Precision Machine Design

Topic 7

Mapping geometric and thermal errors in a turning center[1]

Purpose:

It is important for the machine design engineer to be aware of the measurement processes that the machine will be subject to after it is built. This can help the designer to make sure that the design is measurable.

Outline:

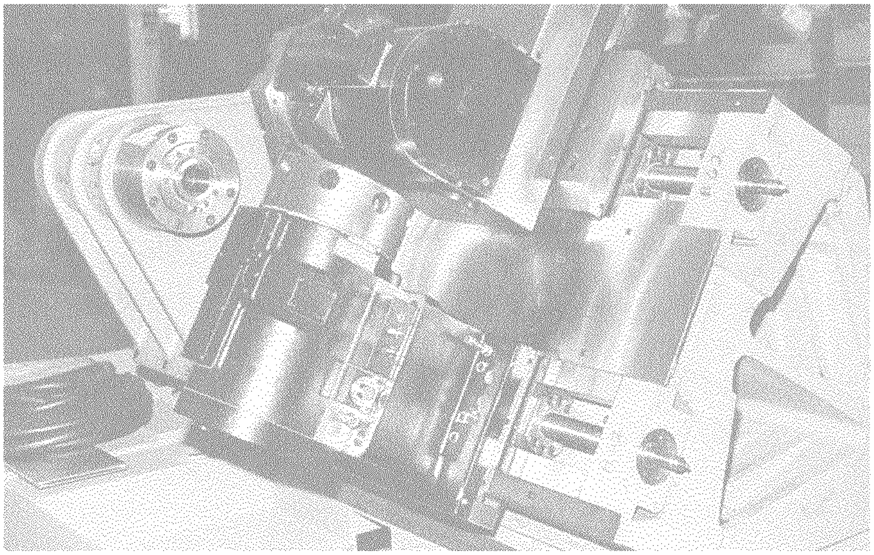
- **Assembling the HTM model of the turning center**
- **Calibration measurement results**
- **Compensating for the measured errors**
- **Cutting test results**

"Condemn the fault, and not the act of it?"

Shakespeare

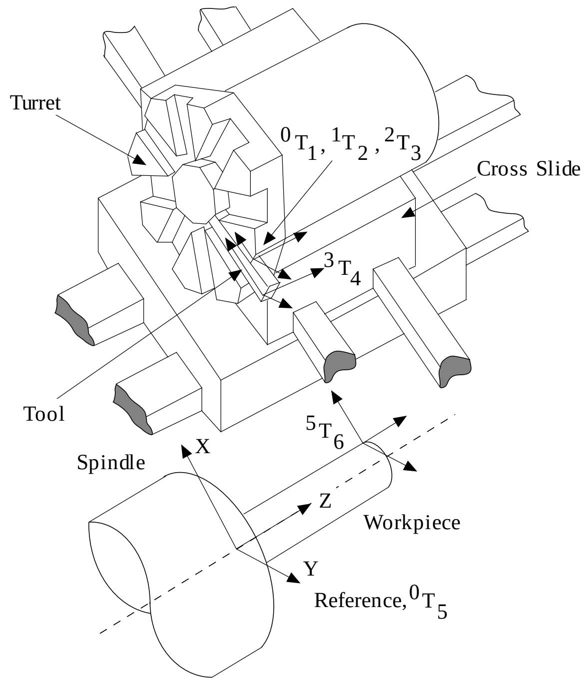
[1] From the Ph.D. thesis by A. Donmez , "A General Methodology for Machine Tool Accuracy Enhancement: Theory, Application and Implementation." Dr. Donmez received the Ph.D. degree from Purdue University in 1985. The experimental portion of his thesis was conducted at the National Institute of Standards and Technology (formerly, NBS). Dr. Donmez still works at NIST, Building 233, Room B106, Gaithersburg, MD 20899; alkan@gauss.aptd.nist.gov.

Two-axis slantbed turning center after assembly of principal components (Courtesy of Hardinge Brothers, Inc.):



- **The servomotor drives will be installed next followed by the protective covers**

Coordinate frame assignments on a two axis slantbed turning center



- **The global reference frame is chosen to coincide with the spindle frame at the spindle nose.**
- **${}^0T_1$: upper carriage coordinate frame wrt the reference frame.**
- **${}^1T_2$: upper cross slide coordinate frame wrt the carriage.**
- **${}^2T_3$: tool turret coordinate frame wrt the cross slide frame.**
- **All are located at a point on the turret where measurements of error motions can easily be made.**
- **${}^3T_4$: cutting tool coordinate frame wrt the tool turret frame.**
- **${}^0T_5$: spindle coordinate frame wrt the reference frame (they coincide).**
- **${}^5T_6$: workpiece frame wrt the spindle frame.**

