Real time control of spindle runout

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Abstract. An example of a physical system whose mechanical accuracy can be improved by feedback control is a motor-driven spindle. Such a system is being used as a test-bed to study measurement and actuation systems as well as control algorithms. The specific apparatus reported utilizes an eddy-current probe for runout error measurement, a piezoelectric crystal to move the spindle to reduce the error, and a minicomputer using a FORTRAN program for the feedback controller. The spindle runout before correction is in the 2.5 μm (100 μin.) range; with the error correction system in place, this error is reduced to less than 0.25 μm (10 μin.)—an order of magnitude improvement. While the corrected runout figures for this spindle are still above those of a precision air-bearing spindle, the technique presents new possibilities for precision spindle performance including correction for wear, thermal deformations, and unbalanced loads.

Subject terms: optical fabrication; spindle; real-time error correction; precision feedback control.

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CONTENTS

1. INTRODUCTION

The machining of optical components requires precise control of the position of the cutting tool with respect to the workpiece. One method of producing such precision parts is single-point diamond turning, in which a stationary diamond tool is used to machine a workpiece mounted on a rotating spindle. Clearly, the precision of such a diamond turning machine is limited by the performance of its spindle. Unless compensated for, any errors in the perfection of the spindle will be reflected in the cut made by the tool on the workpiece. Spindle rotation errors can originate from thermal deformation of the spindle components, imperfections in the spindle support bearings, wear, and imperfections in the squareness and flatness of the spindle face.[1-4] In a given sensitive direction, these errors combine to make up the runout of the spindle. Spindle runout is defined as the total indicator reading between a fixed displacement sensor and a surface of the rotating spindle. It consists of the previously mentioned spindle errors combined with any deformations in the structural loop linking the sensor to the spindle.[3]

To provide a reference in measuring the radial runout of a spindle axis, a master ball is centered above the axis. Radial runout is measured with a probe aligned perpendicularly to the spindle axis (Fig. 1), and it arises from five classes of errors: (1) errors in centering the master ball above the spindle axis, (2) errors in the sphericity of the master ball, (3) thermal and mechanical deformations of the structural loop, (4) tilt error motion of the spindle, and (5) radial error motion of the spindle.

In the past, the tactic most widely used in obtaining an ultraprecision spindle has been to carefully construct the spindle from precisely machined parts and to use hydrostatic fluid bearings to support the spindle axis.

The purpose of this paper is to present an alternative method of obtaining an ultraprecision spindle, by means of closed-loop control of the spindle's radial runout. The aim is to demonstrate that the runout of a ball bearing spindle can be controlled by the use of real-time feedback to piezoelectric transducers that will move the spindle axis as it rotates, resulting in a substantial decrease in the radial runout.

The concept of a corrected spindle is that a blend of standard machining practices and digital feedback control can be used to achieve a level of spindle performance that is presently available only through ultraprecision machining coupled with hydrostatic bearings. The potential of a feedback-controlled spindle exceeds even that of an ultraprecise uncontrolled spindle in that the feed-

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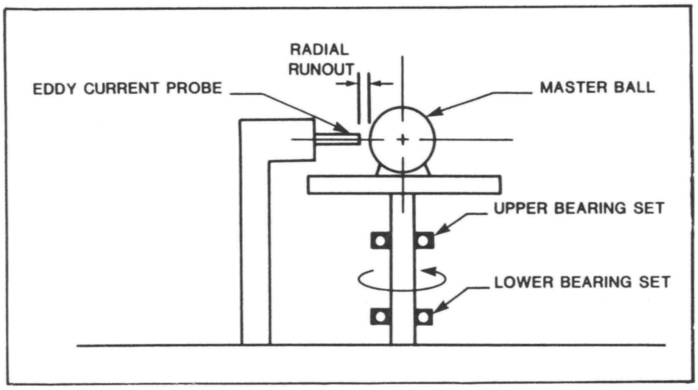

Fig. 1. Radial runout of a spindle measured with a master ball reference.

back loop provides the unique ability to compensate for changes in spindle loading, vibration, and thermal deformations.

Although the feedback-controlled ball bearing spindle discussed is designed to rival the performance of an air-bearing spindle, the two approaches are not mutually exclusive. Ultimately, combining feedback control with an ultraprecision spindle and appropriate transducer-detector systems could result in a substantial increase in the state of the art of spindle performance.

