High Aspect Ratio Sensors with an application to microscale metrology

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1.0 Abstract

Measurement of high aspect ratio microscale features such as holes and channels remains a challenging metrology problem. For example, to assess a high aspect ratio small hole it is common to cut away a cross section and measure the features of interest using an AFM, SPM, or SEM. Typically, these metrology tools may be suitable for surface finish measurement but often lack the capability for dimensional metrology measurement over these feature sizes.

A novel probing methodology referred to as a standing wave force probe will be presented and experimental work reported. In general, the probes are designed with a high aspect ratio (up to 700:1) probe shanks, fabricated with a 7 µm diameter, and attached at one end to an oscillator. The oscillator produces a standing wave in the probe shank and as a result the free end of the shank generates an amplitude of oscillation greater than the probe shank diameter. Thus, the probe does not require a spherical ball to serve as the contact point and simply uses the contact diameter of the free end of the vibrating shank. Moreover, as a result of the standing wave's inertia the mechanical contact interactions are able to overcome attraction forces. The aim of this report is to discuss a variety of measurement results which have been obtained. In particular, we will report the measurement results for high aspect-ratio microscale holes. The features measured have diameters ranging from 128 to 500 µm and depths up to 2 mm. A constant force methodology is utilized to ensure low contact forces (<10 nN estimated). The scanning methodology enables a high sampling rate (14,250 data points) per circular trace and high repeatability of local features (< ±10 nm). During the conference session, we expect to report results on uncertainty estimates and further performance analysis. Some of these additional experiments include the probe's signal variation as a function of environmental conditions, sensitivity variations as a function of contact angle, and assessment of touch triggering along the longitudinal and lateral directions.

2.0 Summary

Micromanufacturing is becoming more mainstream with applications ranging from the medical industry for bioMEMS to diesel injectors for automotive industry, Figure 1. Many of these application areas have high aspect ratio features exceeding 20:1 (i.e. depth of feature compared to width of feature). In order to measure within these features such as microscale holes for example, a new class of sensor and tool is required. First, this manuscript only considers contact based sensors because the known state of the art in optical techniques are currently unable to measure inside microfeatures (less than 50 µm).

Considering contact based methods, the sensor's contact diameter typically should be at least 10 times smaller than the feature of interest. This is necessary in order to measure asperities and form on the feature. Consider a 50 µm hole having a length of 2.5 mm, which is the state of the art for a diesel injector spray holes. In this case, the sensor should be approximately 5 μm in diameter with a free length of over 2.5 mm therefore has a 500:1 aspect ratio. Furthermore, conventional methods typically require a microsphere on the end of the stylus in order to ensure a defined contact region. As a result, the shaft is typically smaller in diameter than the sphere tip and therefore will increase the aspect ratio even higher.

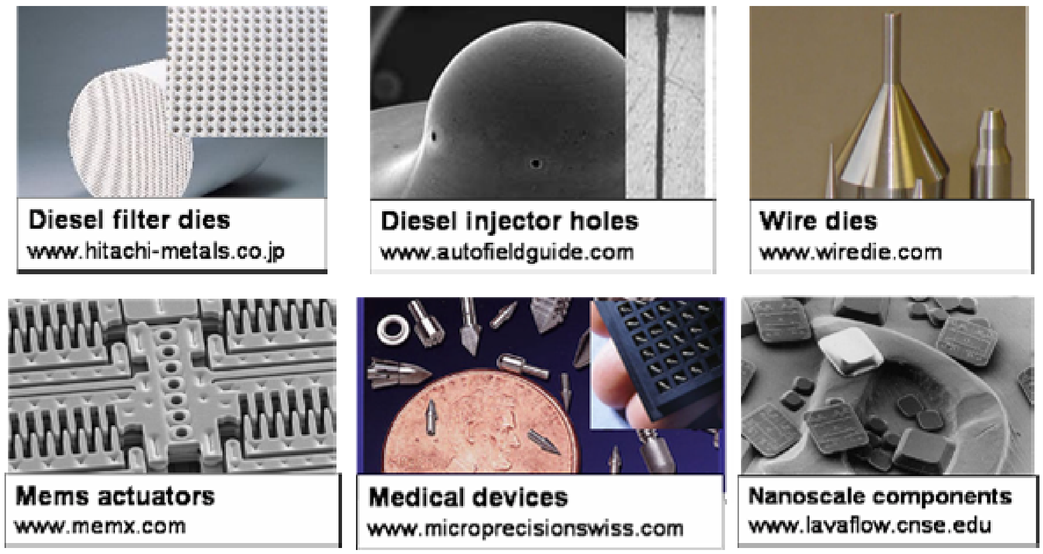

Figure 1: Photographs of applications requiring high aspect ratio microscale probes

