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Surface profilometry of high aspect ratio features

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ABSTRACT

Three-dimensional surface profilometry of microscale features such as high aspect ratio holes, pins, channels, gears, threads and more complex geometries such as free form, convex and concave shapes remain challenging metrology problems. Existing profilometers are designed to measure easy accessible surfaces with macroscale dimensions, while microscale features are usually assessed with, SPM, and optical methods. Continuous miniaturization and increased complexity of manufactured components requires new profilometry methods that enable co-ordinate metrology as well as surface metrology. In this paper a new class of tactile sensing probe referred to as a standing wave sensor has been assessed for such applications. The probe is 7 μm in diameter and 3.5 mm in free length, and is incorporated into a scanning system capable of measuring surface texture and form in the same data set. This paper discusses the principle of operation of this sensor and presents example data obtained from measurements of surface texture standards, a precision thread, and form and surface texture of 128 μm hole.

1. Introduction

Characterization of surface topography on specific features of mechanical workpieces with complex geometries presents a significant challenge. Such requirements occur across a wide range of products and industries that include: medical components, turbine blades, electronics, free form diamond turned parts, injection molding dies, optics, diesel injector nozzles, and many more. Metrology needs for this class of parts are characterized by the desire to scan large areas of the surface located at significant distances from each other on the part in order to properly characterize the quality of the component. Another significant challenge is access to the relevant features such as in the case of high aspect ratio, microscale parts.

There are two measurement classifications to consider in metrology which are co-ordinate metrology (component geometry, surface profilometry) and surface metrology (i.e. roughness and waviness). Each measurement gives different information about a part function. As both part tolerances and feature size decrease the significance of the surface relative to the function of the part has become more important. Also, because of their different requirements, each measurement type (surface texture vs. form) generally requires different metrology tools. Existing tools available to industry and researchers are often characterized by an amplitude wavelength map shown in Fig. 1 with the aspect ratios between 1:1 and 100:1 highlighted [1].

Scanning stylus instruments are characterized by large range to resolution ratios but are limited to the micrometer regime and 1:1 aspect ratios. Contact forces of many of these stylus based instruments are often greater than 1 μN (typically 1 mN for a conventional stylus instrument), and for small probe tip radii, can elastically or even plastically deform the measured surface [2]. Tools such as scanning electron microscopes (SEMs) and scanning probe microscopes (SPMs) are generally used for measurements on the smaller dimensional scales, but are only capable of scanning small areas and have very limited aspect ratios. These devices are generally considered 2½ D measurement devices, meaning that only portions of the surface can be accessed and characterized. The classical coordinate measuring machine (CMM) is the most common, traceable method for dimensional metrology providing true 3D measurement capability. However, CMM dynamic capability and probe geometry are not suitable for surface texture measurements [3,4].

As the lateral dimension decreases and the vertical dimension increases, all of the tools shown in Fig. 1 fall short in their measurement capability for one reason or another. In 2002 Lonardo et al. [5] analyzed the emerging trends in surface metrology and concluded that “there is a clear need to produce a new tool for true 3D characterization of surface topography suitable for quantitative characterization of surface featuring steep slopes, abrupt contours, re-entrances, and high aspect ratios.” As a solution to the above problems hybrid techniques have been suggested in the literature [5–7], including combining an AFM and a CMM [8].

This manuscript addresses a novel probing technology, which when integrated with a CMM can provide true 3D dimensional

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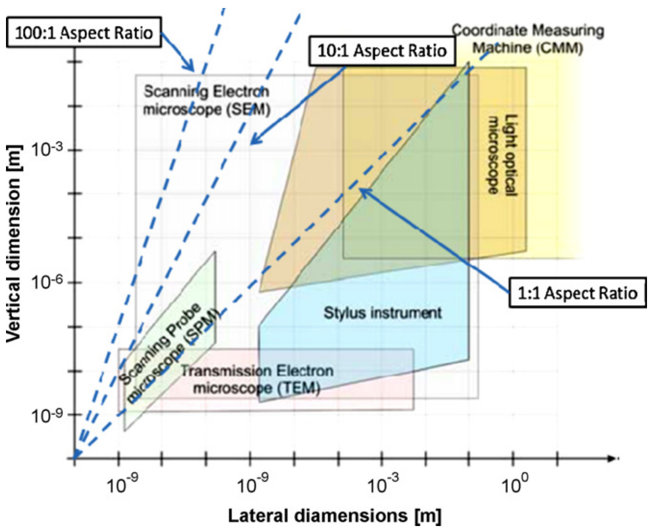