2. SPINDLE AND CONTROL SYSTEM DESIGN

At the heart of the apparatus is a pair of ABEC 9, 12 mm bore duplex ball bearings mounted on a steel shaft (Fig. 2). The bearings are press fit into a steel housing that is attached by eight cantilever springs to the spindle support housing. The spindle support housing in turn is rigidly connected to a vibration-isolated table. The cantilevers are designed to allow motion in one horizontal direction x and in the vertical direction z but are extremely stiff in a perpendicular horizontal direction y. Three piezoelectric transducers are mounted in the spindle support housing. In response to changes in input voltage, these PZTs expand or contract, providing a proportional force to move the bearing housing against the restoring force of the cantilever springs. Two PZTs are mounted horizontally in the least stiff direction x of the bearing housing at the upper and lower bearing centers. The third PZT is mounted vertically beneath the center of the spindle axis z and provides the potential for axial error motion control of the spindle. For the data presented in this paper, runout correction is accomplished using only the upper horizontal PZT. This is the simplest configuration that demonstrates the correction technique.

A 100 mm (4 in.) diameter by 25 mm (1 in.) thick aluminum plate is mounted on the tapered end of the spindle shaft and forms the spindle face. The plate and shaft are rotated by means of a dc servomotor and a belt. A 500 pulse/revolution incremental encoder, also belt driven, is used in conjunction with a once-per-revolution magnetic pickup to trigger data collection. On top of the spindle face is the 37 mm (1.5 in.) diameter master ball that rests on a three-point support. The support rests on the spindle face and can be tapped lightly to center the master ball over the spindle axis.

A noncontacting eddy-current probe is mounted horizontally in the spindle's x-direction and faces the equator of the ball. The probe is capable of resolving microinch changes in the position of the master ball. It is mounted in a support frame that is bolted to the spindle support housing. The structural loop linking the probe to the spindle consists of the probe support and the spindle support housing. Any deformations in this structural loop will contribute to the measured spindle runout.

A schematic of the runout signal path used for feedback control is shown in Fig. 3. The eddy-current probe detects radial runout and outputs a voltage proportional to the gap between the probe face and the master ball. Since the probe is noncontacting, its output is always offset at some dc level proportional to the initial gap

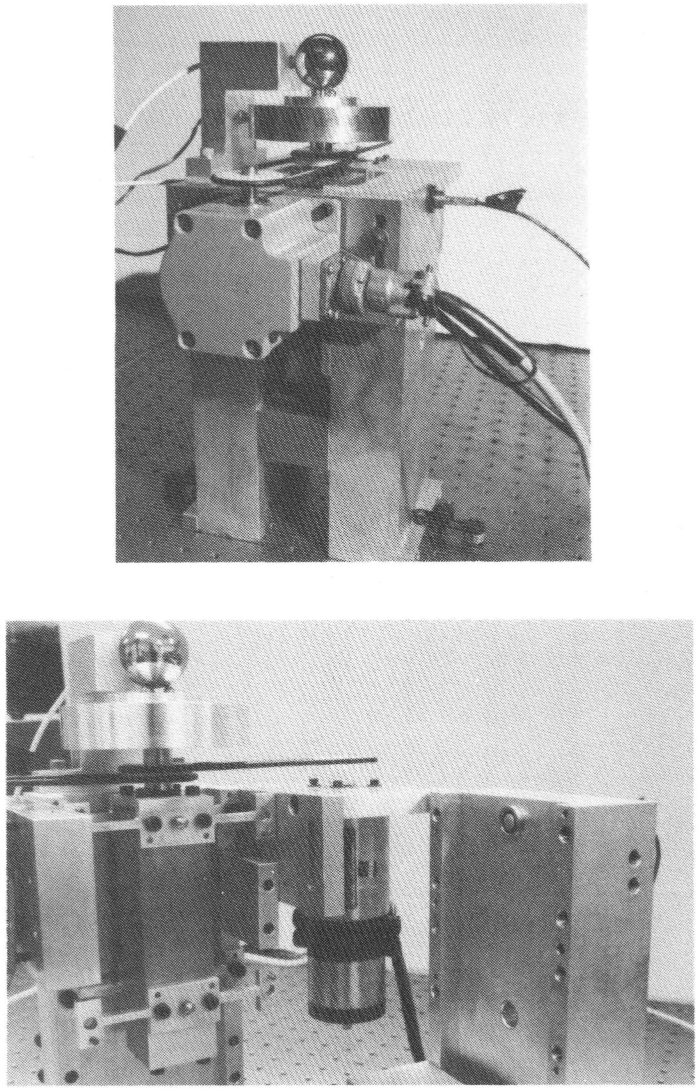

Fig. 2. Experimental spindle apparatus.