At the microscale level, attraction forces such as electrostatic, meniscus, and adhesion forces will significantly influence contact based sensors. Figure 2(a) plots attraction forces versus contact radius of the sensor (approximated as a sphere) while interacting with a surface. As shown, the two dominant forces are adhesion and meniscus forces. Typically, adhesion forces are only present when surfaces are extremely clean and flat. As a result, meniscus forces will tend to dominant as an attraction force. Considering this, a 2.5 μm radius (such as the example above) in the presence of meniscus force will adhere to the surface with an attraction force of 2.4 μN.

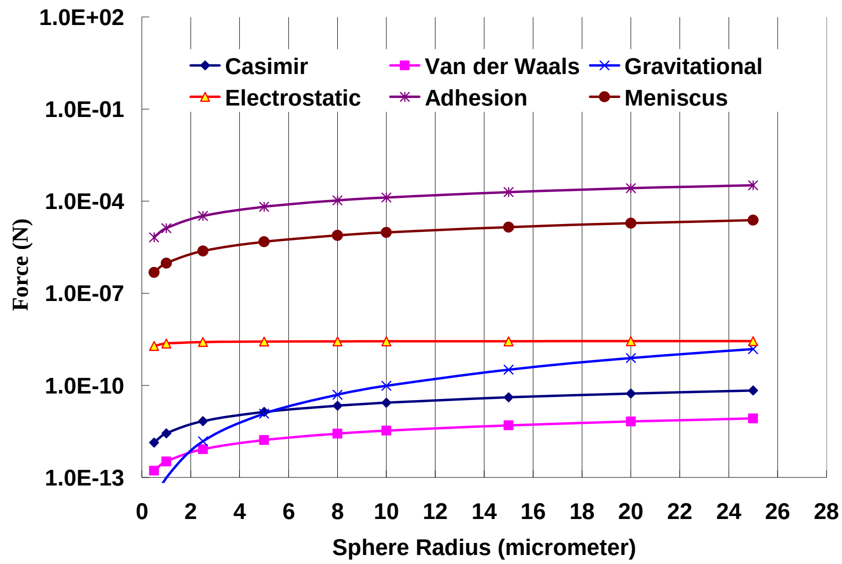

Figure 2: Attraction forces vs. contact radius

Currently, attraction forces are a dominant problem with high aspect ratio static sensors. Many technologies attempt to mitigate this problem using a conventional touch triggering method. Essentially, the sensor is brought into close proximity with the surface and a trigger signal is generated once the sensor is 'snapped' or attracted against the surface. One disadvantage in this type of method is extremely slow because the sensor must then be pulled away from the surface and moved to the next location. As a result, the methodology does not allow scanning capabilities where the sensor has the inherent capability to continuously scan along a workpiece feature surface.

3.0 High Aspect Ratio Force Sensors employing a standing wave

This paper addresses a novel approach referred to as a standing wave force sensor which uses an oscillating beam's inertia to overcome attraction forces. A method co-developed by the authors and Center for Precision Metrology at Charlotte generates a standing wave sensor exhibiting a virtual probe tip on the end [1], Figure 3(a). In general, the sensor is a carbon fiber filament approximately 7 µm in diameter with a free length ranging from 3 to 5 mm (depending upon the application). This provides an aspect ratio of 430:1 to 714:1. The fiber is attached to one tyne of a crystal oscillating tuning fork having a natural frequency at 32.768 kHz [2], [3]. Depending upon the length of carbon fiber, a standing wave with 1 or more modes will be generated along the longitudinal axis of the carbon fiber. As shown in the figure, a carbon fiber with a 3 mm free length produces 3 modes at this drive frequency. Moreover, the virtual tip on the end produces a larger amplitude compared the rest of the fiber length.

The standing wave methodology provides several advantages. First, the virtual probe tip is oscillating at approximately 32 kHz and the high inertia provides the capability to overcome attraction forces. Secondly, the virtual tip's amplitude is programmable and the pk-pk drive signal transferred to the tuning fork may either be increased or decreased which will subsequently cause the virtual tip to be either increased or decreased. Finally, the virtual tip has the inherent ability to swing further out from the shaft and therefore may be used to directly contact the side wall of the micro feature during measurement. As a result, the need for a microsphere on the end is not required and the contact interaction between the virtual tip and surface is defined as the contact radius of the fiber.

