3D Surface Profilometry Employing Standing Wave Probes

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Abstract

This manuscript summarizes some of the recent investigations using a microscale standing wave probe for 3D surface profilometry. The probe is ∅7 µm, 3.5 mm in free length, and can scan surfaces resulting in surface finish and form in the same data set. The objective of this paper is to discuss the principle operation of this sensor in conjunction and to present experimental data using a precision thread as the case study. The affect of the probe oscillation direction with respect to the part surface on the results is discussed.

Keywords: 3D surface profilometry, microscale, high aspect ratio, standing wave probes

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1. General Overview

This manuscript addresses a novel sensor, the Standing Wave Sensor, to enable advanced 3-D measurements for microscale and nanoscale manufacturing. The demand for new and more versatile micro and nanoscale measurement products has been driven by the increasing miniaturization and precision of components across a wide range of products and industries that include; medical components, turbine blades, electronics, free form diamond turned parts, optics, diesel injector nozzles, and many more. Manufacturing these products requires the ability to measure geometric features at the micro or nanoscale and this demand will continue to grow as manufacturing processes continue to miniaturize. Existing measurement technologies are unable to meet the current and future micrometrology needs in these industries/devices. Specifically, they suffer several critical deficiencies

1) limited in their ability to measure deep, narrow features
2) multiple measurement tools are required to measure form, waviness, and roughness and
3) complete inability to measure some very small scale parts and features.

True 3D metrology which measures both surface finish and form is nonexistent in nanoscale and microscale applications. The classical coordinate measuring machine (CMM) traditionally accommodates larger workpiece features on the order of 1 mm or above and traditional CMM probing technologies are unable to measure surface finish and form. Additional technologies such as scanning electron microscopes (SEM) and scanning probe microscopes (SPM) are considered 2½D measurement devices. Furthermore, many of these fall short when attempting to measure high aspect ratios, Figure 1. As the lateral dimension decreases and the vertical dimension increases (i.e. high aspect ratios of 100:1 or greater) there is really no practical tool for measuring such features.

CMMs are used for dimensional metrology and are the most common traceable method providing true 3D measurement capability. The state of the art in CMM techniques employs touch triggering (intermittent contact) or scanning as the contact interaction based measurement technique. Each of these methods uses a probe tip with an attached sphere as a reference for workpiece measurement [1] making it difficult or even impossible to measure microscale features.

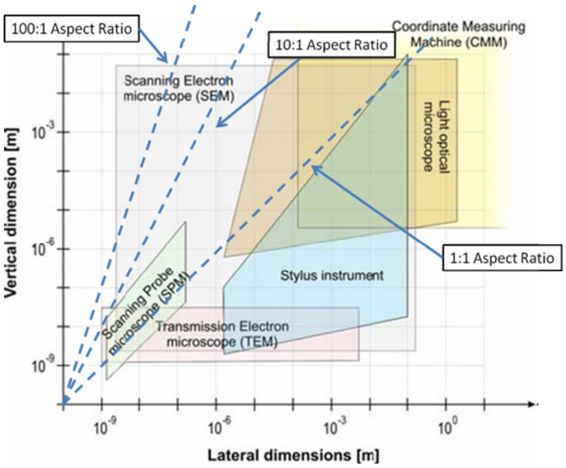

Figure 1: Measurement instruments for dimensional micro and nanometrology, modified based on [2] to show transition to different aspect ratios.

In recent years, a number of new sub millimeter probe tip designs and methodologies have been developed [3]. However, many small 3D structures require probe tip contact diameters of only a few micrometers in size to provide the ability to resolve small spatial features. Current manufacturing processes for macroscale probe embodiments cannot be easily scaled down to micro and nanometer scales. Additionally, adhesive and other interactions between the workpiece and contacting probe tip at the nanometer and micrometer feature level are significant [4]. Generally, these adhesion forces reduce the accuracy and repeatability of microscale scanning probes. Correspondingly, at these scales, the related frictional forces introduce uncertainties due to structural distortions caused by the interaction between the probe tip and workpiece surface. Moreover, contact forces of many of these touch probes are often greater than 1 µN and for small probe tip radii can elastically or even plastically deform the measured surface [5].

The standing wave sensor discussed in this manuscript has been previously reported to measure 1D and 2D form measurements [6]. However, the work here discusses a unique approach to using the standing wave sensor for 3D surface profilometry which implies measuring both surface finish and form in the same data set. A brief summary of the principle of operation for both the sensor and the machine integration is provided. Measurement data is presented for a precision thread. Finally a discussion on limitations and capabilities of the current system is presented.

