

Comparison of Three Spindle Error Motion Separation Techniques

Eric Marsh^{1*}, Jeremiah Couey¹, Ryan Vallance²

¹The Pennsylvania State University, 21 Reber Building, University Park, PA 16802, USA

²The George Washington University, 738 Phillips Hall, 801 22nd Street N.W., Washington, DC 20052, USA

Abstract

This work demonstrates the state of the art capabilities of three error separation techniques for nanometer-level measurement of precision spindles and rotationally-symmetric artifacts. Donaldson reversal is compared to a multi-probe and a multi-step technique using a series of measurements carried out on a precision aerostatic spindle with a lapped spherical artifact. The results indicate that sub-nanometer features in both spindle error motion and artifact form are reliably resolved by all three techniques.

Keywords: Spindle metrology, spindle calibration, error separation, roundness metrology

Experimental Setup

This paper documents a series of experiments exploring the capability of ultra-precision spindle measurements, including a comparison of results obtained by the multi-step, a multi-probe (3 probes), and the modified-Donaldson reversal approaches to spindle error separation. The test hardware for this research consists of the spindle being tested (test spindle), a rotary encoder, a precision rotary table, a spherical master artifact, a reversal chuck, and a displacement sensor.

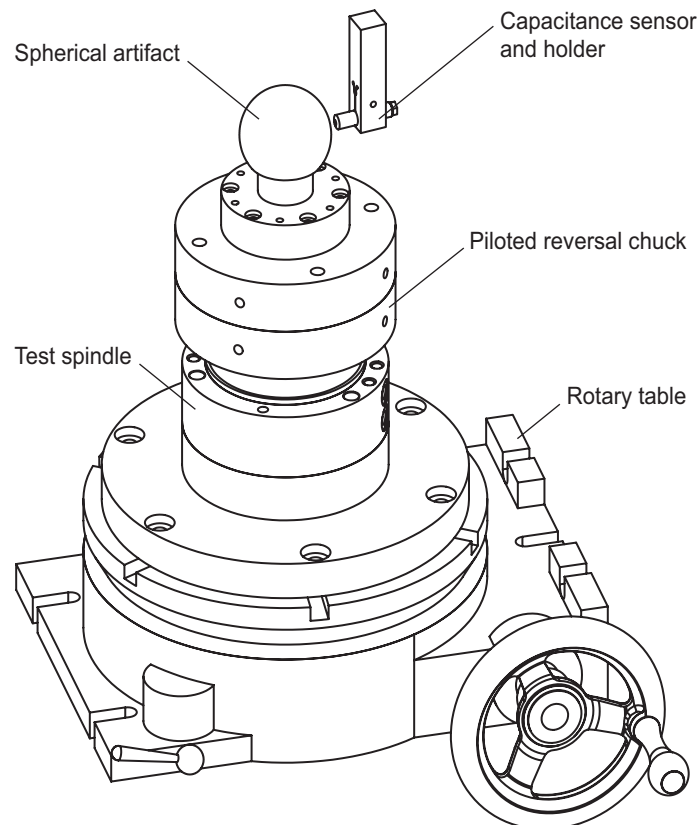


Figure 1: Spindle test assembly with a spherical master artifact.

The test spindle is an externally pressurized, air bearing spindle (Professional Instruments 4R) with a 4096-count rotary encoder (Heidenhain ERO 1324). Spindle motors and drives can have a significant influence on the synchronous component of the measured data. Our test spindle is examined without a motor, requiring that it be spun up by hand (60 RPM). The encoder is used to trigger the data collection at evenly spaced angular increments in the presence of fluctuations in spindle speed. The spindle is mounted on a precision rotary table (Moore LRT). The reversal chuck between the artifact and spindle has a lapped spherical pilot to facilitate accurate indexing of the artifact with respect to the spindle (Professional Instruments). The rotary table, spindle, reversal chuck, and artifact are assembled such that each component lies on the same axis to within 400 nm. This careful alignment reduces the need for adjustments of the displacement sensor standoff distance during indexing of the rotary table. The test hardware shown in Figure 1 is on a three-axis measuring machine (Moore Universal Measuring Machine) to allow for convenient alignment and centering of the displacement sensor (measuring machine not shown in the figure).

