# AN EXPERIMENTAL INVESTIGATION INTO SPINDLE ERROR MOTIONS UNDER LOAD

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## Introduction

Current measurement methods, specified by ANSI/ASME B5.54-1993[1] and B89.3.4-1985[2] standards for spindle error motions, establish error motion characteristics with no load applied to the spindle bearings. It is possible that the application of load to the spindle bearings will result in different error motions, a different response to the error motions, or both.

In this study, a loading device [3], designed and built to apply loads to the spindle of a computer numerically controlled (CNC) machine, was used to study spindle error motions. Brief discussions of the results of spindle error motions under loaded and unloaded conditions and at various rpm's are included below.

The loading device is an external fixture that applies various axial loads to lower and upper bearings of a machine spindle. It allows traditional spindle testing with an artifact to study spindle error motions and the ability to perform the same tests under load while at speed. Further details of the loading device components and a discussion of axial forces due to cutting can be found in reference 3. A commercially available spindle error analyzer [4] (SEA) system with capacitance gauging techniques was used to measure error motions of the spindle.

## Experimental Setup

The experimental setup of the loading device is shown in Figure 1 (SEA system not shown). When testing for spindle error motions under load, a thrust force of 140 lbs was applied to the spindle bearing system. An S-type load cell with a bridge resistance of 350 ohms was used to measure forces applied to the spindle.

All spindle error motions tests were conducted on a Monarch vertical machining center (VMC 45). The Monarch uses tapered roller bearings to support the spindle. Spindle bearing preload is controlled by a hydraulic integrated circuit and automatically reduced at high speeds. From 0-525 rpm, spindle bearing pressure is 400 psi, and from 525-1125 RPM, spindle bearing pressure is lowered to 100 psi.

Loaded and unloaded axial and radial error test runs were conducted at least 12 hours apart. Before starting each test battery, the spindle was operated for two hours to warm up its bearing system. After warm up, each run was conducted for 10-15 minutes at each rpm setting with approximately two minute intervals between test runs. All tests were conducted under stable ambient conditions with 128 data samples per revolution for 20 revolutions. In order to correlate data from a previous study, first test was conducted at 255 rpm.

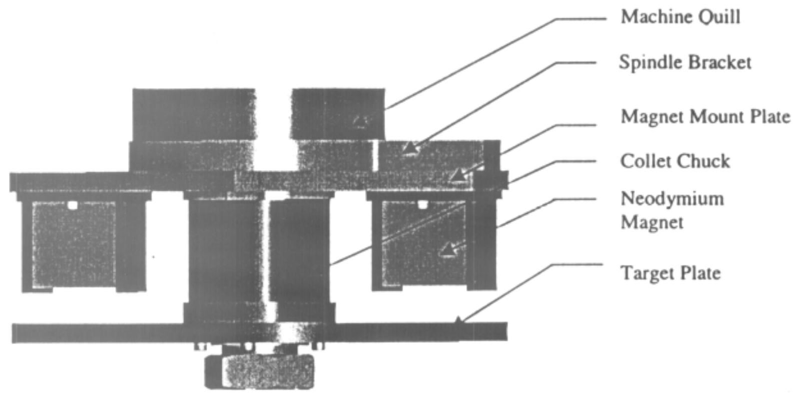


**Figure 1:** Loading Device Setup for Spindle Error Motion

**Spindle Error Motions Under Loaded and Unloaded Conditions**

Axial and radial error motions in a rotating sensitive direction were measured. For radial error motion tests, only asynchronous errors are analyzed and reported. Spindle error motions are defined in ANSI/ASME B89.3.4 – Axis of Rotation [2].

*Axial error motion, rotating sensitive direction*

In the SEA setup for axial error tests, the X-probe determines angular position while the Z-probe detects any in and out (axial) motion of the spindle during each rotation. Target eccentricity was minimized to avoid error in measurements.

Table 1 and Figures 2 (a) and (b) summarize results and show sample plots obtained with the loading device for spindle axial error motion under unloaded and loaded conditions.

**Table 1:** Axial error under loaded and unloaded conditions

| Spindle rpm | Spindle preload (psi) | Axial error in microns at no load | | | Axial error in microns at 140 lbs of load | | |
|---|---|---|---|---|---|---|---|
| | | Run 1 | Run 2 | Run 3 | Run 1 | Run 2 | Run 3 |
| 255 | 400 | 1.5 | 1.3 | 1.3 | 1.5 | 1.4 | 1.3 |
| 500 | 400 | 2.1 | 2.5 | 2.4 | 2.6 | 2.6 | 2.6 |
| 1000 | 200 | 1.3 | 1.3 | 1.4 | 1.7 | 2.0 | 1.9 |

At 255 rpm, the magnitudes of axial error remained same accept for some small variations under loaded and unloaded conditions of the spindle. For all six runs, a variation of 0.2 micron in axial error was noted. At 500 rpm, axial error increased by approximately one micron over similar spindle conditions at 255 rpm. Furthermore, at 500 rpm under load, axial error is slightly higher and constant for all three test runs. Since the difference in axial error under load and no load is smaller than the variation within all measurements, it can not be considered significant in obtaining a correlation between spindle axial error motion at load and no load. Therefore, at 255 and 500 rpm, application of 140 lbs of thrust load did not affect spindle axial error motion.

At 1000 rpm, axial errors are smaller in magnitude compared to the other two test speeds. However, the amount of axial error increased under the application of the thrust load. It is possible that the magnitude of axial error is smaller at this rpm due to the change in preload to the spindle bearing system from 400 psi to 100 psi.

