm}$. This value would somewhat overestimate the true uncertainty if there are non-random form errors at the 16th harmonic that are reduced by more than a factor of $\sqrt{3}$ at the 48th harmonic. As described below, there is some evidence from Fourier analysis that this may be the case, but we will nevertheless make the conservative assumption that the errors are completely random. In fact, this assumption is consistent with what we expect if we model higher-order errors as due to random surface variations at each point, where the standard deviation of the distribution is determined from analysis of straightness measurements at high spatial frequencies (straightness measurements are not described in this paper). Thus we may take 70 nm as an estimate of the error arising from imperfect form in combination with finite sampling.

Fig. 5 shows results of a Fourier analysis of the form error. We see that the amplitude of higher order harmonics, say over 15 undulations per revolution, is less than 50 nm. We may reasonably extrapolate to conclude that higher order harmonics, especially the 48th harmonic (which cannot be detected by a 48-point sampling strategy), to be of small magnitude, under 50 nm amplitude.

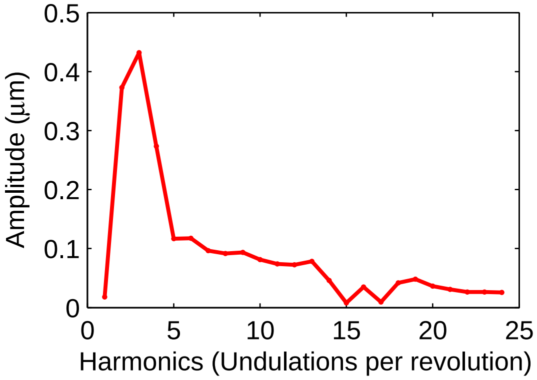


FIGURE 5 Fourier analysis of the average of the sixteen 48-point profiles

Surface Finish and Mechanical Filtering

We have not performed measurements with probes of different sizes and therefore do not have experimental data on the change in diameter due to probe size. Prior studies on other artifacts have indicated that this effect may be of the order of 50 nm. We therefore assign this value as the standard uncertainty in diameter due to mechanical filtering.

Determining Equatorial Plane of Master Ball

Probe ball diameter calibration requires accurately determining the equatorial plane of the nominal 3 mm diameter calibration ball. We can determine the equatorial plane to ±1 µm, and therefore the uncertainty in diameter is about 1 nm. The check sphere is larger and therefore the determination of its equatorial plane is not as critical.

Determining Master Ball Diameter

The uncertainty in master ball diameter is 5 nm. Master ball diameter measurements are performed at NIST using the Strang viewer instrument.

Reproducibility of Check Sphere Data

The long term reproducibility of check sphere (7 mm diameter) measurements has a standard uncertainty of 30 nm. The measurements that make up long term reproducibility sample different table positions, different probe ball sizes etc. It should be noted that part of this term, approximately 10 nm, duplicates other terms already described elsewhere in this budget, but is of sufficiently small magnitude that "double-counting" of the error has negligible effect on the overall result.

Hole Diameter Repeatability

The pooled standard deviation on diameter from the 6 runs at the different depths is approximately 48 nm. The standard deviation of the mean of the 6 runs is therefore 20 nm.

Effect of Dirt, Machining Debris, and Other Protrusions

In some instances, for example in Fig. 4 at z = -0.246 mm, we have noticed that the part profile shows sharp inward protrusions. It is not clear if such protrusions are real surface features (part form error) or dirt/machining debris. If such features are indeed machining debris/dirt, then the computed diameter is in error and the uncertainty in diameter will be larger than that reported earlier. Assuming there is a 2 μm diameter particle spanning two sampling points (somewhat similar to that in Fig. 4, z = -0.246 mm), then this particle will cause a diameter error of about 0.167 μm. Summing this term in quadrature with the previously reported standard uncertainty of 98 nm, we obtain a combined standard uncertainty of 194 nm, or an expanded uncertainty (k = 2) of 388 nm.

Dirt can easily be the largest contributor to uncertainty in diameter. Dirt in the hole will not only increase measurement uncertainty but will also give rise to a bias in the final measurement result. Rigorous application of the GUM would require correcting for this bias, but it is difficult to justify such a correction as we cannot say with certainty that the sharp features that we observe are dirt. Dirt on the calibration sphere would in principle cause an opposite bias, but in practice the calibration sphere is much cleaner than the hole, and consequently dirt on the calibration sphere has very little effect relative to dirt in the hole.

CONCLUSIONS

We discussed the diameter and geometry of one micro-hole measured using the NIST fiber probe in this paper. The hole was tapered and the diameter increased at the rate of 20.2 μm/mm of depth inside the hole. The radial form showed dominant second, third and fourth order harmonics at the different levels. It does not appear that amplitudes of the different harmonics are consistent at the different depths. We had also measured another hole in the same nozzle, and the diameter of this hole increases at the rate 21.4 μm/mm of depth inside the hole. The hole is predominantly oval and maintains the ovality at different depths. It therefore appears that the different holes, although probably manufactured in similar conditions, show different geometry.

Further, we have also noticed sharp protrusions of about 2 μm to 3 μm in size spanning 2 or 3 sampling points that may be surface features (part form) or could also possibly be dirt or machining debris. If such protrusions are dirt/debris, the uncertainty in diameter will significantly be higher. The expanded uncertainty in diameter (k = 2) is 196 nm for most profiles we have measured, but is estimated to be 388 nm when considering protrusions, if present, as dirt/debris.

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