Development of High Aspect Ratio Microscale Force Probes

Marcin B. Bauza[1], Shane C. Woody[1], Robert J. Hocken[2], Stuart T. Smith[2]

[1]*InsituTec Inc., 2750 East W.T. Harris Blvd, Suite 103, Charlotte, NC, USA, 28213*

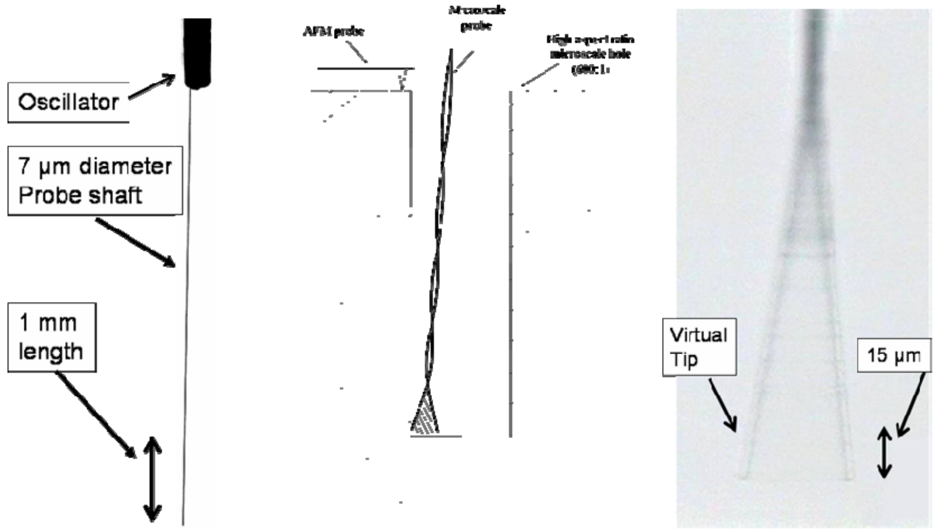
[2]*Center for Precision Metrology, UNC Charlotte, 9201 University City Blvd, Charlotte, NC, USA, 28223*

Abstract

High aspect ratio microscale features such as diesel injector spray holes, air foil cooling holes in turbine blades, optical fiber ferrules, medical devices, and ink jet remain a challenging measurement problem. In particular, federal laws have been placed upon off-road diesel engines to lessen particulate output by 95% and NO_2 by 90% by 2008 [1]. The same report cites that reducing emissions from off-road diesel engines may prevent 8,522 premature deaths in the US per year and save up to \$67 billion annually. One of the key challenges in the automotive industry is to optimize the diesel injector's nozzle (i.e. atomized spray into the chamber). Generally, the nozzle consists of a circular array of holes which range in size from 50-200 µm in diameter with depths up to 3 mm. One of the key challenges is to measure the three dimensional geometry of these holes such that manufacturers may validate computer models and continue to optimize the product function. Current probing techniques both optical and contact based do not provide high aspect ratio (300:1 or better) measurement capabilities. Industry desires probe geometries less than 10 x 10 μm^2 in cross section and lengths of 3-5 mm to achieve measurement of the high aspect ratio microscale features described above. This remains a challenging metrology design problem within this field. The objective of this paper is to describe a unique probing concept referred to as a standing wave probe with a virtual tip. Advantages and disadvantages of this methodology are outlined and preliminary results discussed. Based upon this design concept, high aspect ratio probes (600:1 and greater) with high sensitivity, high bandwidth, minimal adhesive interactions and a contact radius below 7 µm have been developed and are presented in this paper. The report further overviews the development of the microscale probes integrated into a precision scanning roundness gage attached to a Moore™ 1.5 metrology machine in a temperature controlled environment.