- **When coordinate systems are assigned for metrology applications, they can be placed where it is convenient:**
    - **Straightness errors are measured along with angular errors,**
- **When coordinate systems are assigned for error budgeting applications during the design phase:**
    - **They should be placed at the center of stiffness:**
        - **Typically the geometric center of a symmetric arrangement of bearings.**
        - **This decreases error accounting oversights and increases the potential for achieving an accurate model.**
        - **An extra coordinate frame can be placed at the exterior of the axis where measurements will be made after the machine is built.**

- **The position of the cutting tool with respect to the reference frame is represented by the following matrix multiplication:**

$$
\begin{aligned}
{}^{Ref}T_{tool} &= {}^{Ref}T_{carriage}\ {}^{carriage}T_{cross\ slide}\ {}^{cross\ slide}T_{turret}\ {}^{turret}T_{tool} \\
&= {}^{0}T_{1}\ {}^{1}T_{2}\ {}^{2}T_{3}\ {}^{3}T_{4}
\end{aligned}
$$

- **The ideal workpiece-cutting tool interface point on the workpiece with respect to the reference frame is given by:**

$$
\begin{aligned}
{}^{Ref}T_{work} &= {}^{Ref}T_{spindle}\ {}^{spindle}T_{workpiece} \\
&= {}^{0}T_{5}\ {}^{5}T_{6}
\end{aligned}
$$

- **The error matrix E can now be calculated using:**

$$
{}^{R}\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix}_{correction} = {}^{R}\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix}_{work} - {}^{R}\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix}_{tool}
$$

- **The resulting matrix E is also a homogeneous transformation matrix.**
  - **It consists of position and orientation vectors P, o_1, o_2, and o_3, respectively.**
- **The three components of the position vector p_E of the error matrix E are:**

$$P_{Ex} = x(w) + \delta_x(w) + \varepsilon_y(s) * z(w) + \delta_x(s) - X_4 - \delta_x(c) - [\varepsilon_y(z) + \varepsilon_y(x) + \varepsilon_y(t)] * Z_4 - \delta_x(t) - x - X_1 - \delta_x(x) - \delta_x(z)$$

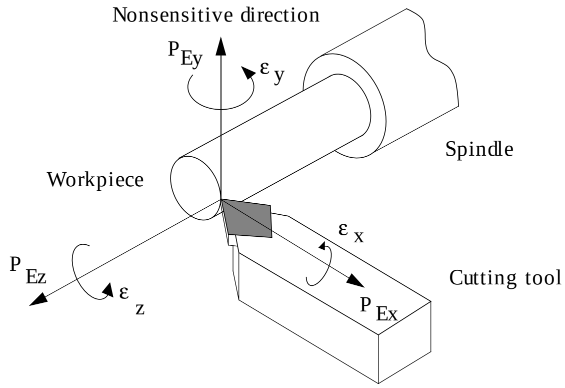
$$P_{Ey} = \delta_y(w) - \varepsilon_x(s) * z(w) + \delta_y(s) - [\varepsilon_z(z) + \varepsilon_z(x) + \varepsilon_z(t)] * X_4 - \delta_y(c) + [\varepsilon_x(z) + \varepsilon_x(x) + \varepsilon_x(t)] * Z_4 - \delta_y(t) - \varepsilon_z(z) * x - \delta_y(x) - \delta_y(z)$$

$$P_{Ez} = - \varepsilon_y(s) * x(w) + z(w) + \delta_z(w) + \delta_z(s) + [\varepsilon_y(z) + \varepsilon_y(x) + \varepsilon_y(t)] * X_4 - Z_4 - \delta_z(c) - \delta_z(t) + \varepsilon_y(z) * x - \delta_z(x) - \delta_z(z) - z$$

  - **x and z are the cutting tool offsets.**
  - **x, z are the nominal machine positions.**
  - **x(w) and z(w) are obtained from workpiece geometry.**

- **The error components ε and δ in these equations are primarily functions of the following:**
    - **$\delta_x(w)$ and $\delta_z(w)$ are workpiece position errors caused by thermal and static load deformations.**
    - **$\delta_x(s)$, $\delta_z(s)$, and $\varepsilon_y(s)$ are spindle thermal drift.**
    - **$\delta_x(c)$, $\delta_z(c)$ are functions of thermal and static load deformations and wear of the cutting tool.**
    - **$\delta_x(t)$, $\delta_z(t)$ and $\varepsilon_y(t)$ are functions of angular position of the turret.**
    - **$\delta_x(x)$, $\delta_z(x)$, $\varepsilon_y(x)$, $\delta_x(z)$, $\delta_z(z)$, and $\varepsilon_y(z)$ are functions of machine geometry & thermal & static load deformations.**