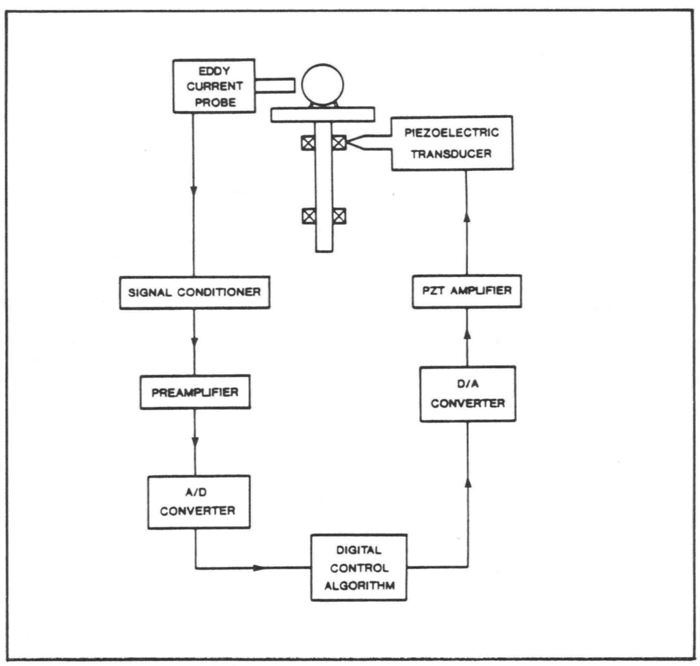

Fig. 3. Schematic of feedback signal path.

width. This dc level is subtracted by manually adjusting a signal conditioning operational amplifier circuit until the signal's dc level is nearly zero. The signal is then amplified and input to the minicomputer that contains the real-time control software.

The output of the control algorithm is transferred from a D/A port on the computer to the PZT amplifier, which provides a driving voltage for the piezoelectric actuator adjacent to the spindle's upper bearing set. The net effect of this integrated system is to incrementally tilt the spindle in opposition to any radial runout so as to eliminate that runout.

2.1. Control algorithm

The control algorithm is a discrete form of integral feedback control. In a continuous system, integral feedback control is governed by the following formula:

$$K \int E dT = G , \tag{1}$$

where K is the gain, E is the error signal, T is the time, and G is the output signal. In this particular case, E represents the runout signal and G represents the feedback signal sent to the PZT. While T is equal to time, it can be converted into an equivalent angular spindle displacement if the spindle rotational speed is known.

Differentiating Eq. (1), we obtain

$$KE = \frac{dG}{dT} . \tag{2}$$

To bring this equation into discrete form,

$$KE_t = \frac{\Delta G}{\Delta T} = \frac{G_t - G_{t-\Delta T}}{\Delta T} . \tag{3}$$

Rearranging,

$$(K\Delta T)E_t + G_{t-\Delta T} = G_t . \tag{4}$$

Replacing $K\Delta T$ with an equivalent gain K' yields

$$K'E_t + G_{t-\Delta T} = G_t , \tag{5}$$

which is exactly the computational algorithm used by the feedback control software.

This FORTRAN program beings by obtaining a digital runout sample E from a 12 bit successive approximation A/D converter. The sample is multiplied by an appropriate scaling factor that depends on both the gain K and the sampling rate ΔT [see Eq. (4)]. This scaled error is added to the previous output value $G_{t-\Delta T}$, and the resulting sum G_t is sent out through a digital-to-analog port to the PZT amplifier.

The integral control algorithm described by Eqs. (1) through (5) is intentionally straightforward and concise. It will serve to demonstrate the dramatic potential for real-time ultraprecision control using no more than a rudimentary algorithm coupled with a conventional ball bearing spindle.

2.2. Results and discussion

The master ball to be used as a reference can be centered by tapping its support base lightly while following a trace of the runout on an oscilloscope and manually rotating the spindle. Using this simple technique, the runout can be reduced to a level of less than 2.5 μm (100 μin.) peak-to-peak.

