DESIGN AND EVALUATION OF A PROTOTYPE INSTRUMENT FOR MEASURING ROUNDNESS PROFILES OF MICRO SHAFTS

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INTRODUCTION

This paper describes the design and some initial evaluation of a prototype instrument for measuring roundness profiles of axially symmetric micro components with diameters below 500 μm. The instrument will measure form error in micro-scale cutting tools used for micro machining, small-hole metrology probes, and other high aspect ratio micro structures. The instrument will operate on the same physical principles as scanning probe microscopes, which measure surface topography using either fluctuations in tunneling of currents between probe and sample (scanning tunneling microscope or STM) or fluctuations in oscillations of a resonating cantilever beam (atomic force microscope or AFM). The instrument will measure roundness profiles using a fixed-sensitive-direction arrangement of the detector, similar to macro scale metrology instruments, as illustrated in Fig. 1. In this paper, we give an overview of the instrument and then concentrate on the design and evaluation of the instrument's axis-of-rotation.

OVERVIEW OF THE INSTRUMENT

The architecture of the new instrument is illustrated in Fig. 2, and it is described in more detail by Loychik *et al.* [1]. The micro component (sample) rotates slightly more than one revolution on a spindle that is indexed with a stepper motor through a traction drive. The stepper motor and traction drive are mounted below the spindle.

As shown in Fig. 1, a nano positioning stage is attached to the top of the air bearing spindle to provide motions x_s and y_s used to center the micro component on the axis-of-rotation. The micro component is held in a collet-style holder. A support structure, symmetrically surrounding the spindle and sample, holds a second nano positioning stage that provides the probe motion in the x_p and y_p directions. A course positioning stage is being designed for the z_p direction, and it will be mounted on the probe's nanopositioning stage.

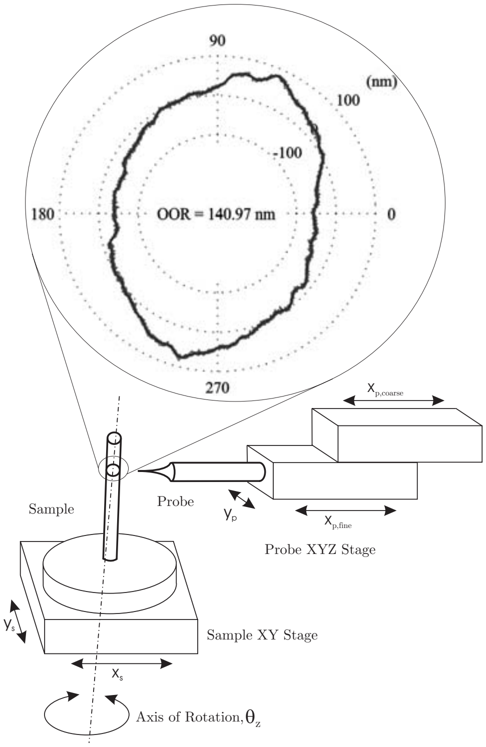


FIGURE 1. Instrument motions for fixed-sensitive direction measurement of roundness profiles on a micro shaft.

SPINDLE'S TRACTION DRIVE

The instrument requires a precise motor-driven spindle to establish an axis-of-rotation. Traditional rolling element (ball or roller) bearings are not precise enough for this application. Instead, the instrument uses an externally pressurized aerostatic spindle (Professional Instruments, Model 4R Blockhead Spindle), which exhibit radial error motions of less than 10 nm [1, 2] during coasting.