The tuning fork provides both actuation to the carbon fiber and detects changes in signal from the carbon fiber. A phase lock loop (PLL) circuit is employed wherein the tuning fork is locked onto a desired part of the characteristic response and the changes in frequency, phase, amplitude, or products thereof are measured. Once in contact, the PLL integrator signal changes the natural frequency to maintain a constant phase relationship. Typically, the frequency of the carrier signal is only changed by up to a few Hz during contact measurements and this is not currently monitored.

One disadvantage with the configuration is the sensor generates a 1D oscillation and therefore is sensitive in one direction only. As a result, the 1D sensor should be maintained normal to the surface of interest by employing multi-degree of freedom positioning system. The following section describes the use of this sensor in conjunction with a novel roundness gauging tool to measure microscale holes [4].

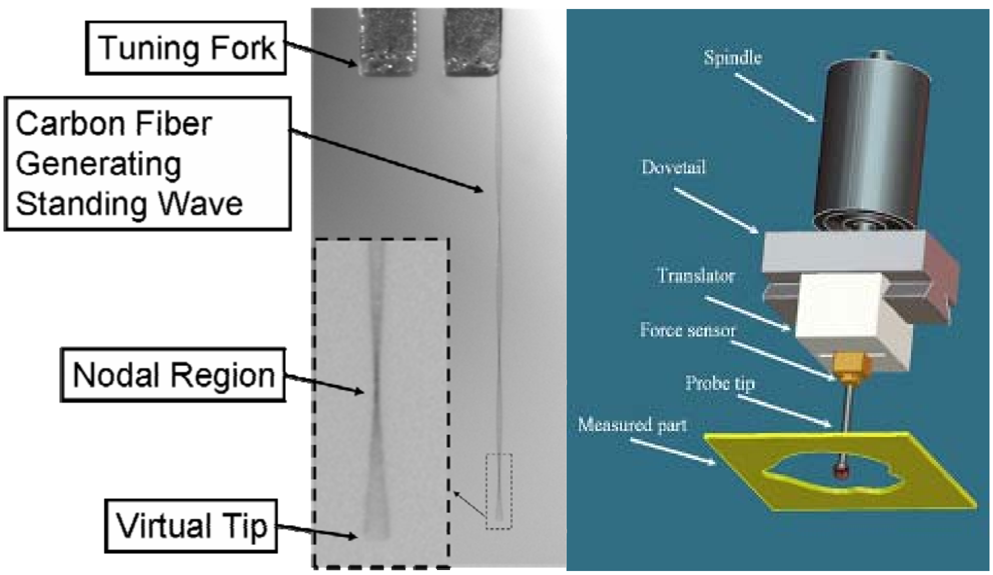

Figure 3: Configuration for a 1D high aspect ratio force sensor (photograph illustrates a fiber length of approximately 3 mm (b) illustrates using the 1D sensor in conjunction with a radial translator and precision spindle to obtain a roundness measurement of a microhole

4.0 Experimental Apparatus

Investigations were undertaken to measure microscale holes using the 1D sensor. A simplified illustration is shown above with a circular hole, sensor, servoing stage, and precision spindle, Figure 3(b). First, the sensor is attached to a nanopositioning stage with the ability to servo along the radial direction with respect to the circular feature. The stage is then attached to a precision spindle which enables the sensor to remain normal to the surface while rotating 360 degrees. The sensor is locked at a constant applied force using the nanopositioning stage and rotated about the hole. During this scanning operation, the stage changes displacement to maintain constant force. Next, a displacement sensor embedded in the positioning stage is used to track the relative motion of the stage and then synchronized with a rotary encoder embedded inside the spindle. Roundness measurements are obtained by synchronizing both the encoder and displacement sensor signals which are then transferred to a host computer. The following section discusses some brief experimental data obtained thus far and further data is anticipated to be discussed during the conference session.

5.0 Experimental Data

The first experiment for the scanning mode evaluated a 500 µm diameter glass ferrule, Figure 4. As shown, the spindle speed was 0.12 RPM, and the scan depth was 1.5 mm. Approximately 29 data points per second were collected. The data is scanned twice and it can be seen in the plot that the two data traces are very repeatable. To further evaluate the repeatability a sectioned view is shown in Figure 5 which indicates the local features repeatability is within ±10 nm.