*Radial error motion, rotating sensitive direction*
In this setup, data is acquired from the X and Y probes positioned 90 degrees to each other. The probes measure X and Y change in position of the axis line of rotation and generate sine and cosine signals to produce a polar plot using the Tlusty method [4,5]. For all radial error measurement tests target eccentricity was maintained constant.

Table 2 and Figures 2 (a) and (b) summarize results and show sample plots obtained with the loading device for spindle radial error motion under unloaded and loaded conditions.

**Table 2:** Asynchronous error under loaded and unloaded conditions

| Spindle rpm | Spindle preload (psi) | Asynchronous error in microns at no load | | | | Asynchronous error in microns at 140 lbs of load | | |
|---|---|---|---|---|---|---|---|---|
| | | Run 1 | Run 2 | Run 3 | | Run 1 | Run 2 | Run 3 |
| 255 | 400 | 4.1 | 3.7 | 3.8 | | 4.0 | 3.2 | 4.1 |
| 500 | 400 | 5.8 | 5.6 | 5.7 | | 6.5 | 4.9 | 5.2 |
| 1000 | 200 | 7.0 | 7.3 | 5.9 | | 5.1 | 5.5 | 5.7 |

At 255 and 500 rpm, it was noted that application of 140 lbs of axial load did not affect the asynchronous error motion of the spindle. However, at 1000 rpm, asynchronous error slightly decreased for all three runs under the application of thrust load to the spindle.

**Conclusions and Future Work**
A loading device designed and built in a previous study was utilized to further investigate spindle error motions under the application of thrust loads. Maximum load and spindle operating speeds were limited to 140 lbs and 1000 rpm.

For spindle error motions, axial and asynchronous error measurements were repeatable to within one-half micron. Due to this uncertainty, and the limited number of test runs, no direct correlation was established for spindle error motions under load and no load.

Future work will include tests conducted with the loading device on a machine that has different type of bearings and preload mechanism. Also, further analysis and tests will be done to separate machine structural motions from error motions of the spindle.

## References


1. ANSI/ASME B5.54-1993, " Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers," American Society of Mechanical Engineers, NY, 1992.
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3. Sharma, A.K., "An Experimental Investigation into Thermal Spindle Growth Under Load", Masters Thesis, The University of North Carolina at Charlotte, 1997.
4. "Spindle Error Analyzer, Instructions Manual," Lion Precision, Inc., St. Paul, MN., 1996.
5. Tlusty, J. "System and methods of testing machine tools," Microtechnic, 13, 162-178, 1959.


## Error Motion Plots

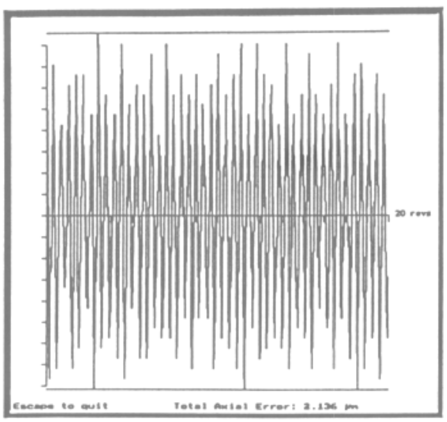


**Figure 2(a):**
Axial error motion at 500 rpm no load

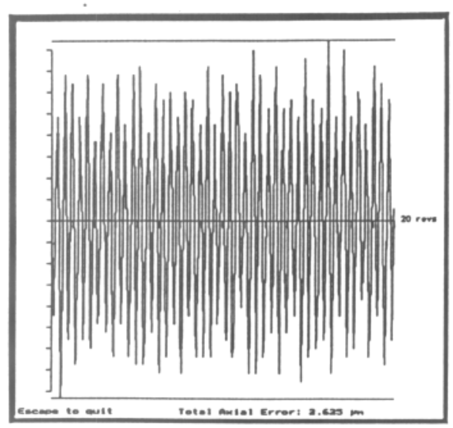


**Figure 2(b):**
Axial error motion at 500 rpm,140 lbs. thrust load

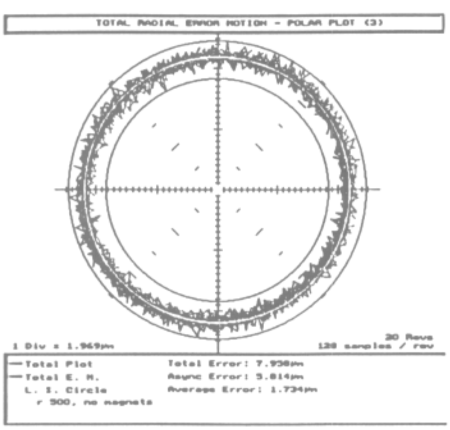


**Figure 3(a):**
Radial error motion at 500 rpm no load

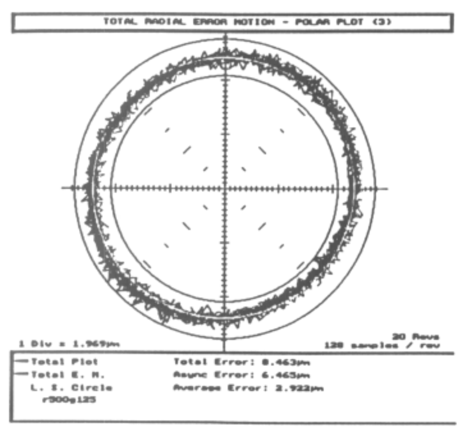


**Figure 3(b):**
Radial error motion at 500 rpm,140 lbs. thrust load