- **The resultant error components at the tip of the cutting tool are:**



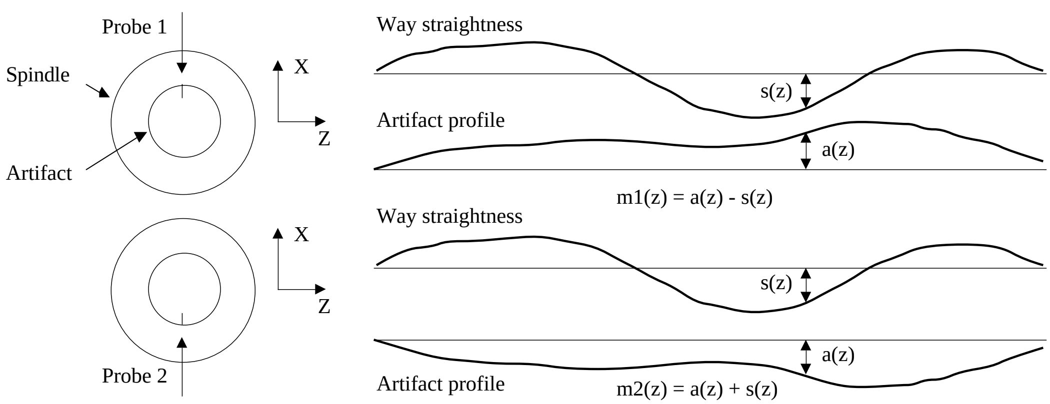
- **The machine tool's servoed axis can only correct for displacement errors.**
  - **Angular errors at the tool tip are not of concern for the error correction algorithm.**
  - **Angular errors may be of concern for the machine's design engineers and users (indicative of a poor design).**
  - **For this machine, the angular errors were not of significance.**

Contrast the closed form solution to the spreadsheet format presented earlier

- **The spreadsheet does not require symbolic multiplication.**
- **The spreadsheet allows for a systematic assembly of the HTM model.**
- **The spreadsheet is pre-formatted so there is no code to write.**
- **The spreadsheet is generalized so one can easily insert rotary axes.**

Machine tool metrology

- **Linear displacement errors:**
    - **Linear displacement interferometers are used.**
- **Angular errors:**
    - **Angular displacement interferometers are used.**
- **Straightness errors:**
    - **An artifact is held in the spindle and the axes move capacitance probes along the artifact.**



- **Two sets of measurements are required along the Z axis.**
- **In the first set, the carriage is moved along the Z axis and the probe outputs are recorded at every measuring interval.**

- **After the first set, the test arbor is rotated 180 degrees and the test repeated.**
- **At any point along Z axis, the first measurement is represented by:**

$$m_1 (z) = a(z) - s(z)$$

  - **$m_1(z)$ is the output of probe l at position z.**
  - **a(z) is the profile nonstraightness of the test arbor.**
  - **s(z) is the straightness of Z motion.**
- **Similarly, the second measurement is given as:**

$$m_2 (z) = a(z) + s(z)$$

  - **$m_2(z)$ is the output of probe 2 at position z.**
- **The straightness of the Z motion is thus:**

$$s(z) = \frac{- m_1(z) + m_2(z)}{2}$$

Parallelism:

- **Ideally, the parallelism between the axis of Z motion and the axis average line of the spindle can be determined by:**
    - **Taking two measurements on the test arbor a distance l apart.**
- **The parallelism error would be the difference divided by the length between these points.**
- **However, this method is impractical because of:**
    - **Z-axis straightness error.**
    - **Test arbor profile error.**
    - **Misalignment between the test arbor and the spindle.**
- **Instead, the spindle was rotated at a very low speed in order to minimize the spindle error motions.**
    - **Measurements at 512 points in one revolution were recorded for each probe at two locations, 12 inches apart, along the Z axis.**
- **Measurement of misalignment between a perfectly round artifact and a spindle with no error motion creates a limacon.**
- **The artifact nonroundness and the spindle error distorts this limacon.**

- **To eliminate the effects of these errors on the data:**
  - **A best fit circle out of 512 data points for one revolution of the spindle must be calculated and used for the analysis:**