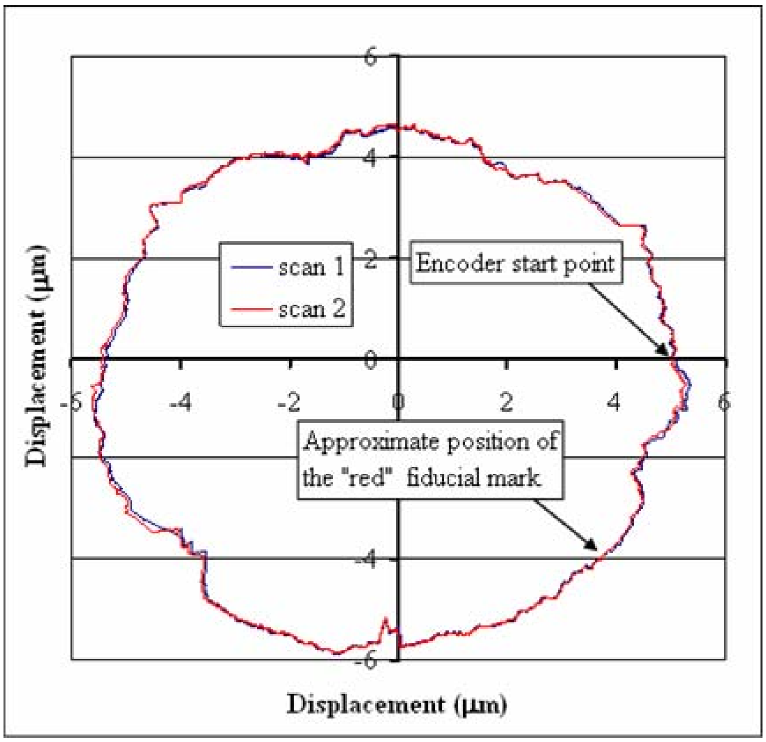

Figure 4: Circular profile is represented by 14,250 data points collected at scanning speed of ~0.12 RPM (6.3 µm s^{-1}), and a bandwidth of 20 Hz. The scanning depth is ~1.5 mm.

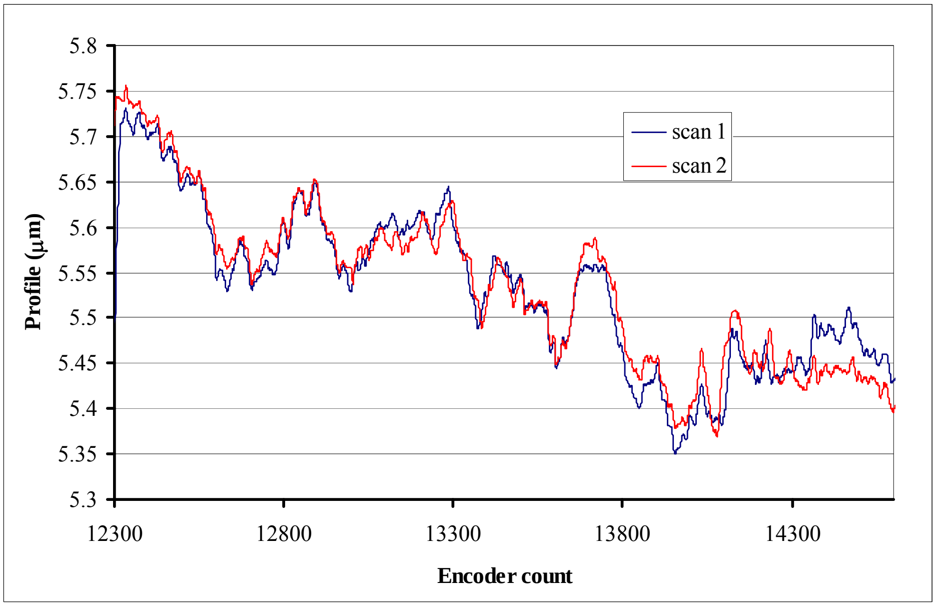

Figure 5: Linear plot showing a small portion of the plot in Figure 6 indicating repeatability between two separate traces

A second experiment inserted the standing wave probe inside a 128 µm diameter hole and scanned the surface, Figure 6 and Figure 7. Again, a repeatability of ±10 nm is observed in local features of the plot. This data also shows a radial error motion of the spindle as great as 50-60 nm. This resulted from a mechanical coupling component located inside the spindle and will be improved in future generations of the spindle. The total depth for both of these experiments was at approximately 500 µm. Investigators did not proceed to measure further depths for this 128 µm because sufficient alignment mechanisms were not available. Alignment mechanism will be implemented in later studies.

