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Experiences with the master axis method for measuring spindle error motions

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Abstract

In this paper, the master axis method of machine tool spindle measurement is described. This method allows spindle measurements to be carried out at speed and under load. For example, a radial load representing the cutting force in a turning operation can be conveniently applied during characterization of a lathe spindle. The synchronous and asynchronous error motions have been observed to vary in both magnitude and shape with changes in load. Test results from both static and dynamic loads during testing are shown to demonstrate the utility of the method. © 2000 Elsevier Science Inc. All rights reserved.

Keywords: Spindle metrology; Axes of rotation; Machine tool; Metrology

1. Introduction

Spindle metrology includes the measurement of error motions, compliance, and thermal drift to characterize an axis of rotation [1–4]. The focus of this paper is on the measurement of error motions. Fig. 1 shows the most familiar result of such a spindle analysis, a polar plot of synchronous error motion measured in the radial direction. The error motions of a machine tool are typically measured with capacitance gauges targeting an artifact such as a steel master ball. Spindle measurements provide valuable insight into error motions and performance as a function of rotational speed. Other findings may include a resonance within the spindle drive system, bearing faults, or imbalance of rotating components. A shortcoming of these measurements is that actual cutting forces are not acting on the spindle. Presumably, the cutting forces affect the spindle dynamics and error motions. For example, some milling spindles take cuts large enough to overcome the bearing preload. Bryan has proposed a method of measuring spindle error motions with a master ball while machining. This approach may be suitable for some classes of machine tools [3]. However, a general purpose method of measuring error motions as a function of spindle load (cutting forces) and as a function of spindle speed is necessary to evaluate a broader range of machine tools. The master axis method of characterizing axes of rotation has been proposed as a suitable method of testing spindles under load [5,6]. Fig. 2 shows a spindle under test with an artifact (lapped master ball) and the master axis. A three-capacitance probe nest is shown to illustrate the gauging locations. As shown in the figure, the master axis method is based on the replacement of a lapped master artifact with a master axis of rotation, in this case, an air- bearing spindle. The rotor of the master axis is rigidly attached to the rotor of the spindle under test. Capacitance gauges are rigidly fixed to the machine tool or test stand structure in a position that includes the desired portion of the structural loop. Perhaps the most common configuration is to locate the capacitance gauges on the machine tool table so that the entire structural loop is measured during testing. It should be noted that there are several sources of vibration on a machine tool including motors, pumps, rotating components, and drive systems. These energy sources will cause relative motion in the structural loop. Consequently, the measured errors are actually a combination of spindle and structural motions. In some cases, this structural motion may be significant as compared to the true error motions of the spindle under test. To understand the sources of error motion best, the spindle can be removed from the measurement loop by relocating the capacitance gauges to target the

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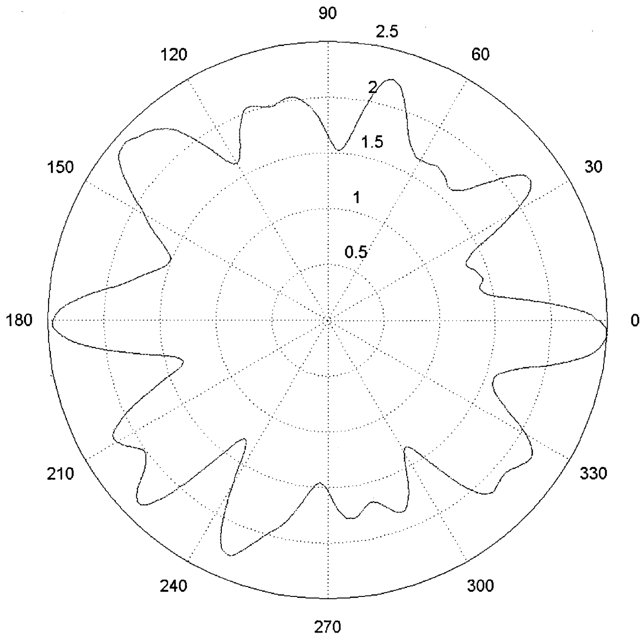

Fig. 1. Rotating sensitive direction synchronous error motion (microns) of a ball-bearing spindle (380 rpm).

quill or spindle housing. Implementation of the proposed approach requires that the master axis stator does not rotate. A simple restraint is shown in Fig. 2b to prevent rotation without constraining the remaining five degrees of freedom. A suitable contact, such as a diamond tip on a lapped gauge block, can be used in precision applications [6]. The motion of the master axis stator will reflect the *x* and *y* tilt, *x* and *y* radial, and axial error motions of the spindle and structure under test. If the gauging (datum) surfaces of the master axis are sufficiently smooth and otherwise ideal conditions are present, a master axis will provide the same error motion measurements as a master artifact. However, several benefits of the master axis motivate its consideration in practical applications of spindle measurement.

