

EXPERIENCES WITH THE MASTER AXIS METHOD FOR MEASURING SPINDLE ERROR MOTIONS

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ABSTRACT

In this paper, a new approach to machine tool spindle measurement is described. This approach, called the Master Axis Method, combines the benefits of traditional spindle testing with an artifact (e.g., synchronous and asynchronous error motions) with the ability to perform the same tests under load while at speed. For example, a load representing the cutting force in a turning operation can be conveniently applied during the characterization of a lathe spindle. The resulting error motions have been observed to vary in both magnitude and character under different loading conditions.

The Master Axis Method provides more appropriate test conditions than traditional artifact-based spindle measurements that are performed without load and traditional compliance tests that are performed at zero speed.

INTRODUCTION

Traditional spindle testing includes the measurement of error motions, compliance, and thermal drift to characterize an axis of rotation. The most familiar result of a spindle analysis is the rotating sensitive direction polar plot of synchronous error motion (in this case a combination of tilt and radial motion). The error motions are measured with capacitance gages targeting an artifact such as a steel ball.

An obvious shortcoming of the error motion tests is that the measurements are made without any load on the spindle. Presumably, the cutting forces will affect the spindle dynamics, and in fact, some milling spindles take cuts large enough to overcome the bearing preload. Bryan proposes a method of measuring spindle error motions with capacitance probes while machining which may be suitable for some classes of machine tools. Clearly, a next step in the characterization of machine tool spindles is the development of a general purpose method to measure error motions as a function of spindle load (cutting forces) and as a function of spindle speed.

In response to this need for a more suitable method of testing spindles, a team of engineers at Professional Instruments, Lion Precision, and Lorien have proposed the Master Axis Method of characterizing axes of rotation. The benefits of the method result from the elimination of artifacts such as the master ball that is used in traditional spindle error measurements. Instead, the method is based on the use of a precision air bearing spindle referred to as the master axis. The master axis typically has smaller error motion than an artifact because of the averaging effect of the high pressure air film, resulting in sub-nanometer error motions. The master axis also provides for the repeatable application of loads during spindle testing. Figure 1 shows a spindle under test with a master axis.

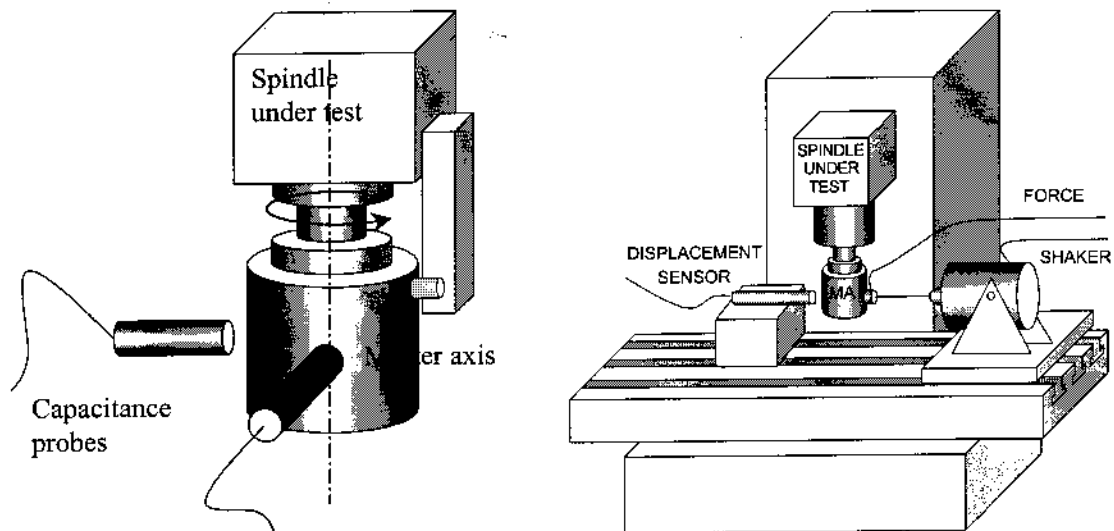


Figure 1: Error motion and compliance testing with a master axis.