$$R = \frac{\Sigma r_i}{n}$$

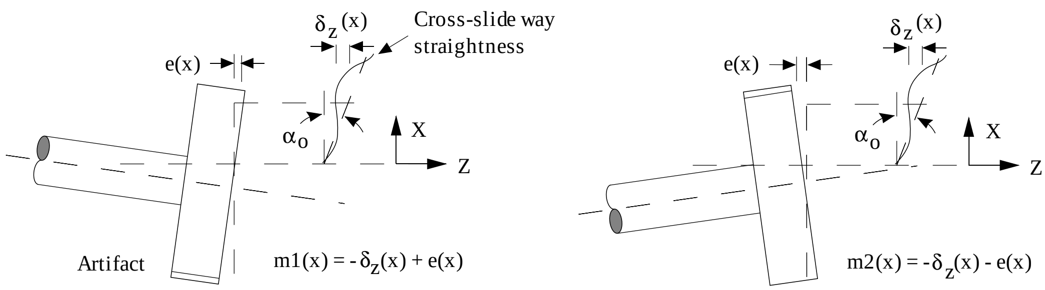
  - **r_i is the probe output at the angular position i and n is the number of data points.**
- **To eliminate the axis straightness errors:**
  - **Best fit circles are constructed by the outputs of two probes 180 degrees apart (either side of the artifact).**
- **The parallelism error α_p is then calculated**

$$\alpha_p = \frac{(R_{21} - R_{11}) - (R_{22} - R_{12})}{2\Delta z}$$

  - **R_{11} is the least square radius from probe 1 at location 1.**
  - **R_{21} is the least square radius from probe 1 at location 2.**
  - **R_{12} is the least square radius from probe 2 at location 1.**
  - **R_{22} is the least square radius from probe 2 at location 2.**
  - **Δz is the distance between location 1 and location 2.**

Orthogonality

- **For X motion Z direction straightness and orthogonality of the X axis to the axis average line of the spindle, another test arbor was used:**



- **It was not possible to look at the back side of the artifact while it was mounted on the spindle.**
- **The flat face was calibrated and found to be flat within 10 microinches**
- **In order to eliminate misalignment and arbor squareness errors, the following method was used:**
    - **While the cross slide moving, the capacitance probe readings were taken at every measuring interval.**
    - **The spindle was then rotated 180 degrees and the measurement repeated with the same probe.**

- **With this procedure, it was possible to find the orthogonality as well as the Z straightness of the X motion.**
- **The following relationships are obtained:**

$$m_1(x) = -\delta_z(x) + e(x)$$

$$m_2(x) = -\delta_z(x) - e(x)$$

  - **$m_1(x)$: probe output for the first set of measurements.**
  - **$m_2(x)$: probe output after the spindle rotated 180^o.**
  - **$\delta_z(x)$: Z straightness of X motion.**
  - **e(x): arbor squareness and misalignment errors.**
- **From equations 6.3.6 and 6.3.7 the straightness is calculated:**

$$\delta_z(x) = \frac{-m_1(x) - m_2(x)}{2}$$

- **The orthogonality is the best fit line slope from the data obtained by averaging respective sets of measurements M_1 and M_2.**

Spindle thermal drift:

- **ANSI B89.6.2:**

  "A changing distance between two objects, associated with a changing temperature distribution within the structural loop due to internal and external sources".

- **Three components of spindle thermal drift are critical to the overall performance of the machine tool:**

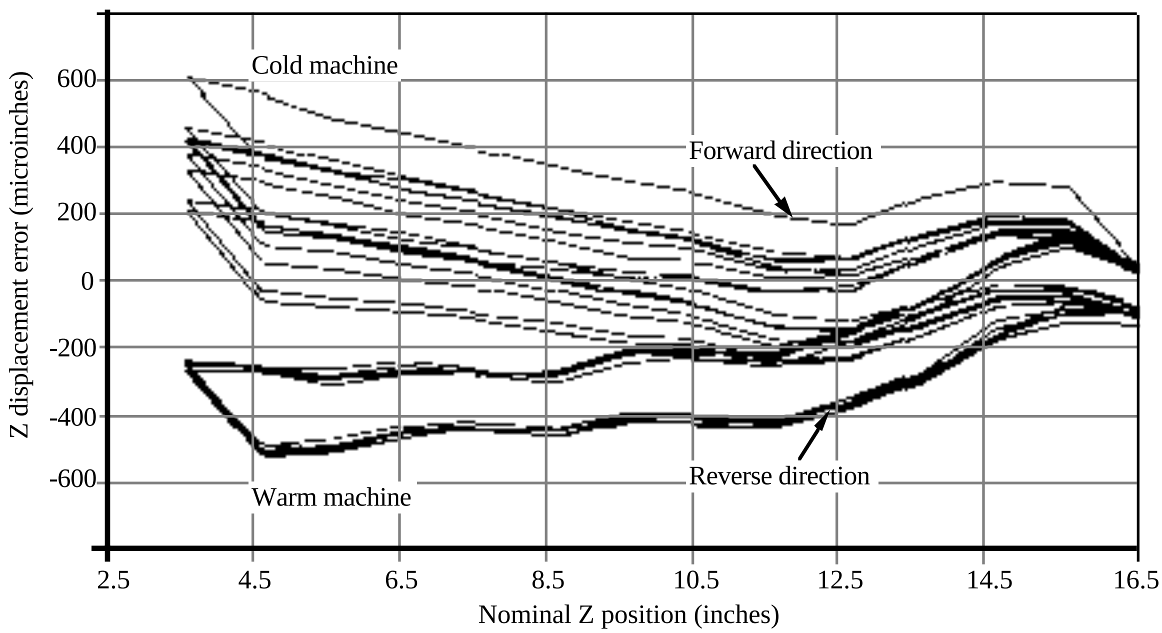
  1) Axial thermal drift, which is the displacement of the spindle along the Z axis.