With a perfect axis of spindle rotation and a perfectly spherical master ball, the radial runout measured against an off-center ball would be (in rectilinear coordinates of runout versus rotation angle) a sinusoidal wave having an amplitude equal to the magnitude of the centering error and a period of one spindle revolution. In polar coordinates, the runout would appear as a circle with a center displaced from the polar chart center by the magnitude of the centering error. Although it is common to attempt to separate radial spindle axis error motion (i.e., tilt error motion and radial error motion) from centering errors in evaluating a spindle's performance, the two are generally impossible to decouple; a once-per-revolution runout component can occur indistinguishably from either.

Clearly, ball centering errors are unrelated to spindle performance; they represent a type of systematic measurement error. To interpret the runout signal measured against a master ball, the assumption is usually made that the spindle itself has no once-per-revolution runout component. Using this assumption, spindle error can be measured from a statistically or geometrically derived center based on the entire record of runout data.

This postprocessing of the runout data to eliminate centering errors poses a problem for real-time feedback control, in which the spindle's center of rotation must be predefined as a reference for correction purposes. Thus, the control algorithm does not permit the use of an averaged center of rotation, and runout measurements are not compensated for ball centering errors. One solution to this problem is to first roughly center the ball, then use the vertical axis of the ball as the assumed center of the spindle rotation. In this way, the ball is assumed to be perfectly centered, and all radial runout is contributed to either spindle error motion, master ball out-of-roundness, or deformations in the structural loop. In effect, this creates a predefined spindle axis free from ball centering errors. All efforts to evaluate or control the spindle runout are made against this newly defined spindle axis.

Correction is based upon the distance between the stationary eddy-current probe and the rotating master ball; consequently, any out-of-roundness of the ball or thermal expansions in the structural loop between the ball and the probe will not be compensated for by the control algorithm. In effect, the control loop forces the spindle to follow a rotational profile equivalent to the profile of the master ball. The master ball used on this spindle is a Grade 5 tungsten carbide ball, conforming to a tolerance of ±0.1 μm (+5 μin.) sphericity.

As mentioned previously, deformations in the structural loop are not diminished by the control algorithm. To reduce these errors, the entire apparatus is mounted on a vibration-isolated table located in a temperature-controlled clean room (±0.1 °C). Under these conditions, static drift of the displacement sensor with respect to the master ball is reduced to less than 10 μin. over a period of 12 h.

The remaining radial runout consists primarily of spindle error motion due to tilt and radial error motions. Polar coordinate plots are a standardized method of representing this type of spindle error motion. The important parameters of such a plot of error motion are[3] (1) polar chart center (PC), the center of the polar chart; (2) minimum radial separation center (MRS), the center that minimizes the radial difference between two concentric circles that contain the error motion polar plot; and (3) total error motion value (TEMV), the scaled difference in radii of two concentric circles from the error motion center (either PC or MRS) just sufficient to contain the error motion plot.

The MRS center is used as a standard for calculations of radial and tilt error motions. It is used instead of the PC center in an effort to minimize master ball centering errors. As described previously, the master ball on this spindle *defines* the spindle axis. All total error motion values therefore will be computed with respect to the polar chart center. The plot of the perfect spindle rotation, then, would be a circle centered upon the origin of the polar plot.

Figure 4 shows an oscilloscope trace of runout versus angular spindle position for approximately five revolutions of the spindle (time duration = 20 s). The peak-to-peak runout in this case corresponds to 2.5 μm (100 μin.) of spindle error motion in the radial direction. The same data are presented in polar coordinates in Fig. 5. Note that the presence of a significant once-per-revolution com-