Fig. 1. Measurement instruments for dimensional micro- and nanometrology (after Hansen et al. [1]).

metrology and surface texture in the same data set. The standing wave sensor discussed in this manuscript has been previously reported to measure 1D and 2D form measurements [9,10]. However, the work here discusses a unique approach to using the standing wave sensor for 3D surface profilometry. A brief summary of the principle of operation for both the sensor and test bed is provided. Measurement data is presented for a precision thread, a microscale hole, and surface texture standards. Finally, a discussion on limitations and capabilities of the current system is presented.

2. Principle of operation

The sensor technology comprises a small microscale fiber which is 7 μm in diameter and up to 3.5 mm in length providing an aspect ratio of 500:1. The fiber is vibrated at 32 kHz using a quartz crystal oscillator which produces a pronounced mechanical standing wave in the fiber, Fig. 2. The contact force calculated based on beam bending theory is approximately 20–50 nN [9]. The standing wave is designed 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. The standing wave's amplitude is highly stable and programmable

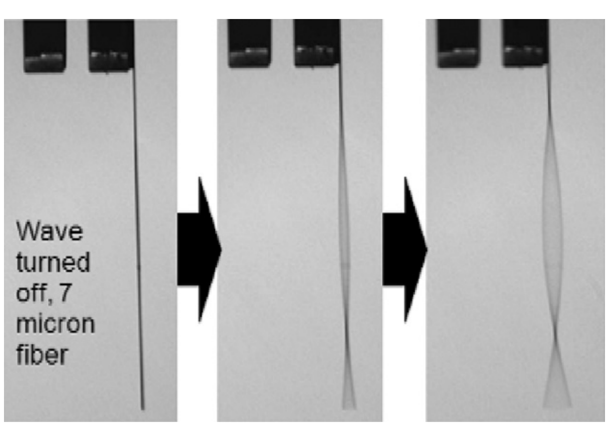

Fig. 2. Close up view of standing wave fiber operating in mode 2 with a free length of 1.6 mm.

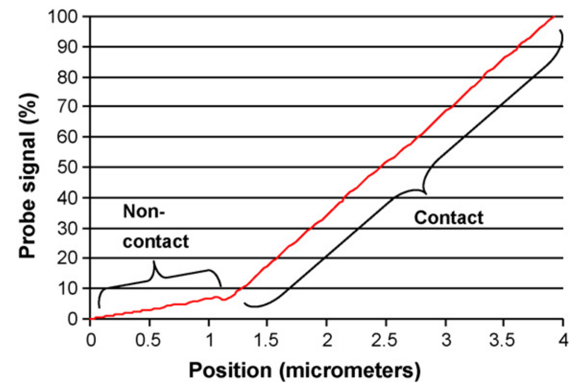

Fig. 3. Sensitivity slope vs. preload.

from a few micrometers up to several tens of micrometers [10]. Most importantly, the dynamic forces generated in the probe store enough energy to overcome adhesive interactions and will not stick to the surface being measured [11]. The ability to overcome these attraction forces enables higher precision measurements as well as the ability to continuously scan surfaces. The typical signal characteristic of the probe showing the probe response versus bending distance is shown in Fig. 3. To achieve this graph, a gauge block is retrofitted to a nanopositioner and moved into close proximity with the standing wave probe. The probe's signal is simultaneously tracked with the position of the gauge block. As shown, the probe generates two sensitivity modes, non-contact mode (mainly used for very delicate surfaces such as aerogels) and contact mode with greater sensitivity slope. In the following experiments, the probe's contact mode is employed during measurements.