  2) Radial thermal drift, which is the displacement perpendicular to the Z axis in the sensitive direction.

  3) Tilt thermal drift, which is the rotation of the spindle in the X-Z plane of the machine.

Calibration measurement results:

- **Carriage (Z) linear displacement error:**



- **Offset from cold to hot machine can be measured by a tool setting station.**

- **Backlash at the end of the preloaded ballscrew's stroke is caused by:**

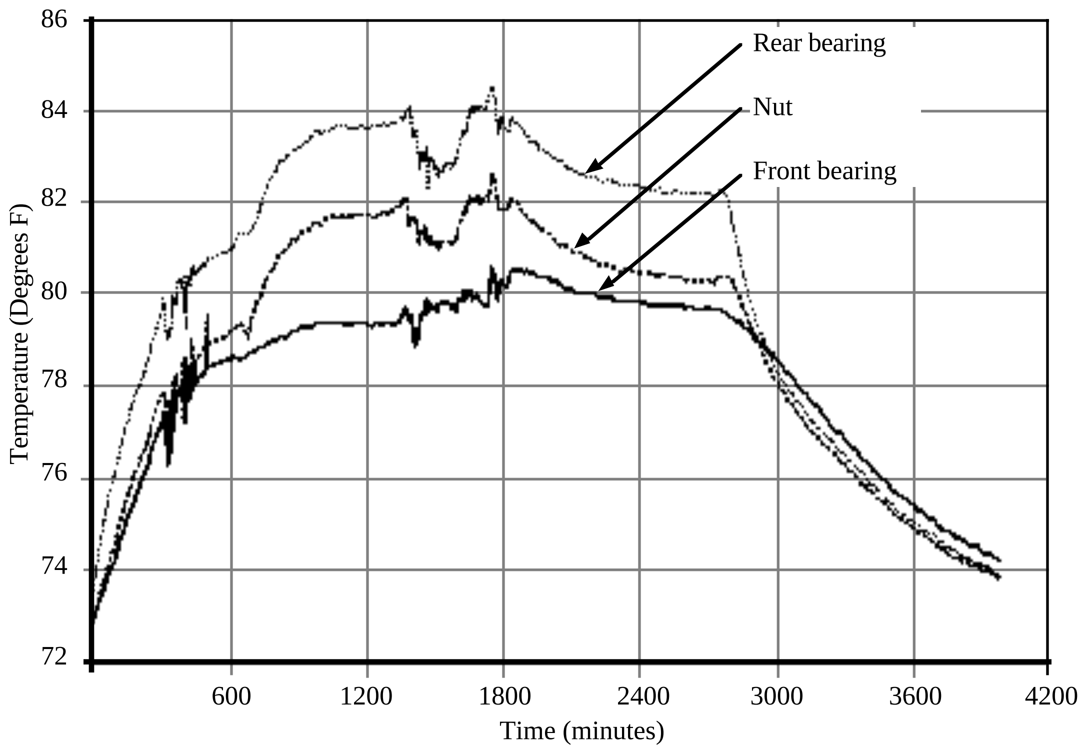
    - **Load reversal in the presence of high stiction.**

    - **Non-linear Hertzian contact deflection of the contact between the balls and the threadform.**