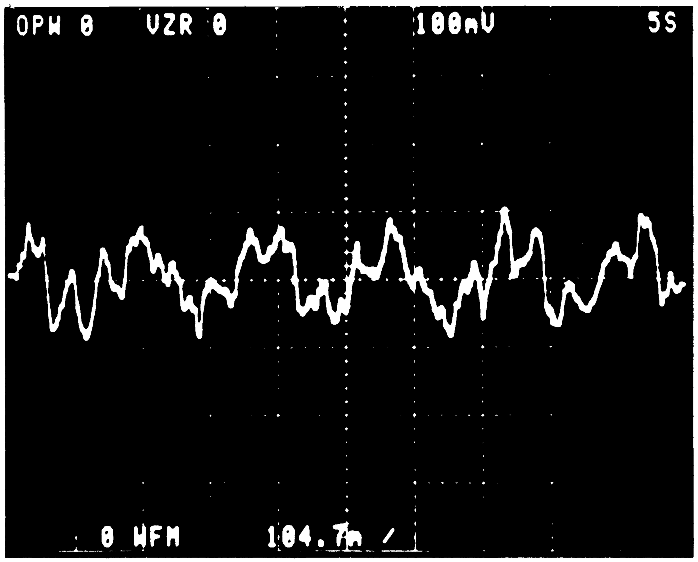

Fig. 4. Uncorrected radial runout versus angular spindle position for five revolutions. Vertical scale = 1.3 μm (55 μin.) / division; horizontal scale = 180° rotation / division.

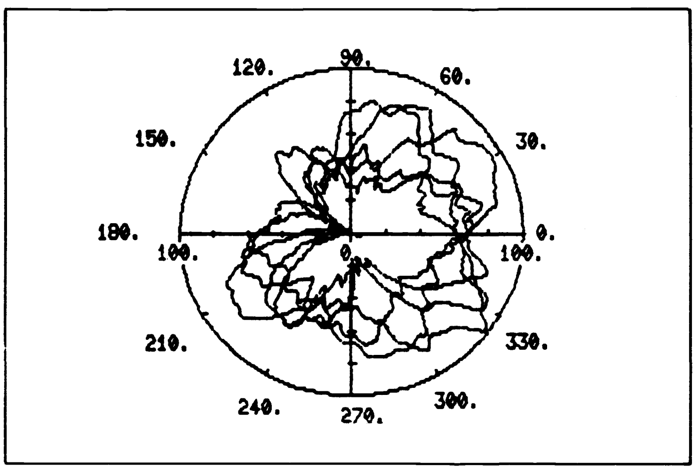

Fig. 5. Uncorrected radial runout versus angular spindle position for five revolutions. TEMV = 2.5 μm (102 μin.).

ponent in the rectilinear plot of Fig. 4 appears as a center offset in the polar plot. Using the PC center, a total error motion value is 2.5 μm (102 μin.).

It is important to note that this TEMV is based on a spindle center of rotation that is defined along the axis of the master ball. A TEMV based on an average center for the runout data would be somewhat less than 2.5 μm and is more indicative of the spindle's actual uncontrolled performance. The 2.5 μm TEMV, however, is the magnitude of the error that must be corrected and is therefore a more relevant representation of the runout data in this case.

Figure 6 shows an oscilloscope trace of the radial runout during the transition from uncontrolled to controlled spindle motion, illustrating a dramatic decrease in the spindle's total radial error motion. A rectilinear trace of the controlled spindle runout over approximately five revolutions is shown in Fig. 7, while Fig. 8 shows the polar plot of the same data. It is easy to see from these plots that the effect of the control algorithm is to center the rotation of the spindle around the ball axis and to reduce the higher order fluctuations of the centered spindle motion. The resulting total error motion value is approximately 0.25 μm (10 μin.), representing an order of magnitude improvement in the radial runout.

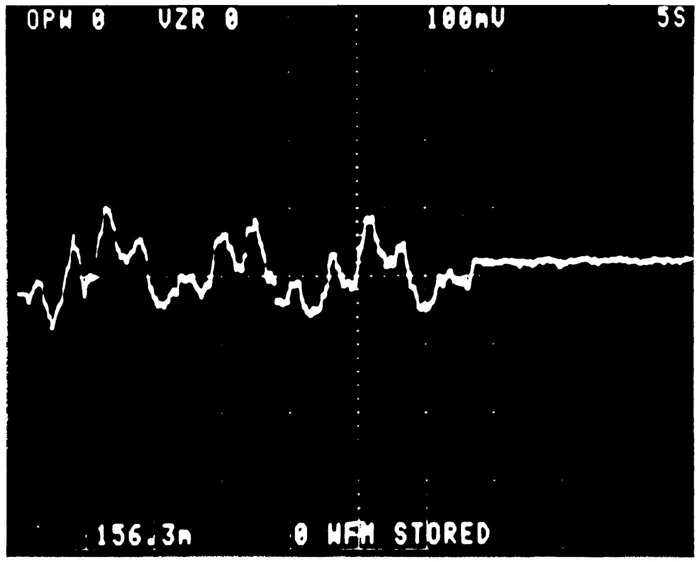

Fig. 6. Transition from uncontrolled spindle runout to controlled spindle runout. Vertical scale = 1.3 μm (55 μin.) / division; horizontal scale = 180° rotation / division.