Methodology

Previously, researchers in this field have attempted to attach micro-spheres to the end of a shaft to produce a rigid CMM type probing system. The objective of these designs was to provide a single point of contact between the probe tip and workpiece as well as prevent the shaft from "shanking" against the sidewall of the workpiece. This type of approach has been problematic, partly because it is challenging to attach or monolithically fabricate spheres on the end of a microscale shaft. Alternatively, investigators at InsituTec Inc. together with UNC Charlotte's Center for Precision Metrology have developed a new methodology which does not require a sphere but rather uses the shaft's harmonic resonances [2], Figure 1. As shown in these figures, a 7 µm diameter shaft (carbon fiber in this case study) with a 5 mm free length is bonded to one prong of a crystal oscillator tuning fork, Figure 1(a) and Figure 2(a). The tuning fork is operated at a first mode natural frequency of 32.76 kHz which consequently excites higher harmonics within the cantilevered shaft. As illustrated in Figure 1(b), the higher mode of the shaft results in the end of the probe tip oscillating beyond the diameter of the shaft thus eliminating the need for a sphere. As shown, the single directional oscillation of the shank causes a point on the free end to move in a one dimensional locus, which together with the surface of the oscillating shank at its free end defines the virtual probe tip. Furthermore, the amplitude oscillation located at the end of the shaft is a function of the signal applied to the tuning fork. Therefore, reducing or increasing the amplitude of the carrier wave to the tuning fork will result in reducing or increasing the amplitude at the end of the fiber. As a result of this characteristic behavior, this methodology is referred to as a standing wave probe with a virtual tip.



(a) (b) (c)

Figure 1: Images illustrating the concept for the standing wave probe and virtual tip (a) microscopic photograph of the 7 µm diameter and a 700:1 aspect ratio shaft attached to a crystal oscillator (b) illustration of the virtual probe tip contacting a workpiece sidewall (c) magnified image of the virtual tip

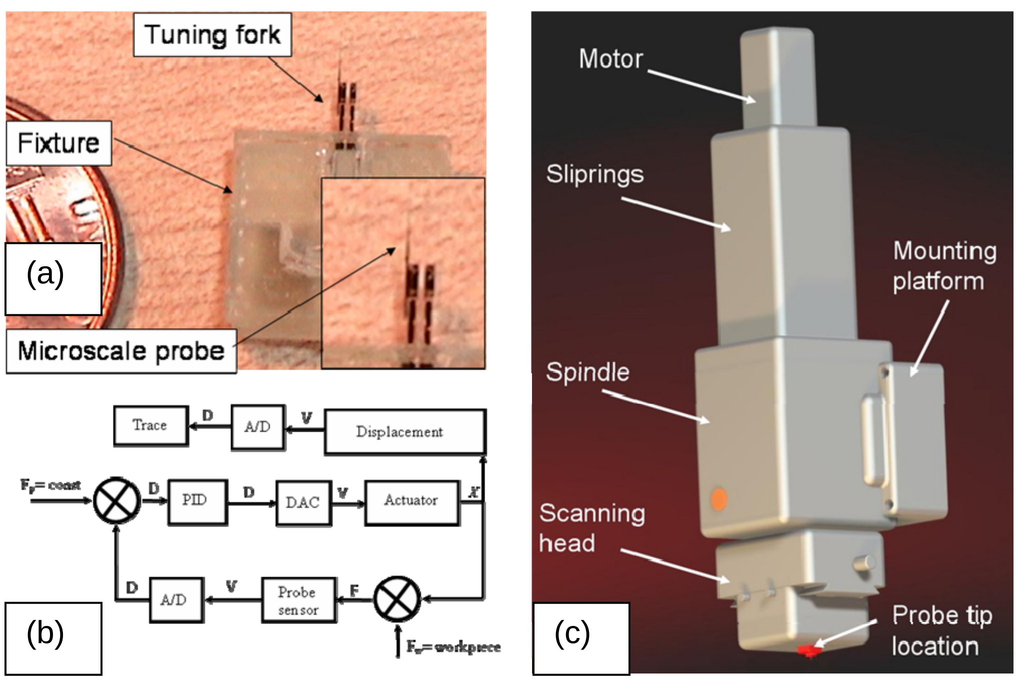


Figure 2: Images of the microscale probe and roundness gage (a) photograph of a tuning fork with a bonded probe (b) simplified control diagram (c) simplified solid model of the roundness gauge

Based upon previous work in macroscale roundness gaging [3], a high bandwidth scanning head designed with a single degree of freedom motion along the radial direction, Figure 2(c) has been used. As illustrated in this figure, the scanning head is attached to a precision spindle and rotated. In this methodology the measurement head is rotated rather than rotating the workpiece. For roundness measurement on large holes, a conventional flexure-based force sensor is attached to the scanning head. Attached to the force sensor is a standard CMM probe which contacts the side wall of a circular feature

