ENHANCED CAPABILITIES OF THE NIST FIBER PROBE FOR MICROFEATURE METROLOGY

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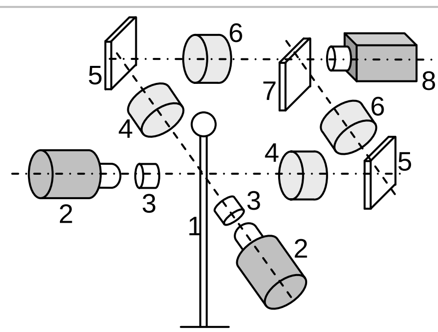
INTRODUCTION

In a previous publication [1] we have described a fiber probe, developed at the National Institute of Standards and Technology (NIST) that is used for coordinate metrology of microfeatures. In this paper we describe two new methods of operation of the probe. The probe, which we refer to as the NIST Fiber Probe, functions by optically imaging the fiber stem from two orthogonal directions a few millimeters away from the ball end of the fiber (see Fig. 1). Upon contacting a part, the fiber bends by a small amount; the magnitude of the deflection at the point of observation indicates the amount of over-travel of the probe. The probe is well characterized and has demonstrated performance of 70 nm (k = 2) for diameter measurements of micro holes (100 µm nominal diameter holes, 5 mm deep). This probe was essentially used as a 2D probe and also only in point-to-point measurement mode. We have since extended the capability of the probe to full 3D measurements and have also made profile measurements in point-to-point and pseudo-scanning mode. We describe these enhancements in this paper.



1. Fiber, 2. Source, 3. Collimating lens, 4. Objective, 5. Fold Mirror, 6. Eyepiece, 7. Thin mirror to split pixel array, 8. Camera

Figure 1: Optical setup for fiber deflection measurement

Z DIRECTION MEASUREMENT CAPABILITY - FIBER BUCKLING TECHNIQUE

In order to measure position along the *Z* direction, we exploit the fact that the fiber is slender and therefore buckles under compressive loading (see Fig. 2). We image only a 100 µm segment of the 20 mm long stem, and consequently this buckling of the fiber appears as a translation of the imaged segment along *X* and/or *Y*. This buckling behavior is experimentally determined to be repeatable (20 nm, one standard deviation) and therefore the vertical motion of the probe tip can be assessed by determining the horizontal translation of the images and using a previously determined calibration factor. We should point out that the fiber is imaged from two orthogonal axes as with the deflection method (only one axis imaging is shown in Fig. 2), and therefore the magnitude of buckling in the plane of bending can be determined.

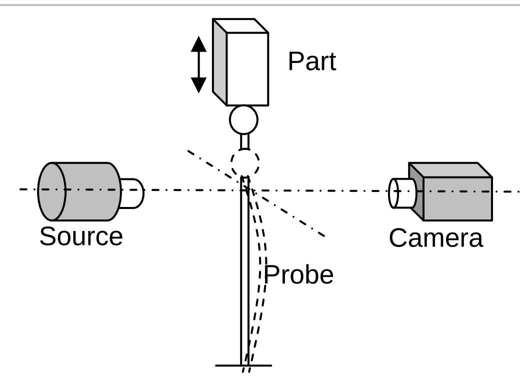


Figure 2: Buckling measurement principle

Because the fiber undergoes extremely large amounts of buckling for very small motion along *Z*, this fiber buckling technique is much more sensitive than the previously reported fiber deflection technique [1]. Fig. 3 shows a plot of the observed translation of the fiber image (in the plane of bending) as a function of motion of the tip along *Z*. From the plot, the sensitivity of the fiber buckling technique is 3 nm/pixel.

Typical sensitivity values for deflection mode measurement are approximately 300 nm/pixel. Therefore, this method yields almost 100 times improvement in sensitivity over the previous method. The measurement range is however reduced; prior knowledge of the location of the surface to within 1 µm is necessary before automatic search for surface location can be commenced.

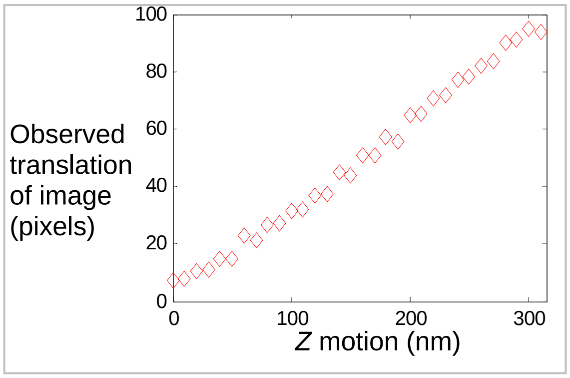


Figure 3: Plot of observed translation of image as a function of motion of tip along Z

Analysis of buckling induced deflection is reported by Stone *et al* [2]. We have measured hemispheres where the pole point was determined in buckling mode while the remaining points distributed uniformly about the hemisphere were determined in deflection mode. The overall sphericity of a ruby sphere (33 sampling points; eight sampling points per circular trace for four traces, and one pole point) was determined to be under 300 nm (one standard deviation repeatability in diameter was 30 nm), which is well within that expected for such spheres. The steepest surface normal was inclined at 22.5° with the probe axis. We are currently conducting experiments on inclined surfaces to determine if a clear transition point exists when the fiber switches from buckling to deflection mode.