2. Standing Wave Probes: Principle of operation

The sensor technology comprises a small microscale fiber which is ∅7µm up to 3.5 mm in length providing aspect ratio of > 500:1. The fiber is vibrated using a quartz crystal oscillator which produces a pronounced mechanical standing wave in the fiber, Figure 2. The image further shows the fiber modulating at 32 kHz while simultaneously exciting a pronounced bending mode in the fiber. A pronounced mechanical wave is shown in the image which is programmable up to 100 µm pk-pk . The standing wave is tuned such that the free end moves the greatest distance laterally compared to any location along the rod, providing a method by which the tip will contact a specimen before the shank. As a result, there is no need to attach a micro-sphere on the end and moreover the contact interaction is defined as a function of the stylus radius. Still further, the input signal parameters, amplitude, frequency, and phase are adjustable providing a programmable oscillation amplitude at the free end ranging from a few micrometers up to several tens of micrometers [7]. Most importantly, the dynamic forces generated in the probe stores enough energy to overcome adhesive interactions and will not stick to the surface being measured. The ability to overcome these attraction forces enables higher precision measurements as well as the ability to continuously scan surfaces.

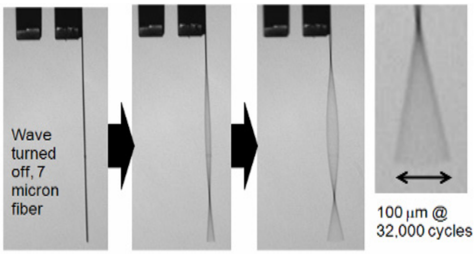

Figure 2: close up view of standing wave fiber operating in mode 2 with a free length of 1.6 mm

The mechanical oscillator uses a tuning fork with the ability to mechanically excite and sense. The signal output from the tuning fork is a sinusoidal signal which is demodulated and used as a force signal during contact. A nanopositioner is used to position the probe against a gauge block surface and the probe signal and position are recorded, Figure 3. This chart shows the sensitivity of the probe's signal with respect to the contact position. The reader should observe a smaller slope prior to contact and a larger slope after contact occurs. The results are startling indicating both a non-contact region with a sensitivity slope of 5 mV/µm RMS and a contact region with a sensitivity slope of 59 mV/µm RMS. We believe the non-contact interaction occurs due to the inherent nature of the standing wave tip. Essentially, the tip is modulating back and forth at a rate of 1 m/s velocity. As a result, air flow between the tip and workpiece is being pushed in and out between the tip-workpiece interface and possibly causing squeeze film damping to occur. In future studies, we will explore this non-contact region; however, this report uses the contact region for scanning parts.

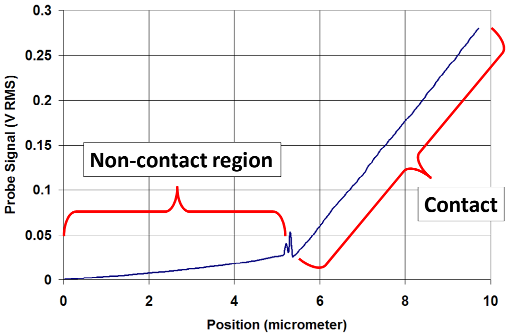

Figure 3: Sensitivity slope showing probe's sensitive signals for non-contact and contact.

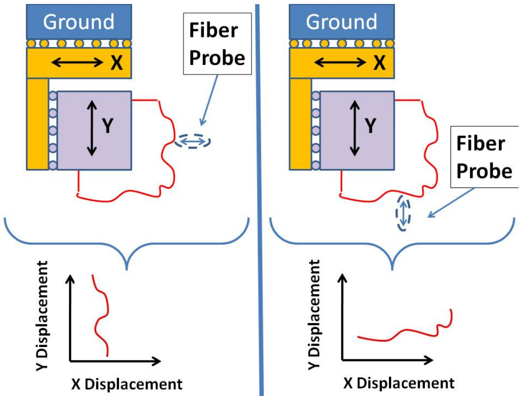

Figure 4: Illustration using 2 axis linear stage and the fiber probe (a) servo controls X-axis to fiber probe signal and Y-axis is traversed (b) fiber probe is rotated 90 degrees and Y-axis is servo controlled to force signal and X-axis is traversed

The probe signal described above is then used as a feedback signal with precision linear stages for closed loop scanning. A simple illustration is shown to describe how we obtain multi-dimensional measurements using a two axis linear stage assembly combined with a fiber probe, Figure 4.