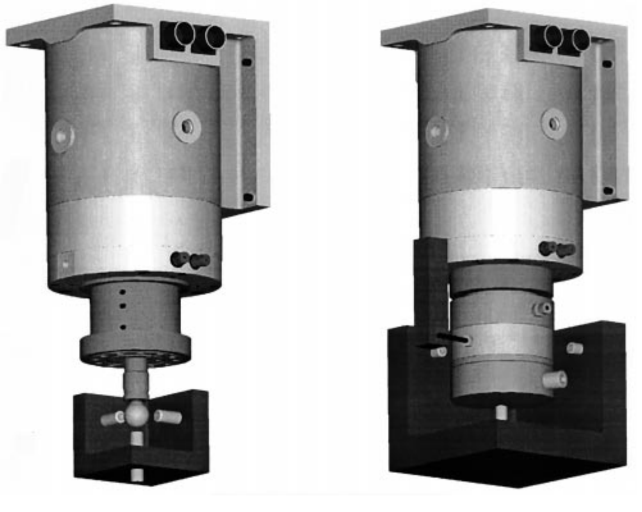

Fig. 2. Spindle error measurement with a spherical master artifact (a) and with a master axis (b). This configuration is representative of how rotating sensitive direction error motions are measured with radial capacitance gauges spaced 90° apart [6].

2. Benefits of the master axis

The master axis method offers several advantages to traditional methods of spindle metrology [3]. In the proposed method, capacitance or eddy current gauges target a stationary surface allowing a reliable electrical ground to be maintained between gauge and target resulting in low noise measurements. Furthermore, a Faraday shield may be used to isolate the gauging components from radio frequency (RF) radiation. Unlike a lapped master ball, the accuracy of the master axis of rotation comes from surfaces that are internal to the air-bearing spindle. This provides a mechanically robust system, which also allows a built-in and well-aligned rotary encoder. The reversal methods introduced by Donaldson and Estler may be used with either artifacts or the master axis to improve measurement accuracy further [7,8]. Liebers et al. describe the use of the master axis to detect faults in individual spindle bearings [6]. Using rigid brackets mounted to the master axis stator, radial error motions can be measured in line with the functional plane of interest (e.g., the plane of the bearings). This method has been nicknamed the “over-the-shoulder” method. Such measurements exclude the influence of structural error motion in the rest of the structural loop and target a nonmoving surface. Bryan (personal communication) suggests that the term “stationary point runout” be used to describe this type of measurement. The stationary gauging surface of the master axis provides an additional capability that is the subject of the balance of this paper. The nonrotating stator of the master axis may be conveniently used to simulate different loading (i.e., cutting) conditions during testing. For example, the error motions of a turning or milling machine may be measured using statically or dynamically applied forces. Furthermore, the compliance of a hydrodynamic spindle bearing may be conveniently tested while rotating.

3. Experimental setup

A series of experiments are described that demonstrate the use of a portable master axis (PMA). The PMA is a specific embodiment of the master axis concept that may be used to assess the error motions of machine tools. The experiments are performed on a Bridgeport milling machine equipped with the standard ball-bearing spindle and variable speed drive. As mentioned in the previous section, static or dynamic loads can be applied to the master axis during testing. In the first experiment, a static load is applied in the cross-axis (*x*)-direction in a rough approximation of an average side milling force. A wire attaches to the master axis stator and carries a static load provided by weights

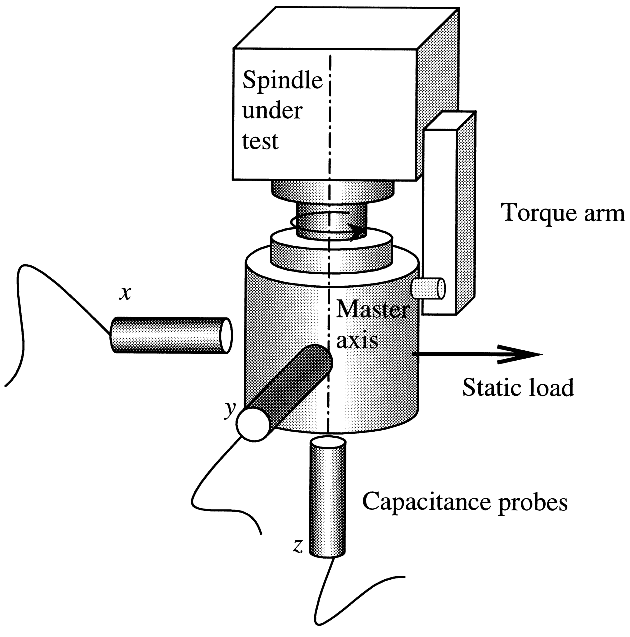

Fig. 3. Schematic of the master axis with three capacitance probes.