PROFILING CAPABILITY – PSEUDO SCANNING BY ACOUSTICALLY EXCITING THE FIBER

Straightness profiles along the vertical direction (for surfaces whose normals are in the *XY* plane; in Fig. 4, the surface normal is along the *X* axis for the gaging surface and the measured profile is along the *Z* axis) can be obtained by simply dragging the fiber along the surface, as is done in traditional stylus profilometry. This method fails for profiles oriented horizontally (for example, a profile along the *Y* axis for the gaging surface in Fig. 4 whose surface normal is along the *X* axis) because the fiber tends to adhere to the surface and remain stuck to the previous sampling position even as the probe is commanded to move to the next position.

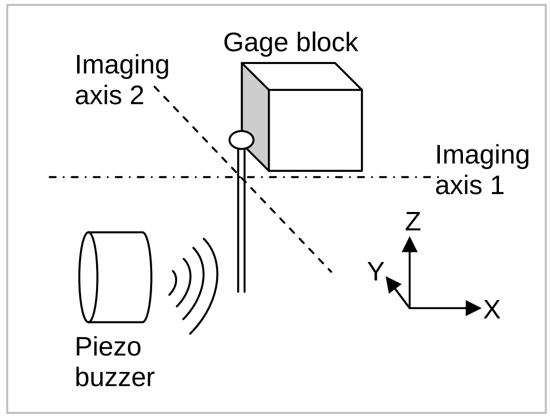


Figure 4: Fiber excited using piezo buzzer

One solution to overcome these attractive forces is to simply retract the fiber from the surface by providing a suitably large motion away from the surface and/or along *Z* before contacting the part at the next sampling location, as we typically do for circular traces inside micro-holes. This method is slow; it takes approximately 40 min to measure a typical straightness trace containing 50 sampling points. To achieve faster scanning, we excited vibrations in the fiber during the motion of the probe from one sampling point to the next to overcome the adhesive forces. To induce oscillations, we use a piezo buzzer to acoustically excite the fiber (see Fig. 4). We use this indirect method of excitation, rather than mounting the probe directly to the piezo buzzer, because it allows us to mount the fiber in a very stable V-groove assembly on a stable base. We did not achieve satisfactory stability of the fiber position when the fiber was mounted directly on the piezo.

A fiber free on one end (not contacting the test surface) and forced to vibrate in the *XZ* plane has several nodes along its length depending on the forcing frequency [3]. It is therefore possible to observe and image the fiber at one of these nodes. However, when the fiber is brought in contact with a test surface, the vibration characteristics change and a stable node is not available for imaging. Therefore, we excite the fiber only during the motion of the test surface and not during the imaging. We refer to this method as vibration assisted pseudo-scanning.

We have experimentally noticed that the fiber can stick to the surface, and will remain stuck even when the base of the probe is retracted away from the surface by as much as 400 µm. For our fiber made of glass (Young's modulus E = 80 GPa), this maximum deflection of 400 µm translates to a force at the tip of approximately 3 µN, and a stored energy of $e = \frac{1}{2}(\frac{3EI}{l^3})y^2$ [3], numerically equal to 6×10^{-10} Nm. (Here y is the deflection of the tip and l is the fiber length.) In order to break the bond via vibration, it will be necessary to provide this same force and energy, and hence it will be necessary to vibrate the probe with about 400 µm amplitude. We see experimentally that this cannot be achieved unless the driving frequency is near to a resonance frequency. Near resonance we observe extremely large amplitudes of vibration, of the order several hundred micrometers, and the fiber is able to overcome the attractive forces.

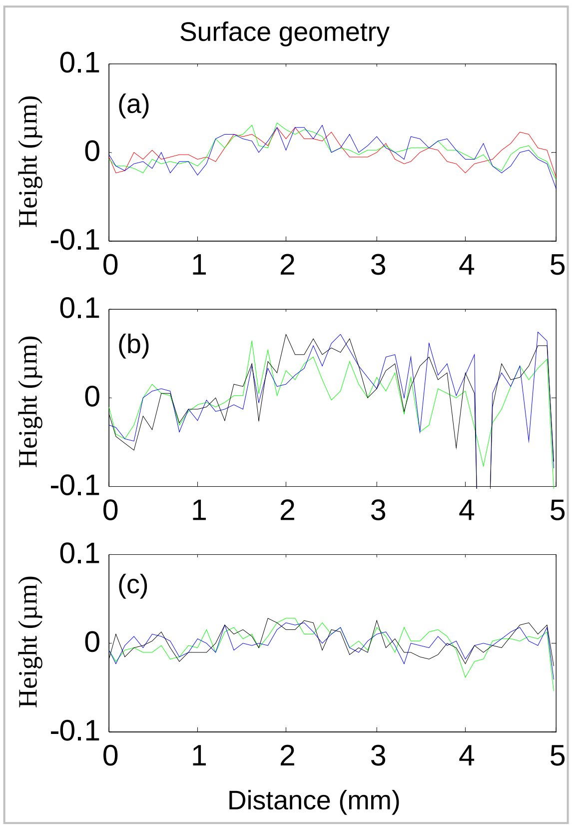


Figure 5: Surface geometry - three methods (a) point-to-point mode (bench marking technique), (b) dragging but no vibration (c) vibration assisted pseudo-scanning