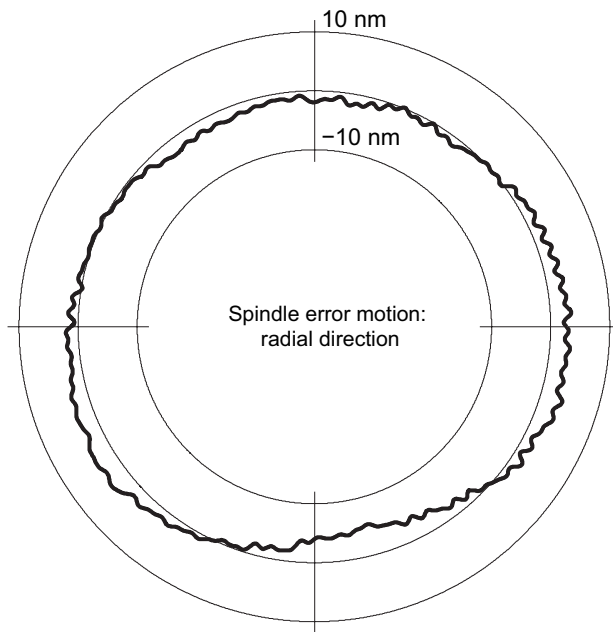
The capacitive displacement sensor (Lion Precision C-1C 0.5 nm/mV) targets a $\text{Ø}64$ mm lapped spherical master artifact (Professional Instruments). Previous work has demonstrated that the finite radius of the artifact results in a slight nonlinearity in the capacitance sensor output. In order to achieve the nanometer-level repeatability results that are shown in the results that follow, it is imperative that the standoff distance of the sensor remain constant during all measurements of a given error separation procedure [1]. For this reason, the electronic zeroing adjustment on the capacitive sensor system is bypassed and the nominal sensor standoff is manually adjusted when necessary.

The data acquisition system (National Instruments PCI-6110E) includes low-pass, analog filters with a 100 Hz cutoff (equivalent to 100 cycles per revolution at 60 RPM) to prevent aliasing and to remove higher frequency spectral content from the data. Additionally, the quasi-static frequency components caused by thermal drift and fluctuations in air bearing supply pressure are removed by high pass digital filtering (0.1 Hz). These procedures are performed in accordance with the B89.3.4M ANSI standard on axis of rotation metrology.

Experimental Results and Discussion

The first experiment establishes the baseline measurement repeatability and only includes the separation of the synchronous and asynchronous components. In this experiment, the spindle stator is never rotated on the rotary table and the artifact remains fixed with respect to the spindle rotor. The plotted results therefore include the combined synchronous spindle radial error motion and the artifact form error, but not disturbances related to physically indexing the spindle and artifact as required by any of the three error separation techniques considered below.

The first experiment examines the repeatability for the modified (rotary table-based) implementation of Donaldson reversal. Figure 2 shows the repeatability results for the radial synchronous spindle error motion and artifact form error for ten consecutive reversals. In these tests the spindle and artifact results, which are now fully separated from each other, show sub-nanometer-level repeatability across ten tests.



Test	Spindle	Artifact
1	9.1 nm	12.9 nm
2	9.0	12.8
3	9.1	12.9
4	9.2	12.9
5	9.2	12.8
6	9.3	13.0
7	9.3	12.8
8	9.1	12.9
9	9.1	13.0
10	9.2	12.9
Mean	9.2 nm	12.9 nm
Std. dev.	0.09 nm	0.08 nm

Figure 2: Synchronous spindle error motion (by modified Donaldson reversal) for 10 tests.

The rotary table simplifies the execution of the tests, but requires that the measurements be post processed to reflect the changing angular location of the spindle stator because the encoder read head rotates with respect to the sensor location. The 3-probe error separation calculations are computed using the same data set collected for the 16-step multi-step test with the three sensor positions chosen as 0°, 135°, and the 247.5°. The spacing is deliberately asymmetric to avoid the suppression of low order harmonics in the error motion.

Figure 3 shows the synchronous radial error motion for all three separation methods on the same plot. These results have been digitally low-pass filtered in post-processing to 15 cycles per revolution. This cutoff frequency is deliberately chosen because it is below the 16 cpr harmonic at which the multi-probe method becomes inaccurate. All three methods give similar values for the error motion to within less than one nanometer.