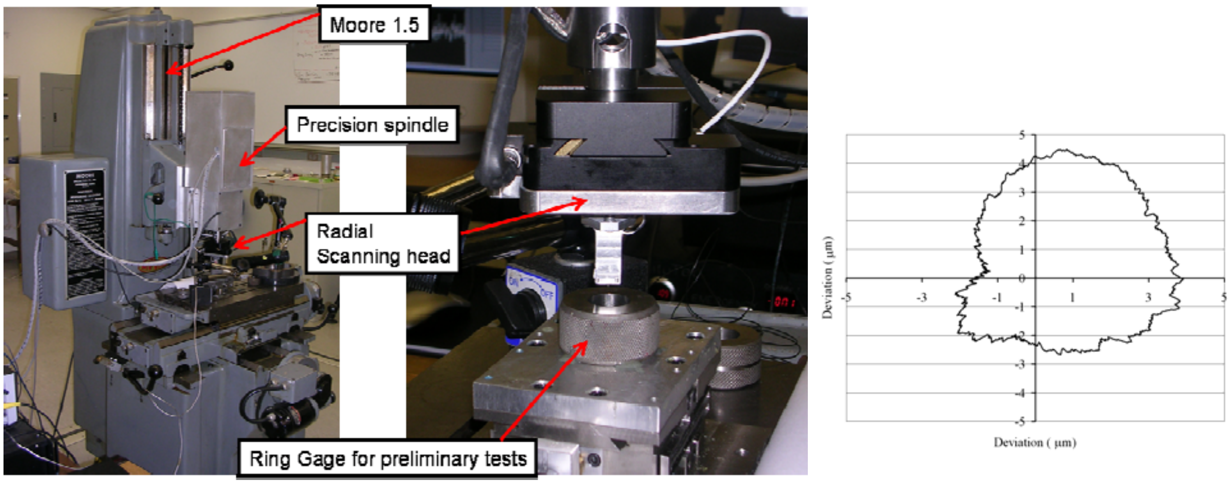
(OD or ID). As shown in the simplified controller algorithm in Figure 2(b), the force sensor signal is transferred into the summing junction of a PID controller referenced to a fixed set-point value representing the force during scanning. The output from the PID algorithm is transferred to a high voltage amplifier and then to a piezoelectric actuator which serves to displace the scanning head. Thus, the objective of the scanning head is to maintain a constant applied force between the probe tip and workpiece. A displacement sensor tracks the position of the scanning head relative to a fixed frame in the scanning head and is synchronized in real-time with the spindle's rotary encoder. Similarly, this methodology may also be applied to scanning microscale features. In this case, the conventional force probe is replaced with the microscale probe described above. The signal from the microscale probe is obtained in the following manner; first, a sensor on the tuning fork is used to detect a signal change when the probe tip interacts with the surface of a workpiece. A surface mount phase locking circuit is employed wherein the 32.76 kHz frequency is locked and the changes in phase, amplitude or products thereof are measured. The standing wave exhibited in the shank has the greatest sensitivity along the direction of oscillation. In this case, the oscillation of the microscale probe is oriented normal to the workpiece wall and remains normal as the scanning head is rotated.

Experimental Test Stand and Results

For these investigations, a precision spindle design was developed. This new axi-symmetric spindle design incorporates a robust housing, frameless motor, Heidenhain rotary encoder, and in-house slip-rings, Figure 3(a) and 3(b). The completed spindle assembly provides nanometer level asynchronous errors and is designed without air, Figure 3(c). Presently, the scanning head operates with a range of 55 μm and is calibrated with an HP laser interferometer 5518A. The scanning head's displacement sensor provides 2 nm of resolution with a 3 kHz sampling rate and the accuracy is better than 0.01% over full range. Next, the microscale probes are fixtured to the scanning head and the sensitive axis is oriented normal to the scanning head's motion. The completed assembly is rigidly attached to a Moore 1.5 located in a temperature controlled environment. The Moore provides two linear axis precision slideways for horizontally aligning the workpiece with respect to the center axis of the spindle and a *Z* axis for moving the probe into the hole to be measured. A National Instrument's compact RIO™ is used to provide a digital PID to control the spindle motion and provide amplitude demodulation for the in-house capacitance sensor located in the scanning head. Additionally, the Heidenhain encoder provides 16,348 counts per revolution and is digitally synchronized with the displacement sensor.