Table 1
Milling machine test parameters

Spindle speeds:	
Low range	60, 140, 220, 300, 380, and 500 rpm
High range	500, 1,400, 2,300 and 3,200 rpm
Capacitance probes	40 mV/micron
Spindle load	0, 18, 36 53, 71, 89, 107 N
Data capture rate	5,000 points/rev
Capture period	50 revolutions

hanging to the side of the machine. The wire cannot carry a moment, resulting in a nearly pure radial load on the master axis. Fig. 3 shows the PMA installed on the vertical milling spindle. In the second experiment, the static load is replaced with a 100 Newton electrodynamic shaker to apply dynamic loads in the *x*-direction. The PMA shown in Fig. 3 is built from a Professional Instruments BLOCK-HEAD 3R spindle with an integral Data General, 1024 count rotary encoder. The 3R spindle is rated to 15,000 rpm with error motions less than 25 nanometers. The integral rotary encoder provides tachometer and timing pulses used in data collection and spindle error motion calculations. The PMA is held in the milling machine with a collet holding a 2-cm arbor rigidly bolted to the rotor of the master axis. All measurements are made with Lion Precision DMT10 capacitance gauges calibrated to 40 mV/micron. The tests are performed with both *x* and *y* capacitance gauges to calculate the rotating sensitive direction error motions. The probes are mounted directly to the machine table using stiff indicator mounts and precision ground 246 blocks. The capacitance probe data and encoder output are sampled and stored using a Hewlett-Packard 35670A data acquisition system for off-line analysis. MATLAB scripts are used to manipulate the data files, analyze the data, and produce the plots that follow. The approach to the data analysis follows the framework of the ANSI Standard B89.3.4M (1985) on Axes of Rotation. Although the B89 standard suggests that error motion polar plots be centered using minimum radial separation, the computer has since made least-squares centering the preferred choice for most applications. The spindle and structural error motions are measured under various combinations of speed and load to explore the machine's behavior under a range of conditions. The static load experimental tests are performed by measuring the error motions at 10 different spindle speeds and seven different levels of load, resulting in 70 tests. The 70 tests are carried out with the capacitance gauges targeting the master axis and repeated by targeting the quill to assess both the total error motion and the error motion of the structural loop without the spindle. Separate tests were run with a lapped master ball to validate the master axis results. Table 1 outlines the parameters used in the spindle error motion measurements. An important consideration for spindle testing is the eccentricity of the artifact or master axis. Spindle metrology literature includes several papers in which the eccentricity of the artifact mounting is used to generate the base circle of an oscilloscope polar plot [2]. In our work, the master axis is centered to within a micron to minimize the imbalance on the rotating system. This is accomplished by loosening the 12 screws that bolt the master axis to the spindle under test and tapping the joint to adjust the eccentricity. A better approach would be to use a flexure arrangement allowing convenient adjustment of both eccentricity and parallelism. The static loop stiffness (*x* direction) of the milling machine was measured and verified in separate tests to be 3.5 N/micron.

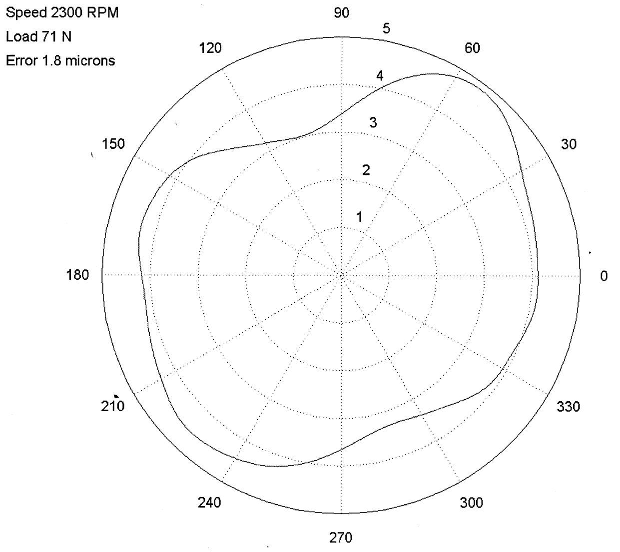

Fig. 4. Rotating sensitive direction synchronous error motion at 2,300 rpm.