Fig. 5(a) shows the actual surface geometry as detected by the active axis of the probe, in point-to-point mode (fiber retracted from surface before contacting next sampling point). Fig. 5(b) shows profiles obtained by dragging without any vibration, and Fig. 5(c) shows profiles obtained by vibration assisted pseudo-scanning. It can be seen that the data from the vibration assisted scan has a similar straightness value to that obtained with a point-to-point mode scan (≈ 75 nm), but dragging in absence of any vibration is quite noisy (≈ 200 nm after excluding large outlier).

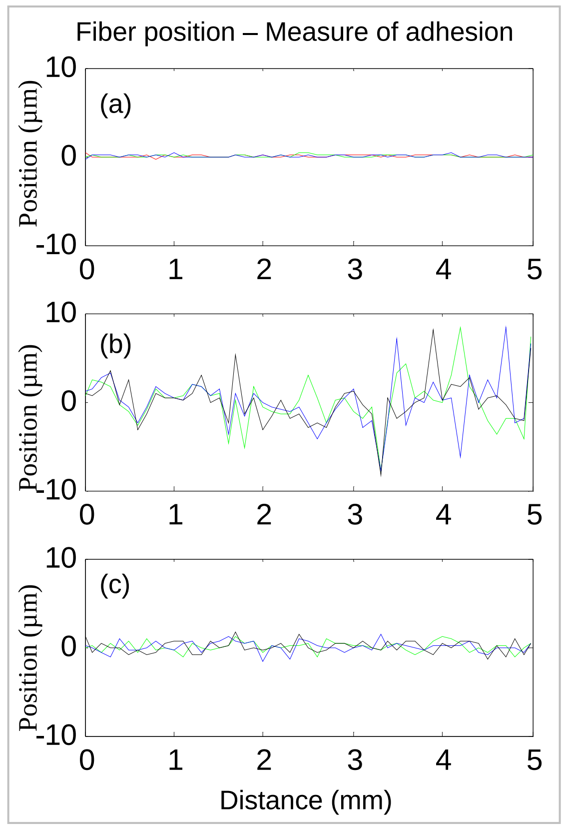


Figure 6: Fiber position for three measurement methods (a) point-to-point mode (bench marking technique), (b) dragging but no vibration (c) vibration assisted pseudo-scanning

Fig. 6 shows plots of the non-active axis (position along the surface in the direction of measurement; and therefore a measure of surface adhesion) in the three modes of measurement (point-to-point, dragging but no vibration, vibration assisted pseudo-scanning) of the fiber probe as the fiber traverses the block. In these plots, the fiber must ideally remain at a neutral position and not bend along the direction of motion. When the probe is removed from the surface before each sampling point as in Fig. 6(a), the fiber always remains at the same unbent position. However, when dragged along the surface in absence of vibration (Fig. 6(b)), the fiber sticks to the surface and releases, resulting in significant noise. In the presence of vibration (Fig. 6(c)), the magnitude of this noise decreases considerably.

It takes only 10 min to acquire a profile (such as those in Fig. 5(c) with 50 sampling points over 5 mm length) by pseudo-scanning (a factor of 4 savings in time), and with no significant degradation in performance in comparison with our traditional fiber deflection measurement method (point-to-point measurement); therefore this technique holds considerable promise.

In its current configuration, the vibration assisted pseudo-scanning method appears to be a 1-D probing technique and is ideal for profile measurements. We have not attempted a circular scan on a CMM with this probe yet. In all our experiments, the fiber has been forced to vibrate in and out of the surface (*XZ* plane in Fig. 4). The effect of vibrating the fiber in a plane parallel to the gaging surface (*YZ* plane in Fig. 4) has not yet been investigated. We are currently exploring the possibility of adapting this probing technique in a roundness measuring machine configuration where the part is mounted on a precision spindle, to measure roundness of micro-holes.

CONCLUSIONS

We have discussed two enhancements to our fiber probing capability in this paper. First, the fiber buckling technique in combination with the fiber deflection technique allows our probe to function as a true 3D CMM probe. Second, acoustically excited vibration assisted pseudo-scanning technique allows our probe to acquire straightness profile data in any orientation (not necessarily vertical profiles). These enhancements expand our capability for micro-feature metrology

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