3. Experimental Setup

Figure 4 is dependent upon both the stages and fiber probe to be highly accurate and repeatable. Therefore, selecting both the right precision mover is important as well as the capability of the fiber probe. The fiber probe enables ability to measure inside very small features, scan continuously against the surface, and extract both surface finish and form. The complete experimental apparatus selected for this project is shown below comprised of a 5 axis mover, Moore 1.5 test bed, a nanometer spindle, and the standing wave fiber probe, Figure 5.

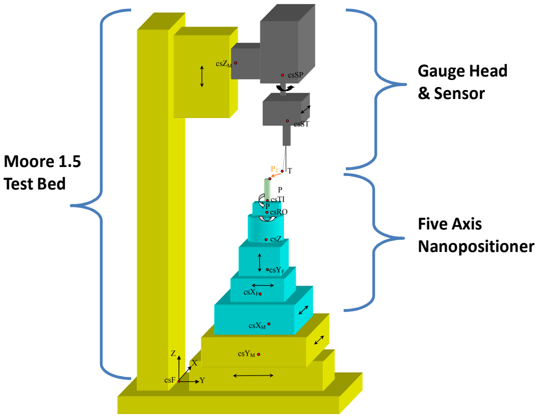

Figure 5: Schematic of experimental test bed

The Moore 1.5 test bed is equipped with a course vertical axis motion and two horizontal *XY* motions. The 5 axis mover is retrofitted on top of the Moore XY platform. The mover selected for this study is a 5 axis positioning system, the FiberMax, from Aerotech™. The FiberMax has good positioning repeatability but not high accuracy. Nonetheless, we were able to modify the controller algorithms to externally accept the fiber probe signal. This led to a number of experiments for three dimensional metrology investigations. It is important to note the test bed has an inherently large metrology loop and hence is more prone to thermal drift. To mitigate the influence of thermal drifts, the experimental test bed is housed in a temperature controlled to 0.1° C.

4. Experimental Data

Experimental measurements are demonstrated on a threaded part having a major OD of 3.48 mm. Although this seems large for microscale manufacturing, the thread pitch is 0.6 mm and measuring inside the thread cavity is challenging. Moreover, measuring surface finish on the face of the threads is even more challenging. A total of 6 scans are performed as shown in Figure 6. This figure shows a three dimensional plot of the profiles comprising the thread profile as well as linear scans of the front face and back face of the part. Using the precision spindle the probe's sensitive axis was oriented normal to the front face or rotated by 90 degrees to scan the thread. Moreover, the left and right threaded profiles are measured at the center of the thread. From this, the major OD, minor OD and thread pitch are calculated. Historically, a thread is typically measured using a 3 wire method. The fiber probe provides a more accurate representation of the pitch.

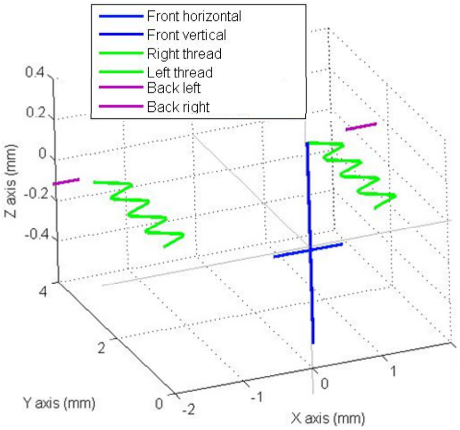

Figure 6: 2D profiles of a thread, each trace is continuous with points spaced every 5 µm

Next, the back right shoulder of the thread is scanned twice with the part removed from the fixture between scans, Figure 7. The part is moved along the X-axis and the servo control is provided by the Y-axis. The two runs show submicron repeatability. This scan shows the capability of the probe to measure surface finish along any surface of the part. The waves exhibited on the surface are machining marks. The roughness and waviness are calculated as follows, Ra=0.25µm, Rq=0.30µm, Wa=0.10µm and Wq =0.14µm which are in units of micrometers.