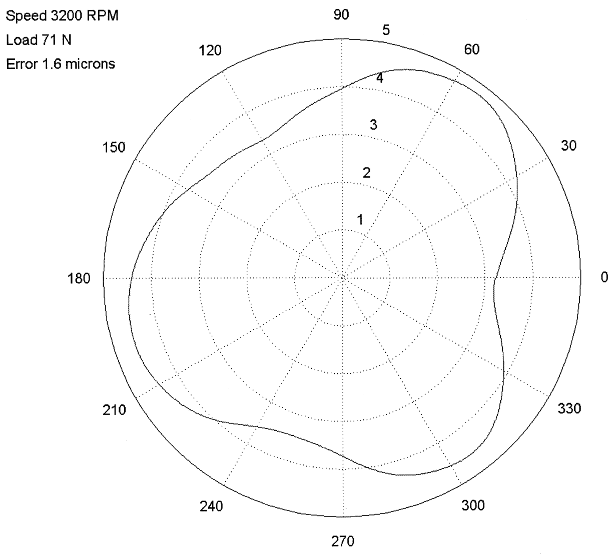

Fig. 5. Rotating sensitive direction synchronous error motion at 3,200 rpm.

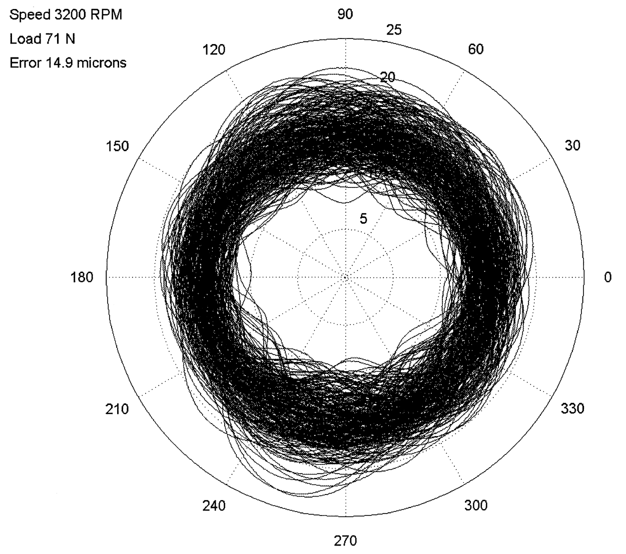

Fig. 7. Rotating sensitive direction asynchronous error motions at 3,200 rpm.

4. Spindle testing at speed, under load

Before testing, the spindle was run for 30 minutes without load at 500 rpm in the high-speed range to reach operating temperature. During testing, the spindle is observed to rotate at nearly constant speed with less than a 0.2% variation in speed over the length of a given test. The polar plots of Figs. 4–7 show the rotating sensitive direction error motions of the spindle at two different speeds in the milling machine's high- speed range. The error motions vary strongly with spindle speed; plots of 2,300 and 3,200 rpm at a radial load of 71 N are chosen for illustrative purposes. As will be seen, the error motion of the spindle becomes worse with increasing load at 3,200 rpm, but better with load at 2,300 rpm. For this reason, an intermediate load was selected for the synchronous and asynchronous polar plots. The plots reflect the combination of pure radial and tilt measured 10 cm from the spindle nose. Figs. 4 and 5 show polar plots of the synchronous error motion of the spindle that are calculated by averaging the total error motion over 50 revolutions of the spindle. The four-lobed characteristic of the 2,300 rpm synchronous error motion occurs corresponds to the same frequency as the three-lobed plot at 3,200 rpm. As shown in Figs. 6 and 7, the asynchronous error motions of the Bridgeport milling machine are of substantially greater magnitude than the synchronous. It should be noted that the error motions in the low-speed

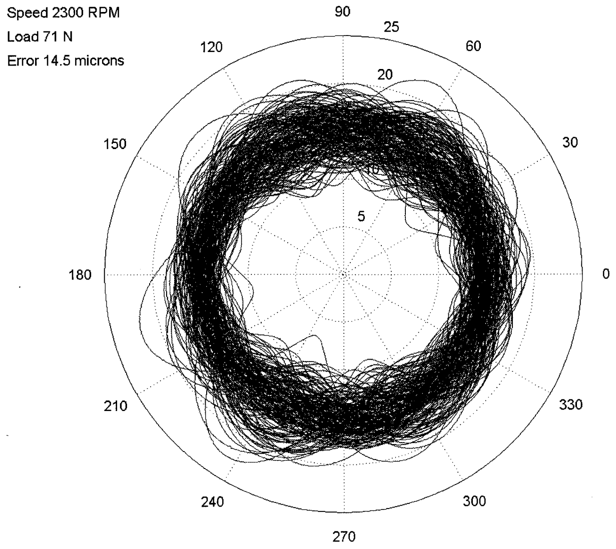

Fig. 6. Rotating sensitive direction asynchronous error motions at 2,300 rpm.