$$\delta = \lambda \left(\frac{2F^2}{3R_eE_e^2}\right)^{1/3}$$

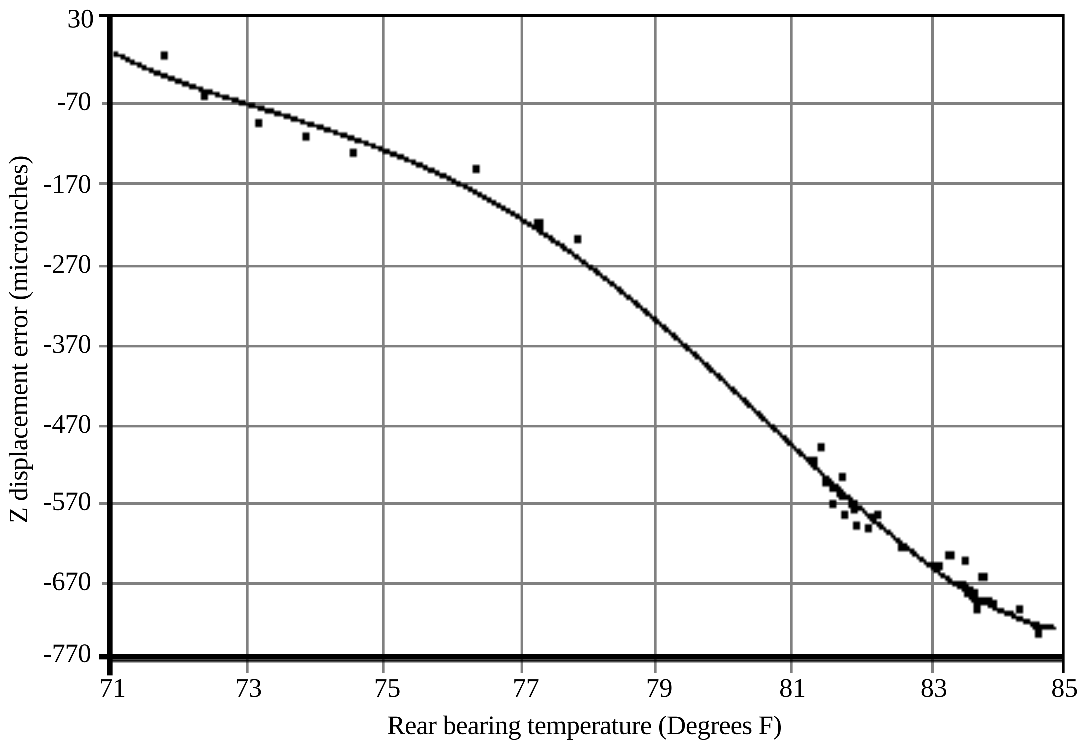
- **The shape of the curves are similar, they are displaced and rotated by the slow increase in temperature of the machine.**

- **Temperature profiles during the Z displacement error measurements:**



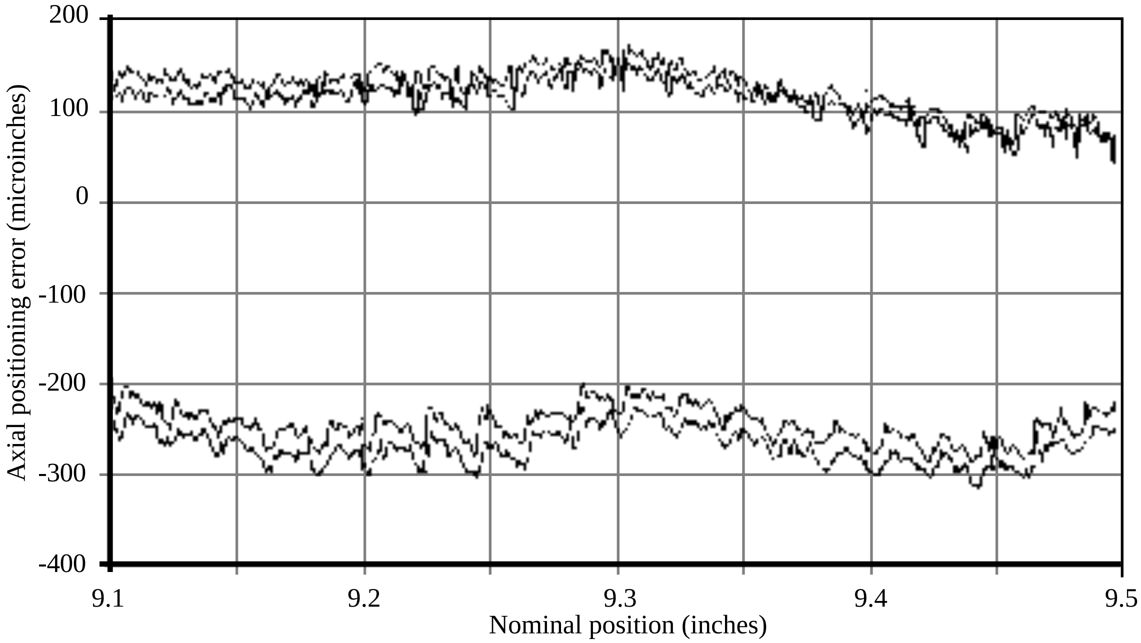
- **The rear bearing is the most sensitive.**
- **Output from a thermocouple attached to this bearing can be used to predict the thermal axial growth error.**
- **Relate this to the earlier figure for axis position error:**
    - **10 ^{o}F x 20" x 6 µin/in = 0.0012" thermal growth.**
    - **The ballscrew was stretched to reduce thermal lead error, but other things expanded!**