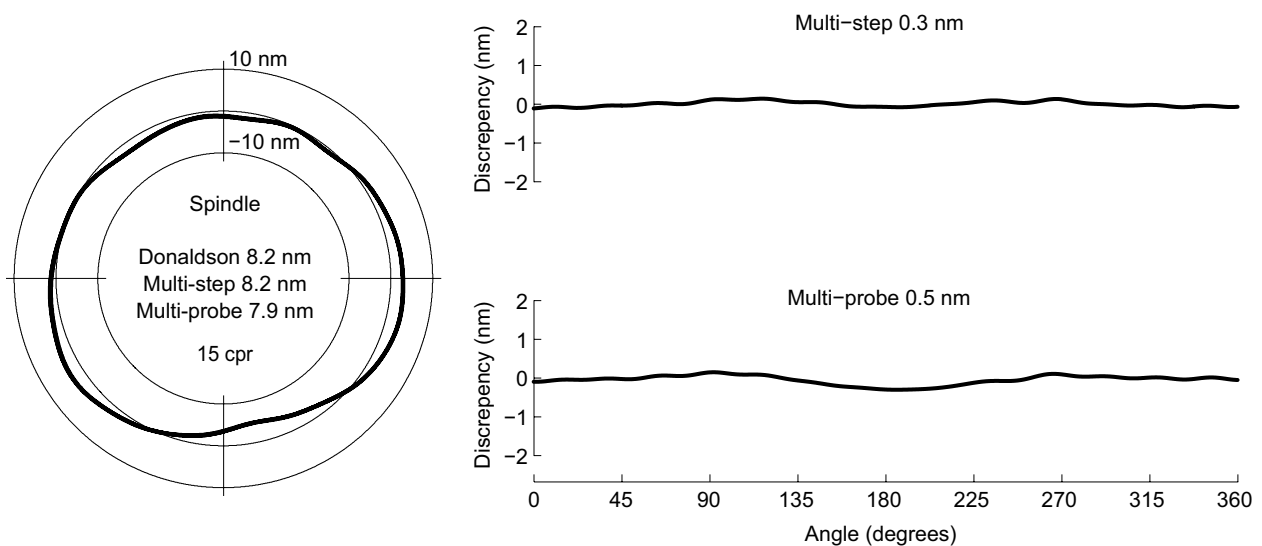


Figure 3: Error separation results and the discrepancies of multi-step and multi-probe with modified Donaldson reversal (data low-pass filtered to 15 cpr).

The same information may also be considered in the frequency domain. Figure 4 shows spectral plots of the error motion and artifact form error as computed by the three methods. The three methods agree remarkably well except at the frequencies that have been predicted to be inaccurate in previous work. In general, these inaccurate spectral components occur at frequencies that are predicted using the number and angular locations of the sensor used in the multi-position methods.

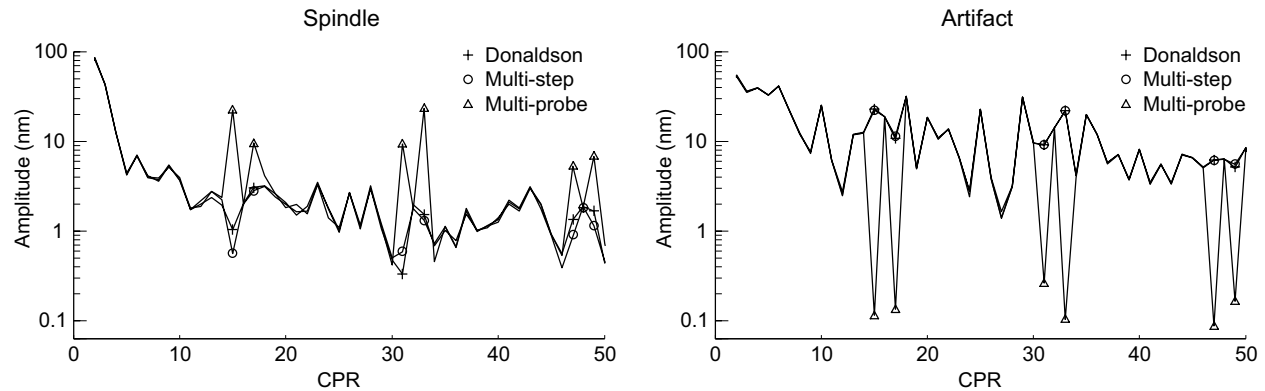


Figure 4: Frequency components of the three error separation methods.

Conclusion and Discussion

A new experimental apparatus enables the comparison of Donaldson reversal, a multi-probe, and a multi-step method for separating spindle error motion from artifact form error. A new modification to the traditional measurement hardware eliminates two of the largest sources of measurement uncertainty, repositioning sensors and multiple sensor sensitivities, to achieve an expanded uncertainty of 2 nm. This is achieved by using a precision rotary table and a precision reversal chuck to carry out the necessary changes in sensor/target orientation. Analog and digital filtering of the displacement measurements eliminates aliasing, thermal drift, and the effects of structural vibration to yield clean data of a controllable bandwidth.

Three experiments, conducted with a lapped spherical artifact rotating on an externally pressurized air-bearing spindle, demonstrate the repeatability of the displacement measurements (peak-to-valley range of 0.2 nm in 10 tests), the repeatability of Donaldson reversal (P-V range of 0.3 nm in 10 tests), and agreement of the three methods (0.3 nm discrepancy between Donaldson reversal and multi-step and 0.5 nm discrepancy between Donaldson and multi-probe when filtered with a 15 cpr low pass cut-off).

In the first experiment, the ten tests demonstrate that the standard deviations of synchronous and asynchronous displacement measurements without error separation are 0.07 nm and 0.93 nm, respectively. In the second experiment, the ten tests demonstrate that conducting the modified Donaldson reversal on this apparatus yields measurements of the radial error motion and the artifact's out-of-roundness that repeat with a standard deviation below 0.1 nm. The final comparison demonstrates that the three methods agree, within their well-documented limitations for not separating certain frequencies, to better than a nanometer. Therefore, the apparatus and techniques described in this paper are well suited for the metrology of high-precision spindles and artifacts at the nanometer level.

References

1. Vallance RR, Marsh ER, and Smith PT. The Effects of Spherical Target Radius on Capacitive Sensor Measurements, ASME Journal of Manufacturing Science and Engineering, in press.