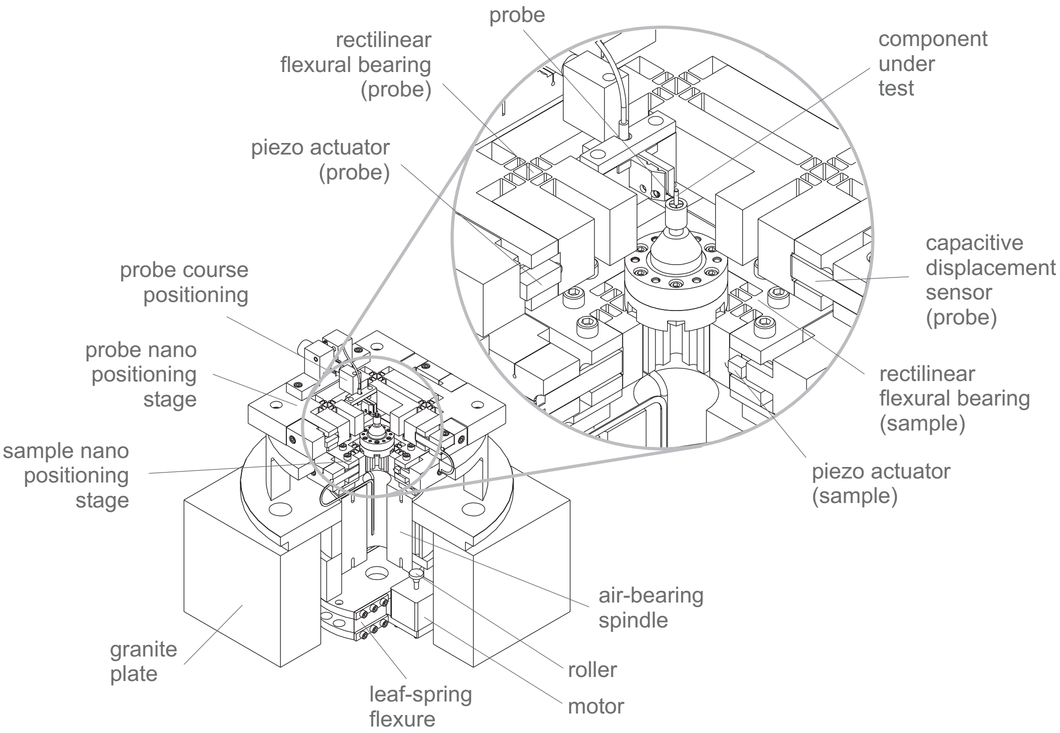


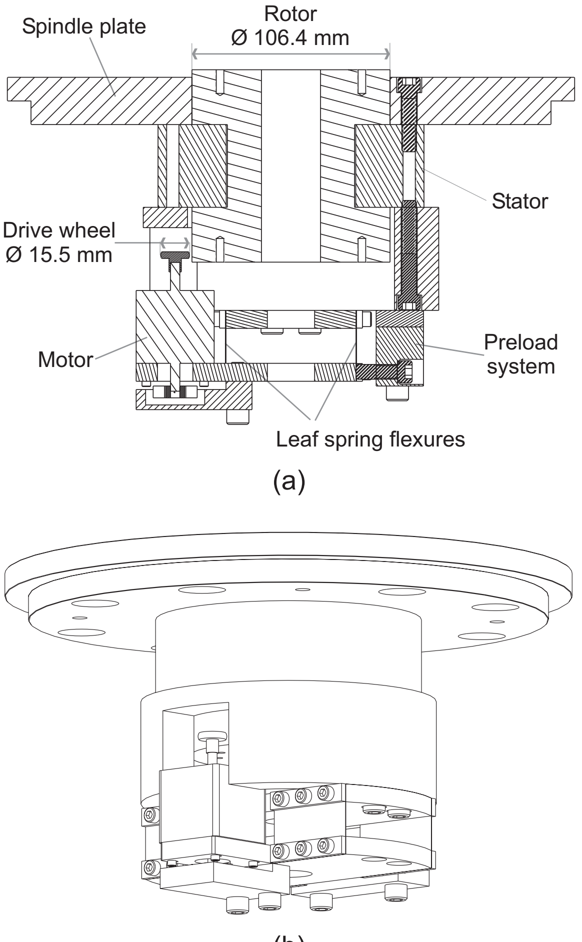
FIGURE 2. Architecture of the instrument, shown with one quarter of the solid model removed to reveal the details through to the centerline (axis-of-rotation) of the instrument.

These spindles consist of a rotor that is made of a hollow steel tube with two thrust plates and a stator that encloses the perimeter of the rotor's central tube. Pressurized air (550-1034 kPa) is supplied through the stator to a very small gap between the surfaces of the rotor and stator. Air flows out of the spindle between the annular gaps between the flange plates and stator. This produces high stiffness in the thrust, radial, and tilt directions.