- **Typical Z displacement error data at a nominal fixed Z position and varying temperature:**

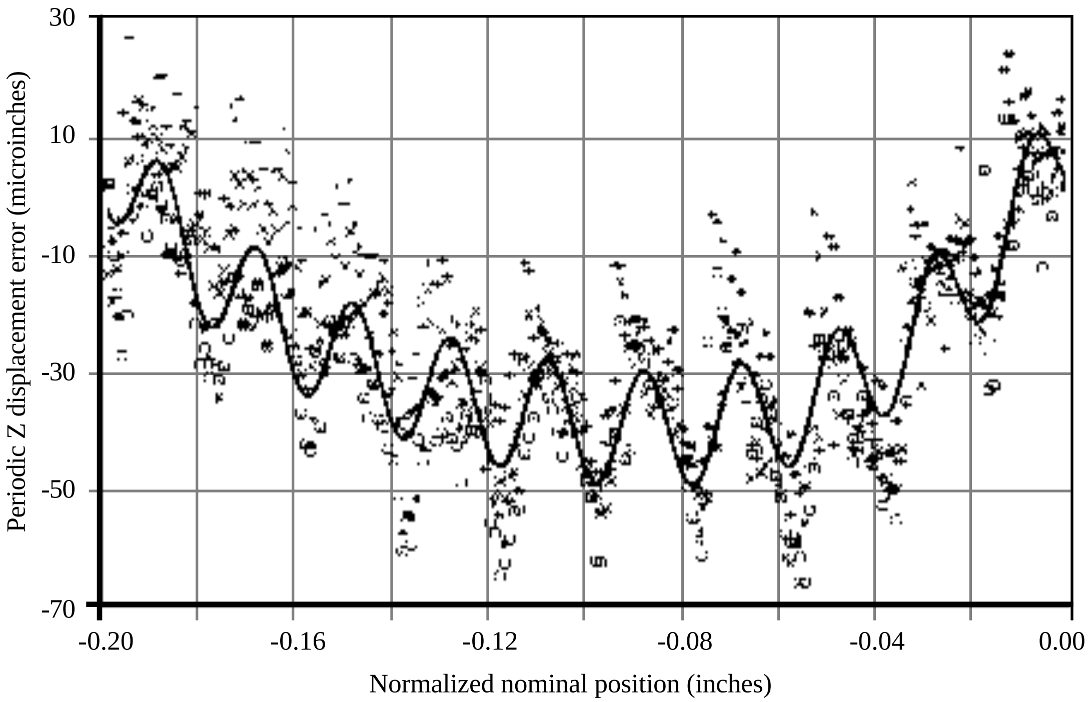


- **A family of these curves at discrete positions along the Z axis can be used to map the error as a function of position and rear bearing temperature.**