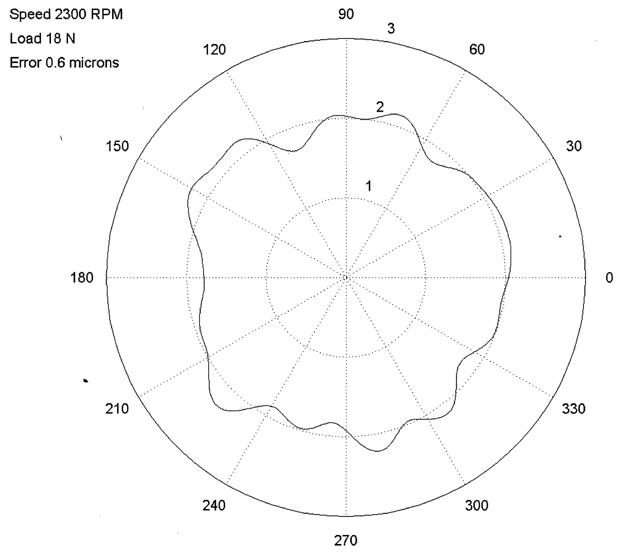

Fig. 8. Rotating sensitive direction synchronous error motion of the quill at 2,300 rpm.

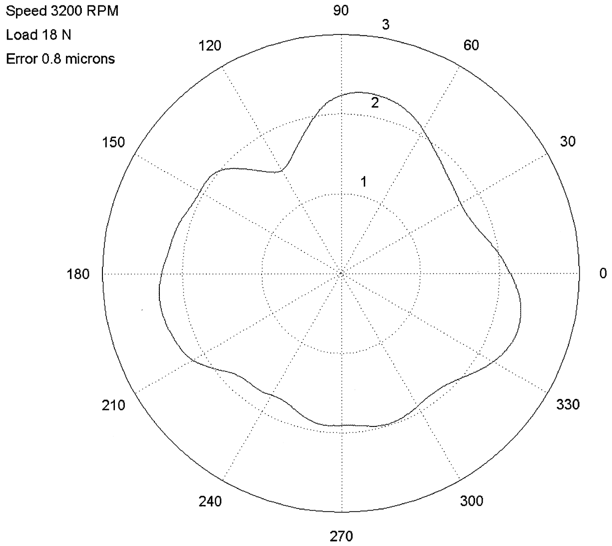

Fig. 9. Rotating sensitive direction synchronous error motion of the quill at 3,200 rpm.

range (not shown) are generally much smaller than the amplitude of the high speed range. The error motion polar plots shown in Figs. 4–7 include the contribution of the spindle as well as the vibration present in the rest of the structural loop (structural error motion). The motion of the quill relative to the workpiece was measured separately. Figs. 8 and 9 show that the quill moves with considerable amplitude and a different pattern during the rotation of the spindle, presumably as a result of imbalanced drive components and a relatively compliant structure. Therefore, the errors shown in the results of this study cannot be attributed solely to the spindle, and, in fact, provide insight into the behavior of the entire machine tool. Figs. 10 and 11 show the synchronous error motions plotted as a function of radial load. The four traces shown in each figure correspond to the different load levels ranging from 0 to 107 N. The data collected at 2,300 rpm suggest that the synchronous error motion becomes smaller with increasing load. However, with the exception of the 36 N trace, the 3,200 rpm data show the opposite trend, and the synchronous spindle error motion grows with load. The three lobes of the 3,200 rpm traces become more distinct as the load is increased. In fact, at 107 N load, the third lobe (on the right-hand side) is quite pronounced, as compared to the 0 N trace at the bottom of the figure. The polar plots also reveal operating speeds that would not be favorable under the test conditions. The data collected at 1,400 rpm (not shown) indicate error motions that are of substantially higher amplitude (5.5 microns) than even the error motions measured at 3,200 rpm. 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 3,200 rpm driving frequency.