The spindle is driven through a traction drive (crowned roller pressed against the perimeter of the spindle rotor) by a stepper motor (Oriental Motors, CFK544BT) mounted on a compliant flexure. The traction drive provides rolling-point contact, so a preload force is necessary to ensure that the roller remains in contact. A transmission ratio of about 7:1 is provided by the ratio of diameters for the rotor's thrust plate and the crowned roller, as illustrated in Fig. 3(a).

A compliant flexure, formed by four parallel sheet-metal springs, acts as a soft spring between the stepper motor and mechanical ground. The air gap supporting the spindle rotor is much stiffer than the compliant flexure. Therefore, radial error motion introduced from the stepper motor's shaft bearings or the roller causes the compliant flexure to move rather than the spindle's rotor, minimizing the effect on the air bearing spindle's rotor. The compliance of the flexure is adjustable using sheet metal with different width w or modulus of elasticity E, while leaving their length l and thickness t fixed. The preload force is adjusted by advancing a screw that pushes against the moving platform of the flexure. This permits adjustment of the preload force and completely disengaging the traction drive for coasting.

The angular motion of the spindle as driven by the motor is experimentally evaluated in order to determine the resolution of the traction drive and the fluctuations in steady-state position. The step-angle of the motor's controller is set to its smallest possible value, which is 2.88 millidegrees. Due to the 7:1 transmission ratio, the step size of the driven spindle is expected to be about 0.42 millidegrees. A steel lever arm is temporarily installed on the spindle. Its displacement is measured with a capacitance probe, as shown in Fig. 4. The distance between the axis of rotation of the



(a)

(b)

FIGURE 3. Traction drive system.

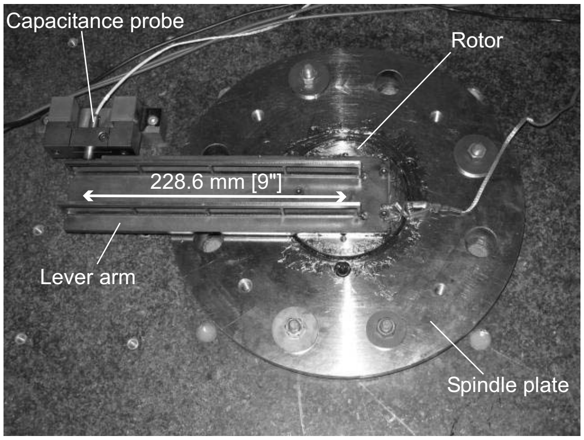
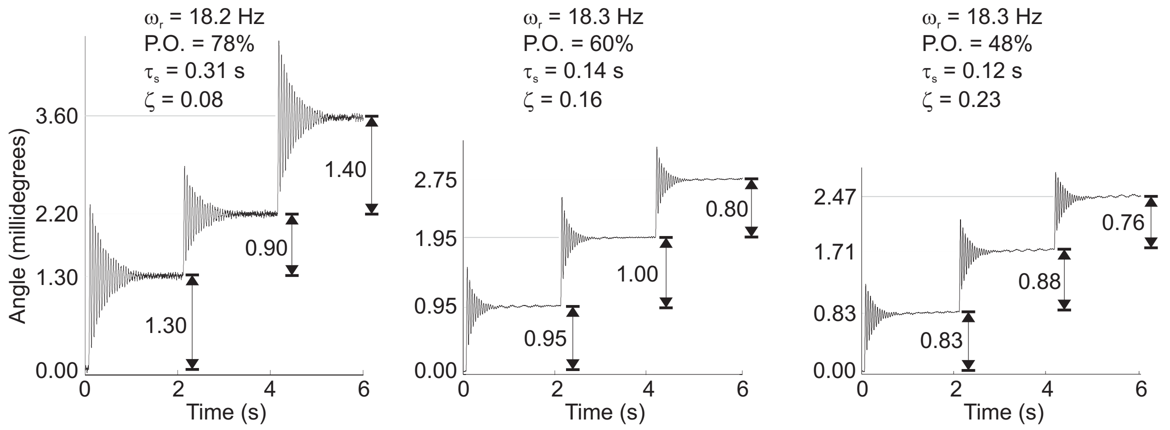


FIGURE 4. Experimental setup for measuring the spindle's step size.

spindle and the probe has been set to 9" (228.6 mm) so that the expected range of displacement of the lever arm moved by a few steps of the motor matches the range of detection of the capacitance probe. The experiments consist of moving the motor by several steps at a frequency of 0.5 Hz, and recording the subsequent displacement of the lever arm. An anti-alias filter with a 5000 Hz cut-off frequency is used on a the analog output of the capacitance probe.