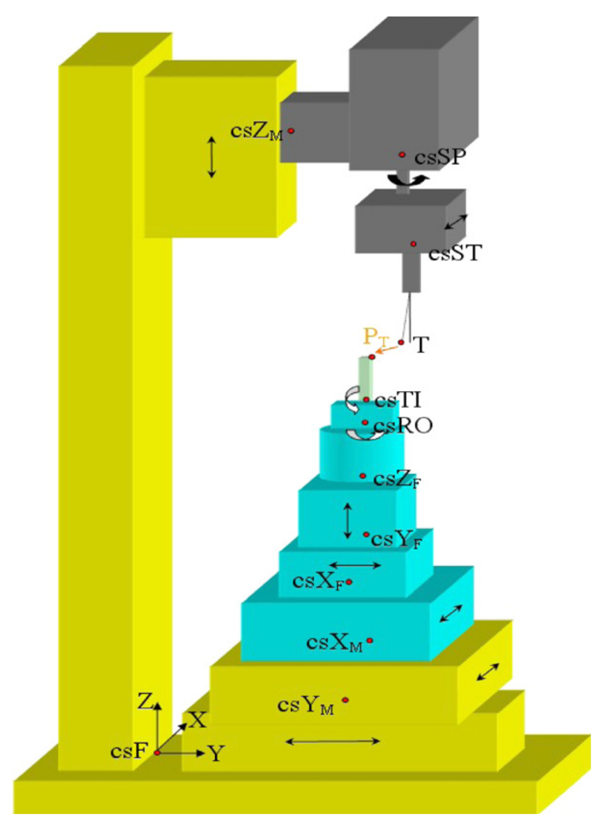

Fig. 4. Block diagram representation of test bed used during experiments.

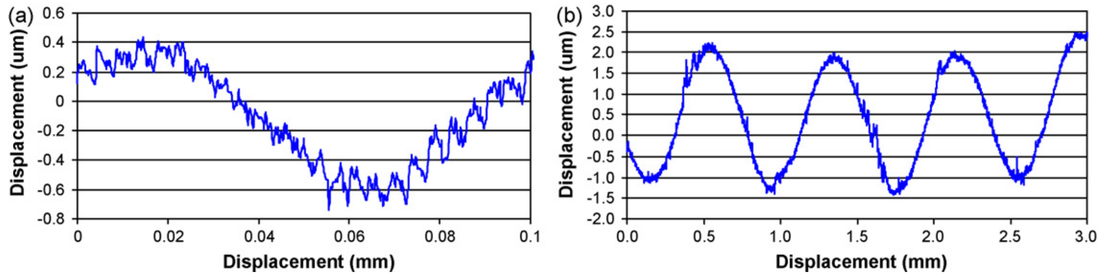

Fig. 5. (a) Zoom in data of NIST prototype SRM 2071, S/N 1049 with Ra = 0.28 μm and Wa = 100 μm. (b) data of NIST brass diamond turned prototype No. 7, Batch #2 with Ra = 1.0 μm and Wa = 800 μm. (Raw data).

3. Experimental apparatus

The apparatus used to conduct the measurements includes a FiberMax 5 axis motion platform on a Moore 1.5 machine that provides both coarse and fine positioning capability [12]. The gauging systems consist of a nanometer precision spindle on the free end of which is a sub-nanometer, high-speed, linear translation stage, and the standing wave fiber probe. The Moore 1.5 test bed is equipped with a coarse vertical axis stage and two horizontal *XY* stages, Fig. 4. The gauge head is mounted to the *Z*-axis of the Moore frame, and the FiberMax positioned on top of the Moore *XY* platform. The FiberMax, purchased from Aerotech™, has good positioning repeatability but not high accuracy. The FiberMax's controller can use either a feedback displacement sensor to control and track the position of each stage or alternatively be controlled with an external signal. In this case, we transferred the microscale probe signal to the FiberMax controller and built custom control algorithms which enable specific stages of the FiberMax to selectively use either the probe signal or displacement sensor as feedback. Thus, one stage might be used to servo control at a constant applied force between the probe tip and workpiece while additional stages are used to transverse the part relative to the probe tip.

