FULL FIVE DEGREE-OF-FREEDOM ERROR CHARACTERIZATION OF ULTRA-PRECISION SPINDLES USING THE MULTIPROBE METHOD

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ABSTRACT
This paper demonstrates an implementation of five degree-of-freedom precision spindle metrology at high speed in a production environment using a multiprobe method. A single probe is used with a purpose-built fixture, enabling measurement of axial, radial and tilt spindle error motion components as defined by the ASME B89.3.4 Standard: Axes of Rotation; Methods for Specifying and Testing [1]. This multiprobe error separation method can be more convenient to perform while still providing results as good as or better than those obtained through reversal.

INTRODUCTION
The ultra-precision air bearing spindle shown in Figure 1 is produced for diamond-turning and grinding applications. The demanding accuracy requirements for this spindle could only be certified through design of a new generation of metrology tooling. The contribution of typical artifact form error to the total measurement exceeds the spindle error specification. Furthermore, if not properly separated, artifact errors can mask spindle errors—such as 2-lobed ball errors cancelling 2-lobed spindle errors. As a result, the nanometer-level artifact form error must be separated from spindle error motion using an error separation technique.

Although the theory and application of error separation is widely known, this work addresses the challenges of hardware design when testing at operating speed. The reversal techniques described by Donaldson and Estler theoretically provide the simplest method for separating spindle error motion from artifact form error [2,3]. However, in a production environment, measurement accuracy of these techniques suffers from the difficulty of exact artifact reversal. Particular care must be taken to accurately remount the artifact exactly 180° without influencing form error, which can be difficult when testing at high speed. Any change in the artifact between the tests, for example a fingerprint or dust, is split evenly between the spindle and artifact. In addition, the probe must be positioned along an identical artifact measurement track after indexing.

FIGURE 1. A Professional Instruments Company ISO 5.5 motorized air bearing spindle.

FIGURE 2. Multiprobe error separation method applied to radial and face measurements.

This implementation of the multiprobe method assesses a single component of synchronous error motion from three asymmetrically orientated measurements. The sensor is moved from 0° to 99.844° and 202.5° without indexing the artifact. While this method does not perfectly separate all of the components of spindle and
artifact error, the chosen orientation angles minimize harmonic distortion.

Spindle error motion is characterized by five components—one axial (Z), two radial (R_x and R_y) and two tilt (a_x and a_y). Three measurements are required to obtain each radial and tilt component. Tilt error motion components are computed from two radial measurements at different axial locations (150 mm separation). The axial component of spindle error does not require error separation.

APPROACH
The spindle under test in this work (Professional Instruments ISO 5.5) features a 1024-count rotary encoder (Renco R22i) and a brushless, frameless motor and amplifier (MCS custom-wound motor and MCS AX-2000 amplifier). The capacitive sensor (Lion Precision C23-C, 0.5 nm/mV) targets a Ø25 mm lapped sphere as shown in Figures 3 and 4. The amplifier (Lion Precision CPL290) incorporates a 15 kHz first-order, low-pass analog filter with linear phase response. The data acquisition system (Lion Precision SEA V8.3) is triggered by the encoder index pulse, providing immunity to synchronization errors caused by speed variation. Further low-pass digital filtering is done in software.

FIGURE 3. Radial multiprobe error separation tooling with Ø25 mm lapped spherical artifact.

Several potential contributors to measurement uncertainty are eliminated by sequentially indexing a single sensor through the three orientation angles. These locations are provided by jigground holes in the stator-mounted index plate shown in Figure 5. Accurate repositioning of the sensor avoids the problems with mismatched sensors, but at the expense of simultaneous data collection.

FIGURE 4. Precision Ø25 mm lapped spherical artifact for spindle error motion testing.

The design of the hardware is consistent with Moore’s requirements of an inspection tool [4].
- It is accurate: The accuracy is based on sensor calibration and probe location.
- It requires a minimum of operator skill: This tooling significantly simplifies the procedure for spindle testing, resulting in improved efficiency and accuracy because it does not require repositioning of the artifact.
- It inspects a specific type of error: The tooling enables measurement of radial, axial and tilt synchronous error motions at known locations.
- It is fast to use: Elimination of the need to unbolt the artifact from the spindle and rotate it 180° significantly decreases the total time to complete a test.
- It is self checking: Each spindle measurement also re-checks the artifact. Furthermore, the index plate can be rotated to different angles to check repeatability. In addition, the tooling is designed to allow Donaldson reversal.

FIGURE 5. Tooling for radial multiprobe error separation method.
RESULTS
Previous work has described various iterations and improvements made to the radial error motion tooling shown in Figure 5 [5]. This tooling was designed to allow separation of artifact and spindle errors with multiprobe separation and Donaldson’s reversal. Multiprobe separation is used with the sensors located at 0°, 99.844° and 202.5°. The sensor indexing plate is then rotated 90° to measure the orthogonal component of radial error and the multiprobe separation procedure is repeated.

Typical synchronous radial error separation results are shown in Figure 6. The measurements recorded at the three orientation angles are a combination of spindle error and artifact form error. A mathematical manipulation of the three measurements enables the separation into 7.6 nm spindle error and 8.7 nm artifact form error.

As mentioned previously, the axial component of spindle error does not require error separation. The artifact’s imperfections do not influence the axial measurement except by second-order effects. Total synchronous axial component is 0.4 nm fundamental and 0.9 nm residual as shown in the measurement in Figure 7.

The tilt error motions shown in Figure 8 are often of greater concern than radial error motions when diamond-turning optics. The tilt error motion at a particular radius when combined with the axial error motion results in the face spindle error motion. We perform the tilt calculation in the X and Y directions using two radial measurements separated by 150 mm in the axial direction (low and high).

The five degree-of-freedom characterization is complete with the combination of Figures 7 (axial) and Figure 8 (two radial and two tilt).
CONCLUSION

Five degree-of-freedom spindle error motion measurement at the nanometer-level is demonstrated in a production environment. The multiprobe error separation method used here eliminates the need to index the artifact which simplifies the testing procedure.

Measurements are made sequentially with a single probe to reduce certain error sources. The tilt error motion is calculated from the radial multiprobe separation result at two axial distances.

These results confirm that multiprobe error separation can be a reasonable alternative to reversal methods in a production environment requiring testing at high speeds. Our next generation of spindle testing tooling will enable the measurement of rotating sensitive face and radial error motions in a single fixture.

REFERENCES