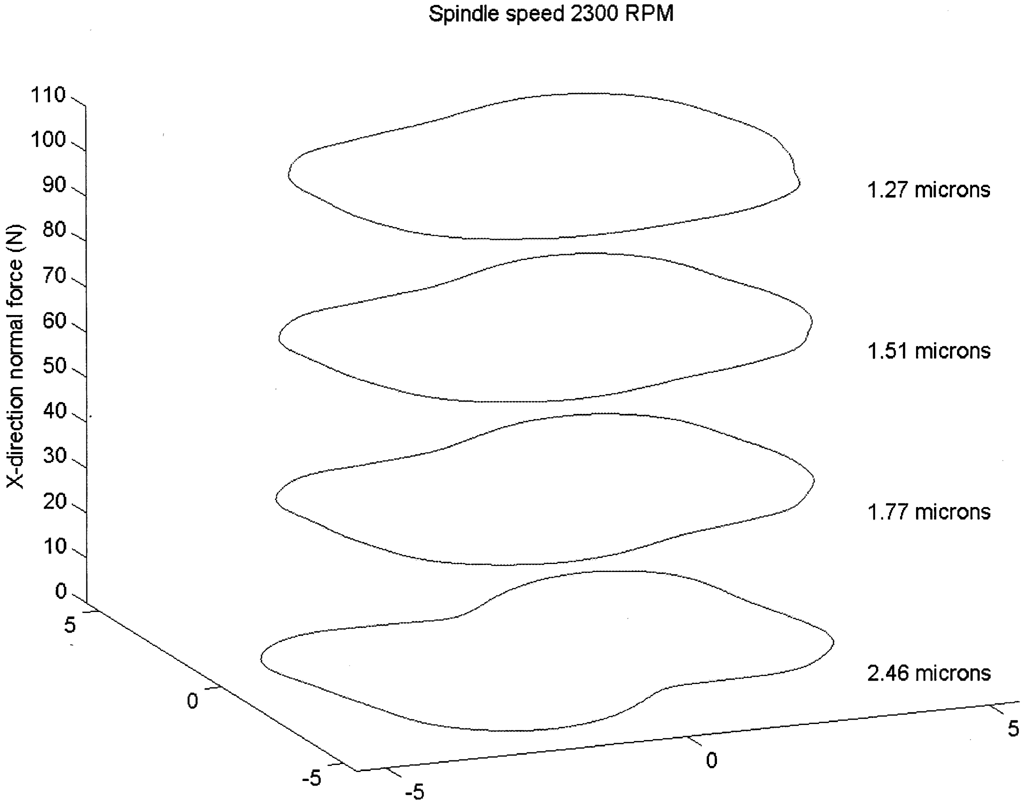

Fig. 10. Rotating sensitive direction synchronous spindle errors with varying radial load (2,300 rpm).

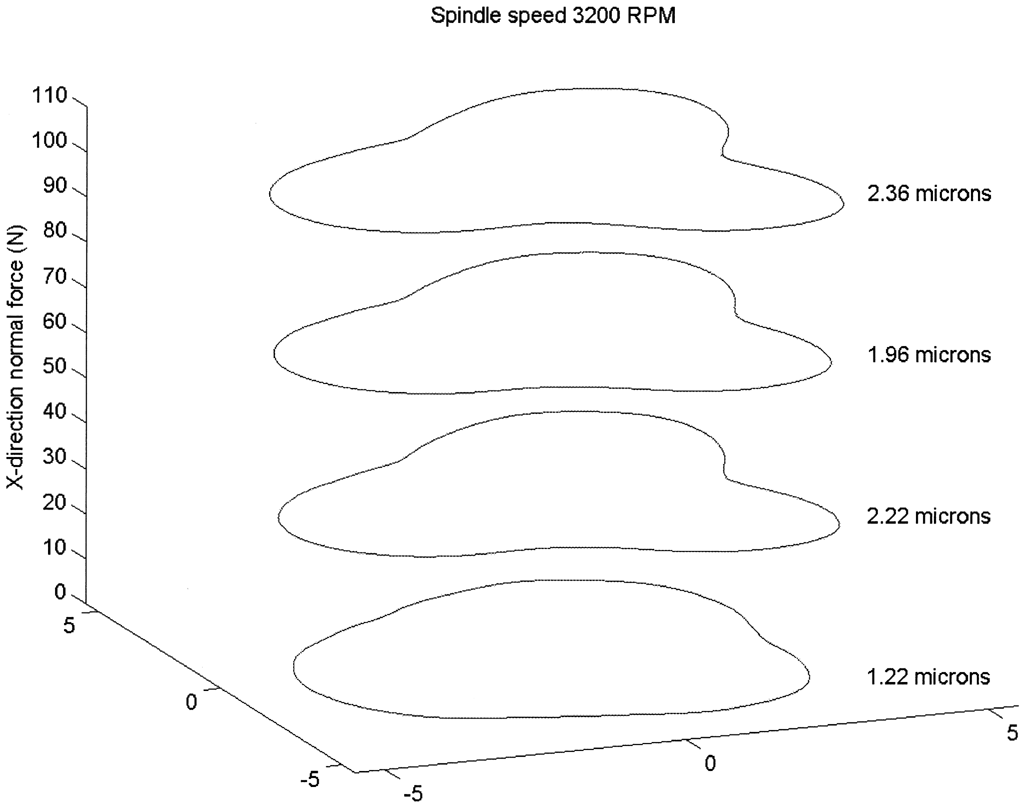

Fig. 11. Rotating sensitive direction synchronous spindle errors with varying radial load (3,200 rpm).