The Master Axis Method offers several advantages to spindle measurement and characterization. First, the method is potentially more accurate than the best artifacts (e.g., polygons, balls, flats). For example, the roundness of a high quality ball is on the order of 25 nanometers, many times the error of a precision air bearing spindle. Second, the method allows both compliance testing and error motion measurement at speed and under load. For example, the compliance of a hydrodynamic spindle bearing may now be properly tested at speed and with very high accuracy. Third, the precision capacitance gages are targeting a stationary surface resulting in sub-nanometer resolution. Finally, the method is self-checking and reversal and multi-step techniques may be used to separate errors in high accuracy spindles from the master axis itself.

The Master Axis Method has led to the design and construction of several prototypes by Professional Instruments Co. The first prototype master axis spindle is embedded in a large granite fixture and features a rigidly mounted structure for holding the capacitance gages used in the testing. A high accuracy rotary encoder and high sensitivity Lion Precision capacitance gages are used along with dedicated software to measure the error motions of the spindle under test. Using this master axis, dubbed the Ultimate Spindle Calibrator, ultra-high precision air bearing spindles can be tested and characterized.

Other prototypes have been built by Professional Instruments to characterize lathe, milling machine, and grinder spindles. These prototypes feature built-in rotary encoders and may be set up on a given machine with one, two, or more capacitance gages depending on the desired information. These portable master axes have been used in the tests described in the rest of this paper.

EXPERIMENTAL SETUP

A series of experiments will be described to demonstrate the use of a portable master axis (PMA). The experiments are performed on a Bridgeport milling machine equipped with a ball bearing spindle. The spindle error motions were measured under a variety of speeds and loads to explore the spindle's behavior under a range of conditions. As expected, the spindle error motions vary with both speed and load. Not surprisingly, the error motions are not necessarily the worst at the highest operating speeds, although the vibrations generated by the spindle

drive do worsen with spindle speed. Table 1 outlines the parameters used in the spindle error motion measurements.

Table 1 Milling machine test parameters.

Spindle speeds:	
Low range	60, 140, 220, 300, 380, and 500 RPM
High range	500, 1400, 2300, and 3200 RPM
Capacitance probes	40 mV/micron
Spindle load	0, 20, 40, 60, 80, and 100 Newtons
Data capture rate	5000 points/rev
Capture period	50 revolutions

The PMA is fixtured in the milling machine using a rigid adapter. The static loop stiffness of the machine tool was measured independently to be only 3.5 N/micron. The loads were applied statically in the x-direction in a rough approximation of an average side milling force.

The three-dimensional plots shown in Figure 2 display the rotating sensitive direction error motions of the milling spindle at four different speeds. No attempt was made in this work to separate out radial, tilt, and axial error motion; the plots show a combination of radial and tilt measured 10 cm from the spindle nose. The spindle is observed to rotate at nearly constant speed through the individual tests (less than 0.5% variation in speed). The vertical axis shows the change that occurs with varying static loading in the x-direction of the machine. The severity of the effect of the radial force varies with spindle speed. For example, the data collected at 3200 RPM show the same general three lobed shape for each load case. However, the three lobes become much more pronounced as the load is increased. In fact, at 100 N radial load, the third lobe (bulge) is quite distinct.

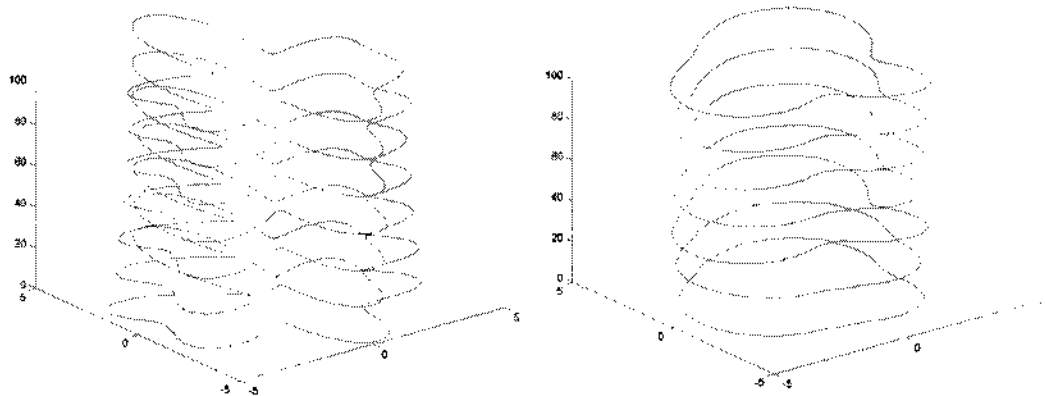


Figure 2: Synchronous error motions (microns) at 1400 and 3200 RPM.