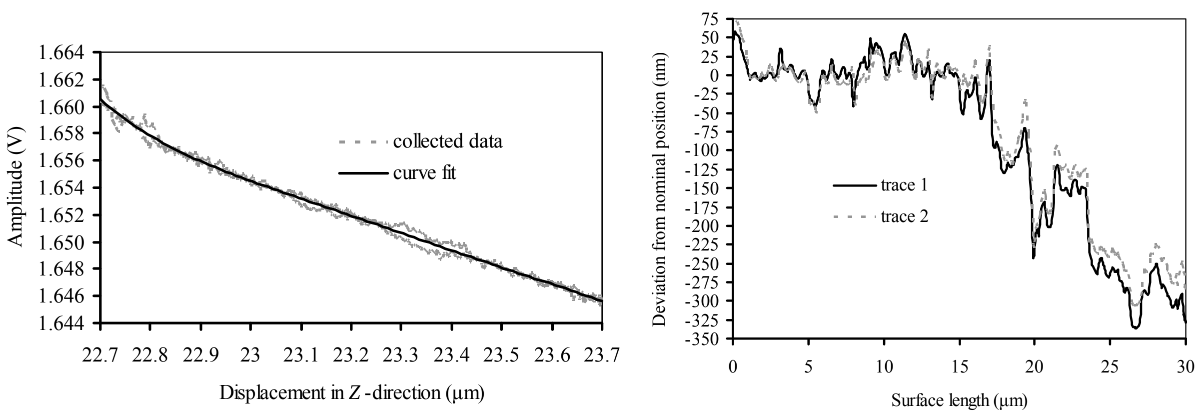
Calibration of the probe tip is necessary to determine sensitivity and functionality in scanning mode. To do this the probe translator was operated in open loop control. After translating the probe tip radially to come in contact with a gauge block surface, the probe is ramped through a displacement of 1 μm and the corresponding probe signal measured, Figure 4(a). A calibration is obtained from this measurement using a third order polynomial curve fit. The presented calibration chart indicates a sensitivity of approximately 14 mV μm^{-1}. The theoretical stiffness for the carbon fiber probes is very small at approximately 650 $\mu N\ m^{-1}$. As a result of this low compliance, the contact forces generated between the workpiece and probe are estimated to be less 1 μN. However, the probe's compliance leads to inherent susceptibility to air flow currents and as a result an enclosed chamber has been built around the scanning head and workpiece (not shown in the photographs). Based upon previous results [3], the probes are capable of measuring electrically conducting and insulating surfaces of solids having almost arbitrary compliance. Other microscale probe systems (such as the ones described above) adhere to dielectric surfaces. This adhesion is due to electrostatic, van der Waal, adhesion, and meniscus forces in the presence of surface liquid films. The standing wave probe appears to be insensitive to these surfaces. Moreover, these earlier experiments used the microscale probes in a profilometer instrumented configuration where the virtual tip was scanned linearly across a gauge block surface, Figure 4(b). As shown, the repeatability of the measurement is observed to be within ± 5 nm.

During the next several months, the microscale probes will be employed on the roundness gage described. The first initial tests will evaluate large scale holes such as the ring gauges and then microscale scale features less than 200 μm will be evaluated at different depths. Furthermore, the standing wave probes will need to be characterized for long term repeatabilility and sensitivity. A 5 degree of freedom nanopositioning platform is being evaluated and may be implemented. The objective is to align the workpiece's circular features (cylindricity and concentricity) relative to the precision spindle and microscale probe. Next, the probes will evaluate form error of various holes having diameters as low as 50 µm versus depth of the hole. Subsequent experiments will also evaluate functionality of the probes as a function of environmental conditions (i.e. air currents, thermal gradients and susceptibility to external vibrations).



(a) (b) (c)

Figure 3: Photographs of the experimental test stand (a) Moore 1.5 located in a temperature control laboratory with an accompanying precision spindle and radial scanning head (b) close up view of the scanning head and the probe is attached to the end of the scanning head (c) asynchronous data measured by a Lion Precision™ spindle analyzer



(a) (b)

Figure 4: experimental data (a) sensitivity of the probe vs. displacement (b) two linear scans traversed over a 30 µm surface

[1] Report issued by STAPPA and ALAPCO, Regulating Air Pollution from Diesel Truck: A Model Rule for States (July 2001), http://www.4cleanair.org/DieselTrucks.pdf

[2] M.B. Bauza, R.J. Hocken, S.T. Smith and S.C. Woody, The development of a virtual probe tip with an application to high aspect ratio microscale features, *Rev. Sci. Instrum.* (2005), submitted

[3]M.B. Bauza, S.C. Woody, S.T. Smith, R.J. Hocken, P. Jain, *Precision Enginering* (2005), submited