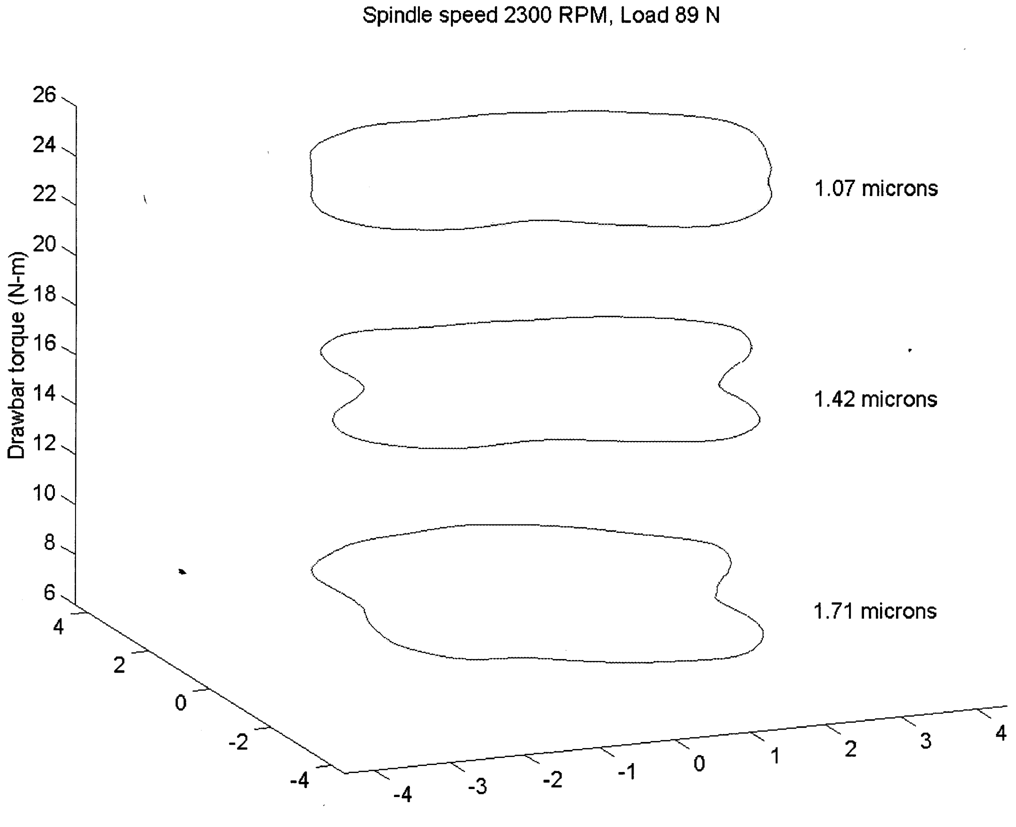

Fig. 12. Synchronous radial error motion for three levels of drawbar torque.

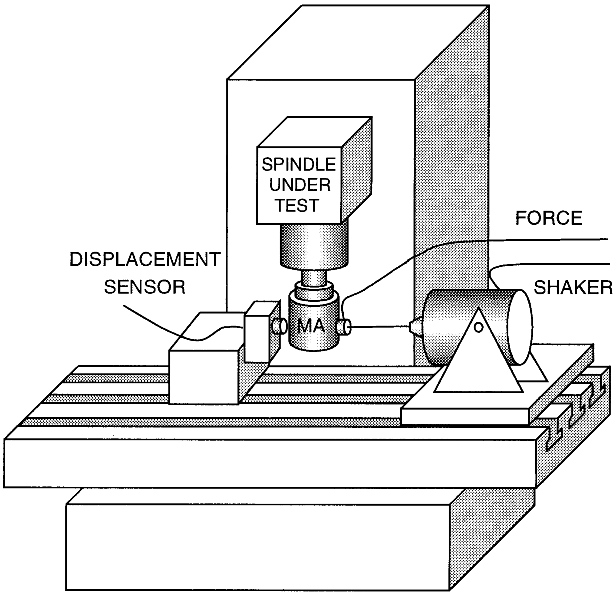

Fig. 13. Test setup for measuring dynamic stiffness at speed on a milling machine.

5. Drawbar testing

Separate tests were made to explore the role of drawbar torque on the Bridgeport spindle. The manufacturer does not provide a specific recommendation, but it is widely recognized that drawbar torque may influence spindle performance. The synchronous error motion results for a spindle speed of 2,300 rpm and 89 N radial load are shown in Fig. 12. As shown in the figure, the error motion shape and magnitude improve appreciably as the drawbar torque is increased to 26 N/m from 8 N/m. Notably, the four lobes of the synchronous error become less pronounced as the drawbar torque is increased.