Also seen in the figures is the dramatic difference in overall synchronous error motion at different spindle speeds. The data collected at 1400 RPM indicate error motions that are of substantially higher amplitude than even the error motions measured at higher speed. It is interesting to note that the first structural mode of vibration of this milling machine is around 100 Hz, which corresponds to roughly twice the 3200 RPM driving frequency.

DYNAMIC STIFFNESS TESTING

The changes in dynamic behavior of high speed rotary systems are well known. The literature contains theoretical analyses of high speed machine tool spindles with angular contact bearings. Previously, experimental verification of these models was complicated by the difficulty of applying a time-varying load to a rotating spindle rotor. A special set of experiments was carried out using the portable master axis to investigate changes in dynamic stiffness of a rotating spindle.

Figure 3 shows the frequency response functions for two load levels, 20 N RMS and 40 N RMS. As expected, the nonlinear stiffness of the spindle bearings yields a slight difference in the apparent modal frequency of the third mode of vibration. Note that the other modes of vibration (structural) are unaffected.

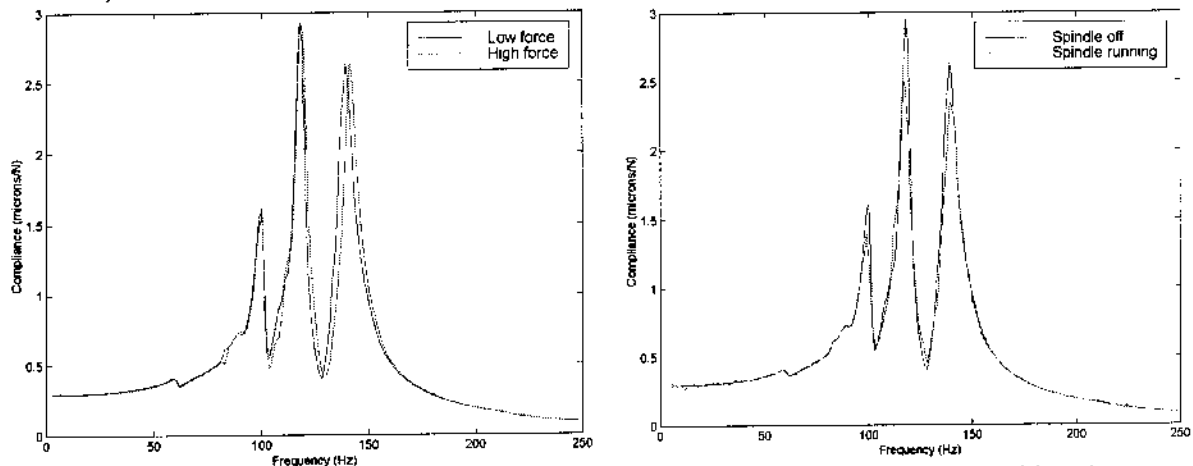


Figure 3 Dynamic compliance of the machine tool at two load and speed levels.

The spindle is then operated at moderate speed and the dynamic compliance again measured. Figure 3 shows two measurements of compliance, one with the spindle idle and the other with the spindle running. The RMS force level is 40 N in both cases. The modal frequencies are the same for both tests, however, the amplitude of the peaks is clearly affected by the spindle running.

CONCLUSION

The portable master axis holds great promise as a tool for axes of rotation metrology. Although it has not been explored in this paper, there is strong evidence to suggest that the uncertainty associated with the Master Axis Method of spindle calibration may be lower than the uncertainty of spindle calibrations performed with traditional artifacts.

As shown in the examples, the portable master axis can be used to measure spindle error motions not only as a function of speed, but also of load. The characteristics of the synchronous error motions were seen to vary with load on a low speed milling spindle. It is expected that further research with higher speed spindles will show even greater dependence with load.

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