Figure 5 displays the results of these experiments run with three different enhancements to damping. The first set of experiments, shown in part (a), is conducted without any damping added to the system. As a result, the overshoot is large (78% of the step size, which leads to a damping ratio of ζ = 0.08) and the settling time is relatively long (0.31 s). The gap between the thrust plate and the spindle plate is then filled with viscous grease to improve the damping and settling time, and the experiments are run again. The results illustrated in part (b) show a dramatic improvement in the damping ratio (ζ = 0.16, which is double the previous value), and the settling time is reduced by more than half (0.14 s). Finally, another damping system is added to the previous one: paddles are mounted at the tip of the motor shaft, then they are plunged into a pocket filled with grease. The graph in (c) shows that the damping ratio is further improved (ζ = 0.23). Throughout the experiments, a 18.3-Hz natural frequency as been constantly measured. When the rotor reaches steady-state position, it fluctuactes with a RMS value of 2.4×10^{-4} millidegrees.

It appears that these damping enhancements affected the axis-of-rotation's step size. As illustrated in Fig. 6, the average value of the spindle step size is 0.87 millidegrees, and it ranges between 0.75 and 1.05 millidegrees. With such a step-size, it would take an unreasonable 11 hours to measure a complete roundness profile, assuming that only 1 step out of 5 would be recorded and that the measured step would last 0.48 s (i.e. 4 times the settling time). Therefore, it will be necessary to increment hundreds of steps during the measurements, which will impose limits on the uncertainty in the position. A step-size of 0.87 millidegrees corresponds to a 0.15-nm step at the surface of a micro shaft with a 10 μm-radius. This suggests that the instrument resolution is smaller than the typical atomic spacing of copper or iron (0.3 to 0.4 nm, typically [3]) if the radius of the tested micro-shaft is less than 20 μm. When testing shafts with 250-μm radius, the step size would



(a) (b) (c)

FIGURE 5. Comparison of step response with different viscous damping treatments. (a) No damping treatment. (b) Viscous grease surrounding rotor's top thrust plate. (c) Viscous grease surrounding rotor's top thrust plate and viscous paddle damper.

be about 3.8 nm.

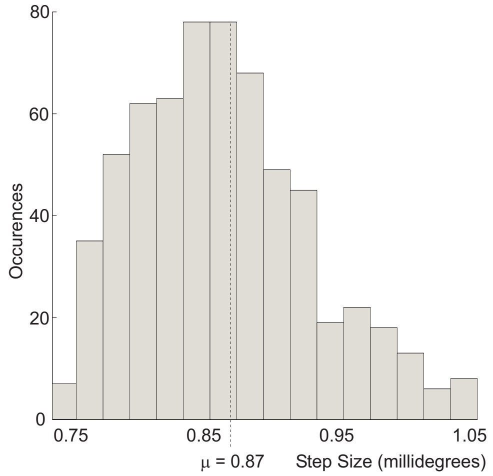


FIGURE 6. Histogram showing variation in angular step size.

CONCLUSIONS

This paper describes the design and evaluation of the axis-of-rotation for a new instrument suitable for measuring the form, waviness and roughness of axially symmetric micro components. The current non-contact metrology instruments with nanometer resolution are only suitable for flat surfaces, while this new instrument will achieve comparable measurements on axially-symmetric micro components. The first experiments performed on our prototype demonstrate that the instrument is able to span a revolved surface with a resolution ranging from 0.15 to 4 nm, depending on the diameter of the sample. The suitability of the selected traction drive system for the rotary axis of motion is confirmed. Further investigations will focus on characterizing the two nanopositioning stages that manipulate the micro component and the probe tip.

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