The current setup has an inherently large metrology loop of 2 m making it sensitive to temperature changes. To mitigate this influence the system is housed in a metrology laboratory with ±0.1 °C temperature control. In the above setup, the fiber probe has the ability to measure inside and outside features and can scan continuously against the surface to extract both surface texture and form. The experimental data below presents 3D surface profiles of three types of parts that include roughness standards, a microscale hole, and a thread profile showing the ability of the system to provide one data set capable of providing both dimensional and surface metrology information.

4. Experimental data

4.1. Roughness standards measurements

Two calibrated surface texture artifacts supplied by NIST were used to evaluate the probe's ability to measure surface texture along a one-dimensional trace. Fig. 5 shows profile measurements on a NIST prototype SRM 2071, S/N 1049 with a 100 μm period and a roughness of 0.28 μm. Next, a NIST brass diamond turned prototype No. 7, Batch #2 with a wavelength of 800 μm was measured. NIST

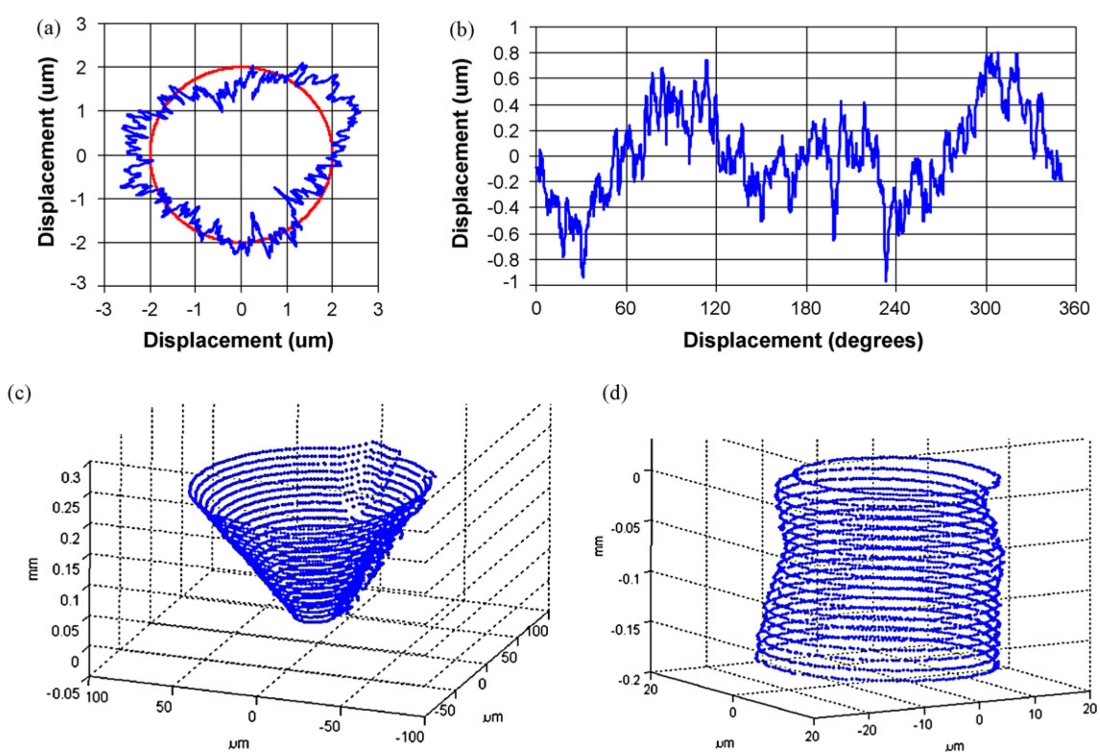

Fig. 6. measurements of a 128 μm glass hole (a) roundness trace, (b) surface measurement (Raw data) and (c) 3D representation of a tapered entrance to the thru hole of glass ferrule. Notice the chipped surface on the backside which is approximately 20 μm deep, (d) 3D representation of the 128 μm glass ferrule where zero in *Z* corresponds to 100 μm depth in to the hole.

