

Correlation of Spindle Errors to Piece-Part Accuracy

Ke Wang & Edward Morse
Center for Precision Metrology
The University of North Carolina at Charlotte
Charlotte, NC 28223

Keywords: Axis of Rotation Errors, In-Process Measurement, Part Geometry

Introduction

Spindle error measurement technology, utilizing a cylindrical or spherical target artifact with non-contact gauges (capacitance gauges, eddy current gauges, etc.) to measure a machine tool spindle's "axis of rotation" errors (including radial, axial, and tilt errors: ANSI/ASME B89.3.4 [1]), plays an important role in metrology and precision engineering. There are a variety of testing methods and equipment available for measuring these errors for a freely rotating machine tool spindle [1] [2]. These methods are widely used by manufacturing industries and precision engineers to determine spindle errors of an *unloaded* machine tool spindle. It is very likely that the error motions of a machine tool spindle during the machining process will be different from those in free rotation. Some attempts have been made to simulate the loading conditions that a machine tool could experience during its cutting process [3] [4], as well as measuring the radial errors induced by cutting [5]. We are not aware of the successful measurement of all 5 error motions of a machine tool spindle during the machining process. This absence of knowledge prevents us from understanding how a machine tool spindle really behaves when it is carrying out machining applications and, ultimately, how these in-process spindle errors affect the accuracy of the parts manufactured by this machine tool.

In this paper we describe an approach for measuring spindle errors during machining process. The motivation for the development of this instrumentation is to better understand how cutting forces influence the deviations from ideal rotor-to-stator spindle motion.

Design of Experimental Instruments

The measuring apparatus we developed in this study is designed for performing in-process spindle error measurements on a Bostomatic M-270 CNC vertical machining center. Our design is based on the conventional method for testing unloaded spindle errors, which is described in appendix A of ANSI/ASME B89.3.4 [1]. This measuring device consists of two parts, the target artifact which rotates with the tool and tool holder, and a mounting fixture that holds five capacitance gauges that measure changes in distance between the stationary mount and the rotating target surface.

- Target Artifact

The target artifact is a disk shape, which permits measurement of all five error motions while protecting the gauges from chips and other debris. While every effort is made to ensure that the surfaces of the target are smooth and the circumference of the disk is centered on the spindle axis, we rely on reversal techniques and information about the spindle's errors from earlier unloaded measurements in lieu of requiring perfect form for the artifact. Figure 1 shows models

of the target mounted on the tool holder, and also shows the relative positions for the capacitance gauges that are used to measure the motion of the disk.

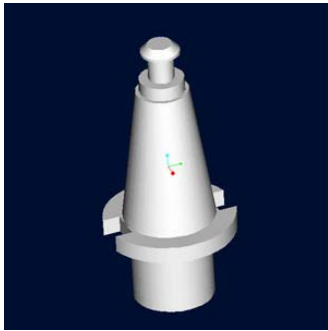


Fig 1.1 BT-40 Tool Holder (Pro-E)

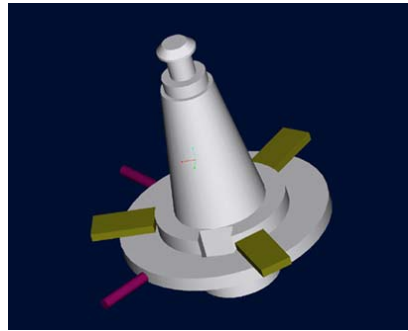


Fig 1.2 Target disk mounted on the tool holder with rectangular and cylindrical capacitance gauges targeting at it (Pro-E)



Fig 1.3 BT-40 tool holder with target disk mounted on it (Actual photo)

Fig 1. Target artifact

The thickness of this target disk is 0.375 inch and its diameter is 4.25 inch; the rim of the disk is machined to a spherical surface – i.e., the disk is really a slice of a sphere. This prevents tilt errors from being interpreted as radial errors, and gives a more uniform target for the capacitance gauges as tilt motion increases.

- Mounting Fixture for the Capacitance Gauges

In order to measure all five error motions simultaneously, we use five capacitance gauges (provided by Lion Precision) to collect error motion data. Three of these gauges are flat, rectangular bodied, model R1-A gauges and the other two are cylindrical bodied model C1-B gauges [6]. The relative positions of these gauges are shown in Figure 1.2. The R1-A gauges look "down" at the flat top surface of the target disk to measure Z axis error motions and tilt error motions, while the C1-B gauges target at the edge of the target disk to measure X- and Y-axis radial error motions. Driver units of the capacitance gauges are model DMT-10 [7], also provided by Lion Precision. A PC data acquisition board, standard to the spindle error analyzer, is used to record and process error motion data collected by the gauges. The mounting fixture for the gauges consists of three parts: a connector plate, the mount for the R1-A gauges, and the mount for the C1-B gauges.