6. Dynamic stiffness testing

The study of the dynamic behavior of high-speed rotary systems has developed into a mature field of research. Included in this body of work are theoretical analyses of high-speed machine tool spindles with angular contact bearings [9]. Previously, experimental verification of these models was complicated by the difficulty of precisely applying a known time-varying load to a rotating spindle. The master axis allows the application of dynamic forces during measurement of the rotating spindle. Therefore, a separate set of experiments is carried out using the portable master axis to investigate changes in dynamic stiffness of a rotating spindle. Fig. 13 shows the test setup used in this study. First, dynamic compliance measurements are taken with the spindle stopped. A time-varying load (i.e., white noise) is ap-

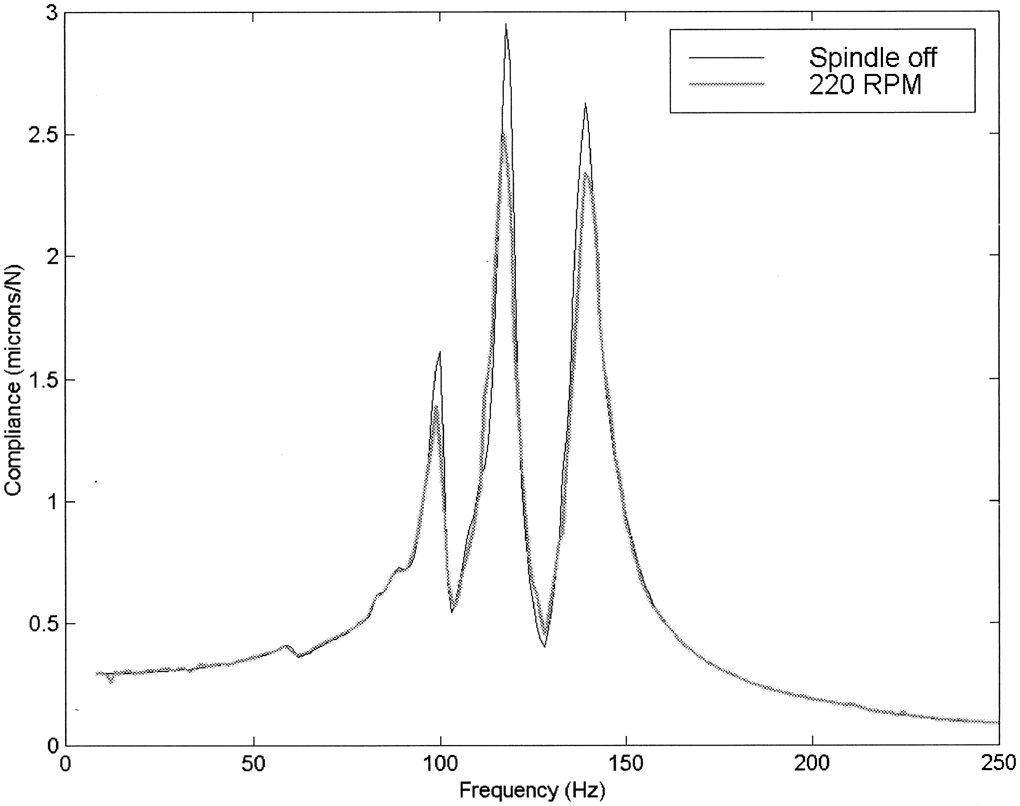

Fig. 14. Dynamic compliance of the machine tool structural loop at rest and rotating.

plied to the portable master axis and measured with a Kistler 10 mV/N force transducer. The resulting relative motion between spindle and table is measured with a Lion Precision DMT10 capacitance gauge. The spindle is then operated at speed (380 rpm) and the dynamic compliance again measured. Fig. 14 shows the at-speed compliance along with the compliance of the spindle at rest. The rms force level is 40 u.c. in both cases. The modal frequencies are the same for both tests; however, the peak amplitudes are clearly affected by the running spindle (15, 15, and 10% reduction in peak amplitude). Care must be taken in these tests to ensure that the coherence is satisfactory, because both the force excitation and the error motion inherent in the rotating spindle influence the dynamic measurement. For this spindle, the motion resulting from a 40-N rms dynamic force is much larger than the error motions of the unloaded spindle. As a result, good coherence is obtained in the measurements. Furthermore, inspection of the spectra taken with and without load (not shown) show that the changes in compliance are attributable to the applied dynamic load. In other words, the system is nonlinear.

7. Conclusion

The portable master axis holds great promise as a tool for axes of rotation metrology. Although it has not been fully explored in this paper, there is strong evidence that the master axis method offers lower uncertainty than conventional artifacts. This paper explores the application of the master axis method to the measurement of a milling machine spindle. As shown in the experimental results, a 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 are seen to vary with load as well as speed on the milling spindle. It is expected that further research with higher-speed spindles will show even greater dependence with load. Finally, the compliance of a spindle can be measured using the portable master axis at speed. Ongoing work with the PMA will further explore the correlation between previous efforts to model machine tool spindles with actual testing results.

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