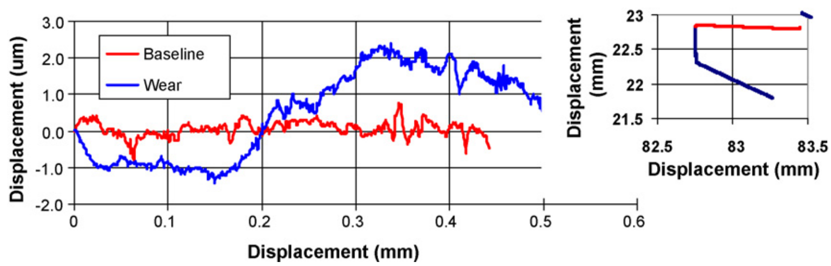

Fig. 7. Surface finish profiles of a precision thread comparing a baseline unused part with a used (worn) part, insert image (right) show one thread profile, where the surface finish data is from the red portion (Raw data).

Table 1
Surface texture values from standing wave probe compared with standards.

Surface standard	Calibrated values	Standing wave probe values
SRM 2071 SN 1049	Ra = 0.28 μm	Ra = 0.286 μm
Brass Artifact No. 7	Pa = 0.9946 μm	Pa = 1.0335 μm

provided the measured roughness reported from unfiltered data as Pa of 0.9946 μm using a Taylor Hobson surface profilometer. The results obtained from the standing wave probe are shown in Table 1, with a difference from the reported values of 0.006 and 0.0389 μm, respectively.

4.2. Measurement of microscale hole

As an example of a high aspect ratio microscale feature, the 128 μm hole in a glass ferrule purchased from Ozoptics Inc., Canada was measured. The ferrule has a through hole with a conical entrance. The ferrule hole was scanned at a depth of 0.5 mm below the hole entrance, Fig. 6, and 1000 data points were collected. The through hole scan shows roundness to be 1.57 μm calculated using a least squares center with a 50 UPR cut-off Gaussian filter. Further analysis yields the surface texture represented by the radial fluctuations during a circular scan, Fig. 6(b), as a Ra of 0.2712 μm with a 0.8 mm cut-off. Additionally, 3D image of the conical hole entrance, Fig. 6(c), as well as cylindrical portion of the hole, Fig. 6(d), was produced.

4.3. Precision thread measurement

As an example of a macroscale component with difficult to access surfaces, a precision thread with a major diameter of 8 mm was measured. In this case the profile measurements were taken along the flank of an individual thread in a radial direction from the screw axis. These surfaces are difficult or impossible to access using traditional surface texture instruments. The inset image in the top right corner of Fig. 7 shows one thread profile with the loaded surface indicated in green. The data in Fig. 7 compares the loaded surface of two threads, one unused and one used. It can be seen from this data that there is a larger form deviation on the used gauges. The surface texture was calculated for both scans yielding a Ra value of 0.0632 μm for the used gauge compared with the nominal surface of new gauge having a Ra of 0.058 μm, both using a 0.08 mm cut-off.

5. Conclusions

Major measurement challenges at the micro- and nanoscale include the ability to measure parts with features such as, high aspect ratio geometries, smooth surfaces with steep slopes, and/or delicate parts or soft materials which are susceptible to scratching. These challenges exist because current measurement technologies:

- do not operate as full 3D measuring tools and are operating instead as a surface measuring system, with some additional capability in the *Z*-direction;
- are susceptible to surface interactions;
- have high probing forces; and
- require multiple tools to measure form, waviness, and roughness.

The standing wave probe and scanning system presented in this work demonstrate the ability to provide surface texture and profile measurements of functional relevance for precision microscale manufacturing on surface features previously considered inaccessible with existing instruments. The uniqueness of this technology is that it provides (1) a high aspect ratio giving the ability to access deep, narrow features, (2) minimal contact forces (on the order of 100 nN), (3) has nanometer precision and repeatability, and (4) is a scanning technology.

Acknowledgements

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