1. Connector Plate

In order to make our instrumentation more flexible, we use a connector plate to fix the gauge mounts to the quill of the spindle. This connector plate is unique to the machine tool used for testing, while the remaining components can be used with any tool. This design allows us to easily test spindles on different machine tools without major redesign. For the M270, we use a connector plate with a six-hole pattern. Three of the holes are used to mount the plate to the lower end cover of the quill. Three other holes are tapped and used to fix the mount of R1-A gauges to the connector plate (Fig 2.2).



Fig 2.1 M-270 machine spindle



Fig 2.2 Connector plate



Fig 2.3 Mounts for the R1-A capacitance gauges



Fig 2.4 Target disk and tool holder



Fig 2.5 Mounts for the C1-B Capacitance gauges

Figure 2: Mounting fixture for the capacitance gauges

2. Mounting for the R1-A Capacitance Gauges

This mount locates the three rectangular R1-A gauges. The locations of these three gauges are distributed evenly at 120 degrees (Fig 2.3). We use three bolts to fix this mount to the connector plate. These three bolts are also used to adjust the distance and parallelism between those R1-A gauges and the target disk (Fig 2.4). Near the rim, there are four boltholes distributed evenly at 90 degrees, which are used to receive the C1-B gauge mount.

3. Mounting for the C1-B Capacitance Gauges

This mount locates the two cylindrical C1-B gauges. These two gauges are located parallel to the X and Y axis of the CNC machine, targeting at the spherical rim of the target disk to pick up X and Y axis error motions. Four bolts are used to fix this part to the mount of R1-A gauges. These four bolts are also used to make small adjustments of the relative positions between the C1-B gauges and the target disk (Fig 2.5).

Testing Procedures and Data Analysis

Before we employ our measuring device on the CNC machine, we need to make sure that the spindle and tool holder combination we use for these experiments has repeatable behavior. We use the two sphere Spindle Error Analyzer (SEA) system made by Lion Precision to measure the unloaded spindle errors. We perform several measurements at various spindle speeds to ensure that the results we obtain are repeatable. Data from the unloaded spindle error measurements are used to map any mechanical errors that occur in the target artifact and the mounting fixture of

our design. This mapping operation is applied to the capacitance gauge measurements taken from the disk target artifact when the spindle is rotating without load. We are also able to easily rotate the tool holder and target disk 180 degrees with respect to the spindle to confirm that the geometric errors we assign to the target are distinguishable from the spindle errors.

We next acquire capacitance gauge data during machining process. The standard PC data acquisition and interface provided with the SEA hardware is used. These data (from our new apparatus) are transformed to match those data that would be obtained from the standard two-sphere artifact. The method used to perform this transformation is described in [8] and, after these data are transformed, they can be displayed with the existing graphics routines for the two-sphere artifact. The spindle's behavior during free rotation is compared with that observed during machining process.

Current and Future Work

After machining the test parts, we will measure them to determine both geometric and surface finish characteristics. Our focus will be to determine what correlation exists between the in-process spindle errors and the geometry and surface finish characteristics of the part. As we are only measuring rotor-to-stator spindle errors, differences between the observed spindle errors and the part geometry can be associated with unwanted motion in the structural loop of the machine. An initial outcome realized by comparing the magnitude of the different errors contributing to the final part geometry will be to guide the machine tool user as to the origin of errors and uncertainty for specific combinations of tool, workpiece, and materials.

Acknowledgements

This research is conducted at UNC Charlotte and is supported by the affiliates of the UNCC Center for Precision Metrology. We are grateful to Lion Precision for providing us with technical information, advice, and measuring equipment.

References

- [1] ANSI/ASME B89.3.4, "Axes of Rotation, Methods for Specifying and Testing" American Society of Mechanical Engineers, NY, 1985.
- [2] Bryan, J., Clouser, R., Holland, E., "Spindle Accuracy", American Machinist, December 4, 1967.
- [3] Sharma, A.K., "An Experimental Investigation into Thermal Spindle Growth Under Load", Master Thesis, The University of North Carolina at Charlotte, 1997.
- [4] Marsh, E., Grejda, R., "Experience with the Master Axis Method for Measuring Spindle Error Motions", Precision Engineering 24 (2000) 50~57.
- [5] Davies, M. A., *et al.*, "On the Dynamics of High-Speed Milling with Long, Slender Endmills", Annals of the CIRP, vol. 47, no. 1, pp. 55-60, 1998.
- [6] "Probe Selection Chart", Lion Precision, Inc., St. Paul, MN, 2000.
- [7] "Spindle Error Analyzer, Instructions Manual", Lion Precision, Inc., St. Paul, MN, 1996.
- [8] Morse, E. P., and Wang, K., "Using alternative artifacts for error motion analysis", *Proc. ASPE Summer Topical Meeting on Precision Bearings and Spindles*, pp. 100-103, State College, PA, June 2001.