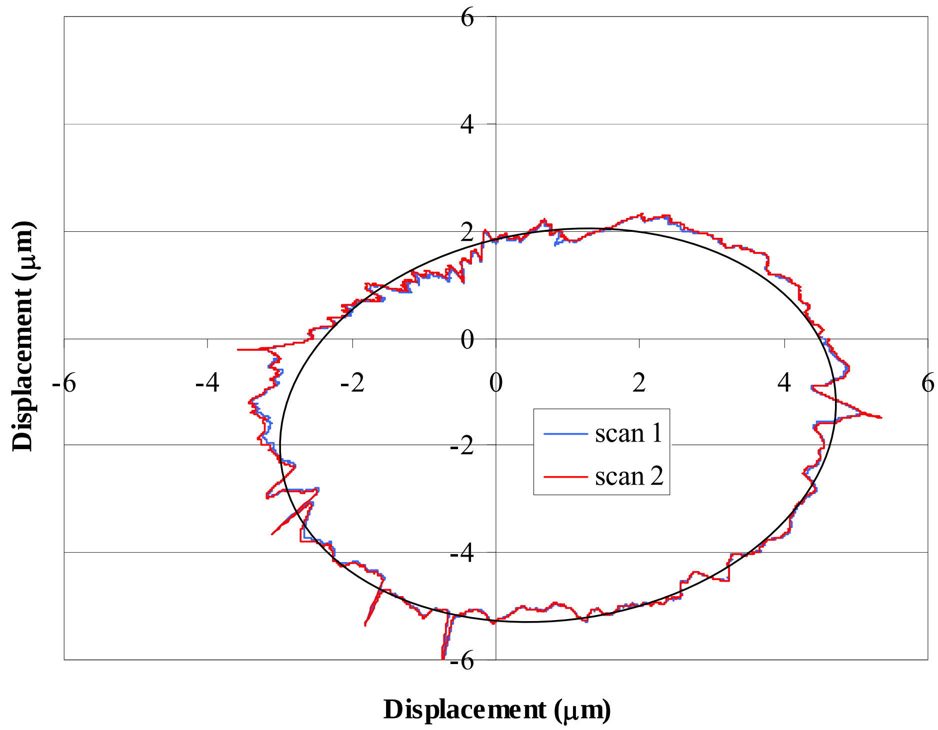

Figure 6: Form error measurements for the 128 μm diameter hole scanned twice.

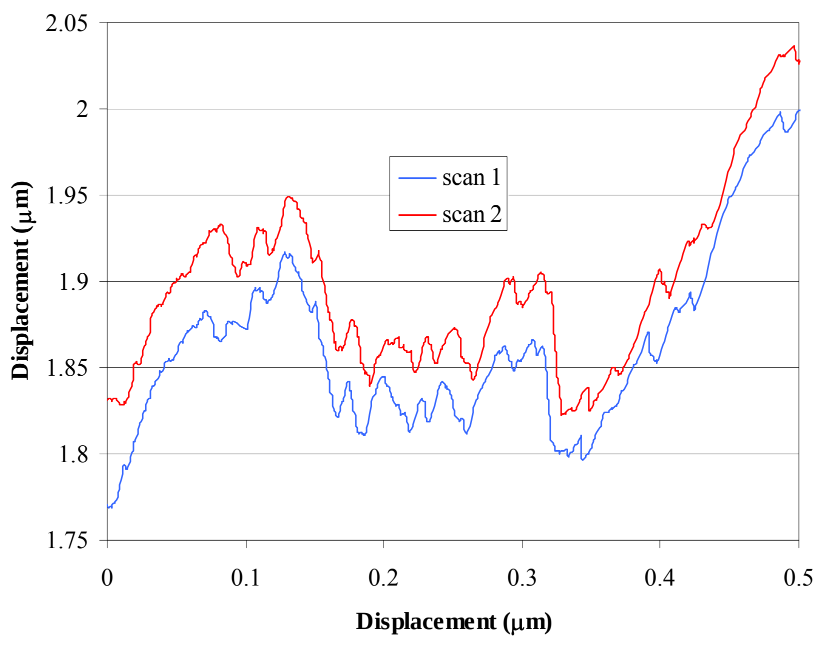

Figure 7: Portion of the scan of the 128 μm hole showing repeatability between two traces.

6.0 Next Steps

Authors are currently working on a 5 axis alignment stage to provide the capability to align the standing sensor with smaller holes. Additionally, a new generation spindle and scanning unit are under construction and expected to be tested and reported during this conference.

7.0 Acknowledgements

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8.0 References

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