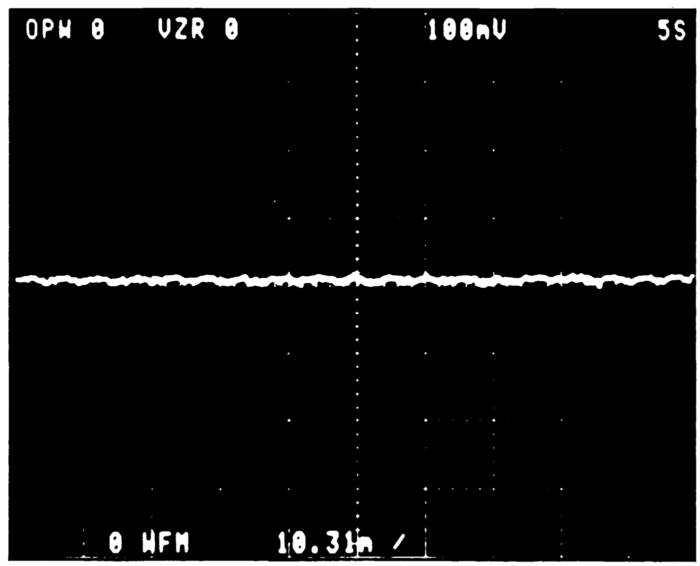

Fig. 7. Corrected radial runout versus angular spindle position for five revolutions. Vertical scale = 1.3 μm (55 μin.) / division; horizontal scale = 180° rotation / division.

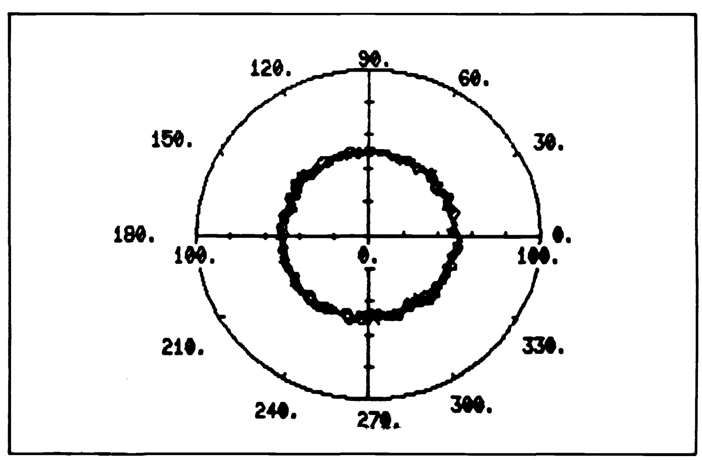

Fig. 8. Corrected radial runout versus angular spindle position. TEMV = 0.25 μm (10 μin.).

Although the corrected spindle's total error motion value represents a substantial increase in the spindle performance, by no means has a minimum runout limit been reached for this system. Planned improvements promise to extend capabilities of this spindle in a variety of respects. To permit the spindle to operate at higher rotational speeds, an assembly language control loop will be implemented, increasing the A/D sampling rate and decreasing the deleterious effects of phase lag between error input and feedback output. In addition, the horizontal piezoelectric transducer located at the spindle's lower bearing set will be incorporated into the control scheme, allowing more complete control over radial and tilt error motions. To include this transducer, a more complex control algorithm will be utilized, including compensation for instantaneous error velocity.

After the radial runout for this spindle has been optimized, the next step involves simultaneously controlling both radial and axial runout.

Clearly, the potential for reducing spindle error motion through feedback control is substantial. An order of magnitude decrease in radial runout can be accomplished with a single detector-force transducer pair, controlled by a simple integral control algorithm. Refinements of this technique, including two- and even three-axis control, are possible, promising new possibilities for the state of the art of ultraprecision spindle performance.

3. ACKNOWLEDGMENT

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4. REFERENCES

1. J. Bryan, R. Clouser, and E. Holland, American Machinist Special Report No. 612, 149 (Dec. 4, 1967).
2. Robert Donaldson, American Machinist, 57 (Jan. 8, 1973).
3. American National Standards Institute, Ann. CIRP 25(2), 545 (1976).
4. John M. Casstevens, Oak Ridge Y-12 Plant Document Y/DA-7751 (1978).