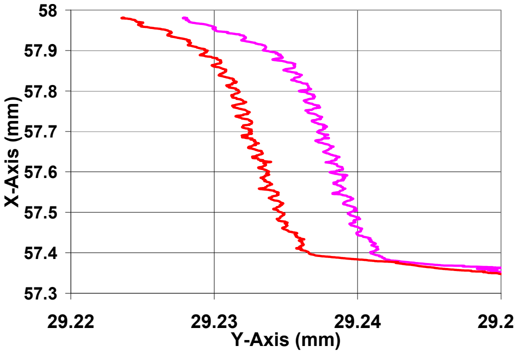

Figure 7: A horizontal scan of the back right shoulder

Next, a study was undertaken to assess surface finish measurements as a function of different probe angles. To accomplish this, a flat ground surface was scanned at angles up to ±20° from normal. The surface finish and waviness parameters are calculated for each data set, and presented in Figure 8. In this figure it can be seen that that surface roughness, Ra and Rq, will diverge once the probe is 10° from normal. The waviness parameters, Wa and Wq, do not diverge as quickly with respect to the probe angle.

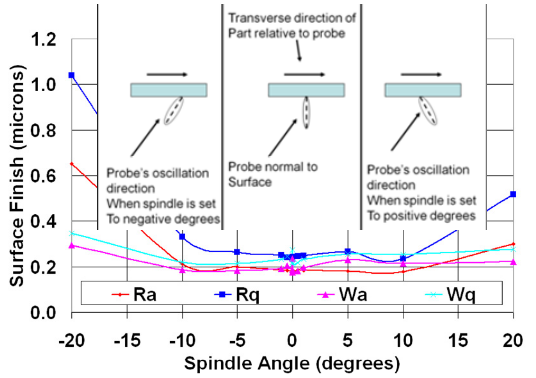

Figure 8: Assessment of probe angle vs. surface roughness and waviness

The study described above provides an indication of the probe's ability to measure surface finish for steep angles or gradients. It also shows the importance of the need to keep the probe normal to the surface. Microscale thread profiles are a classic example where probe angle with respect to the part surface will affect the accuracy of the results, specifically the surface finish and waviness measurements. Figure 8 shows the probe's oscillation direction with respect to the part surface while scanning the thread profile. The servo control is provided by the X-axis stage while the part is moved in the Y direction. The positive and negative angles of the thread profile appear to the probe as a steep angle of nearly 60°. Based upon Figure 8 described above, the surface finish measurements calculated along the surface of these threads will be inaccurate. However, the form measurements are not as sensitive to the oscillation direction and hence could be evaluated in greater depth.

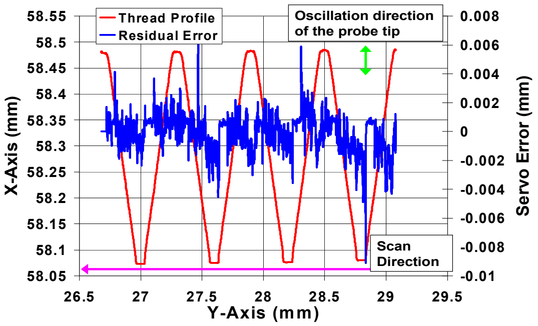

Figure 9: Thread profile scan and the residual error between two consecutive scans

4.1. Surface Finish

Several scans were performed without removing the part from the fixture. Figure 9 shows the measured thread profile and the residual error between two consecutive traces. As indicated in Figure 6, the left and right thread profiles are both measured in one setup. From this data the major diameter, minor diameter, thread pitch, and surface finish can be determined.

5. Conclusions

One of the tradeoffs with this approach is the fiber probe is required to be rotated at different angles using a precision spindle. In the current experiments, the spindle is rotated such that the probe is normal to the surface and then held stationary during the measurement sequence. However, algorithms are envisioned which would enable the spindle to rotate during the scanning sequence. In the case of either scenario, the tradeoff with the spindle-probe methodology is the probe will be offset from the concentric axis of the spindle. A significant uncertainty error would generally be introduced into the measurement if the spindle's error motion is high. However, we are employing a nanometer repeatable spindle of which an asynchronous error motion is better than 10 nm. This leads to the ability to error map both the spindle and probe error motions.

When considering measurement data of a surface there are three elements to consider, form, waviness, and roughness. Each measurement gives different information about a part or surface. Because of their different requirements, each measurement requires a different measurement tool. The standing wave sensor will enable 3 distinctly different measurements to be made on one measuring machine, eliminating the need for multiple tools.

This work has clearly shown that the standing wave sensor technology provides the ability to make unprecedented measurements on micro and nanoscale features. The unique sensor differentiates in that it

- has a high aspect ratio giving the ability to access deep, narrow features that cannot currently be measured.
- has a minimal contact force (on the order of 100 nano-Newtons)
- has nanometer precision and repeatability.

In addition, because of the small size of this sensor, it provides the ability to measure small scale parts and features, many of which currently cannot be measured.

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