- **Typical periodic Z displacement error raw data:**

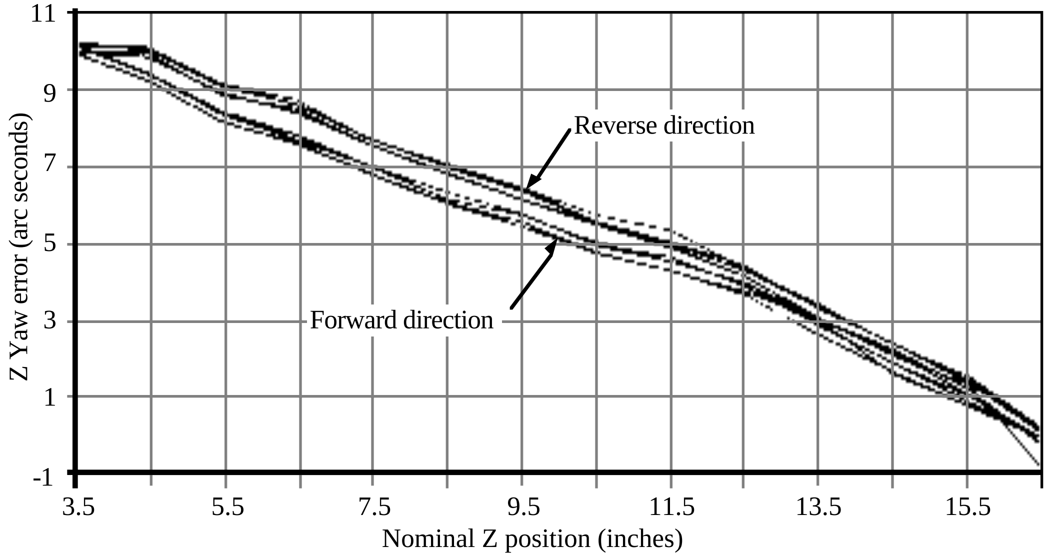


- **Periodic Z displacement error for one ballscrew revolution:**



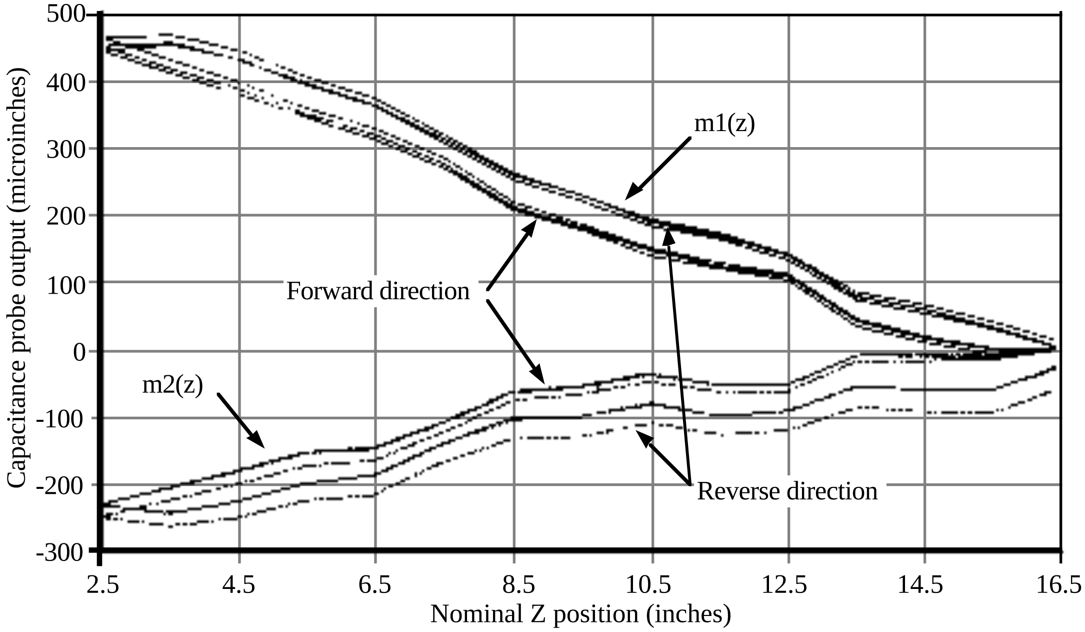
- **What causes the 10th harmonic? Is it the leadscrew or the measurement system?**
- **Even if you could develop a mapping function, given the scatter of the data (non-repeatability):**
  - **You could not achieve any greater accuracy by mapping.**
  - **With mechanical contact systems, mapping is generally limited to improvements by a factor of about 10.**

- **Carriage-cross slide assembly yaw error:**

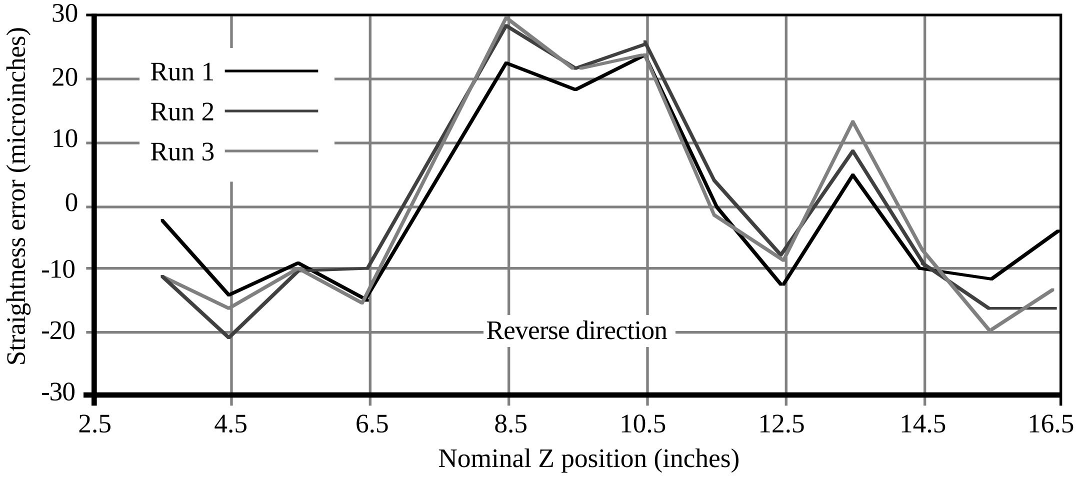


- **Once again, note the repeatability and temperature dependence.**
- **The temperature dependence is mild which indicates the machine expands fairly uniformly.**
  - **Only a few arc-seconds of error are due to the temperature change.**

- **X straightness of the Z motion:**

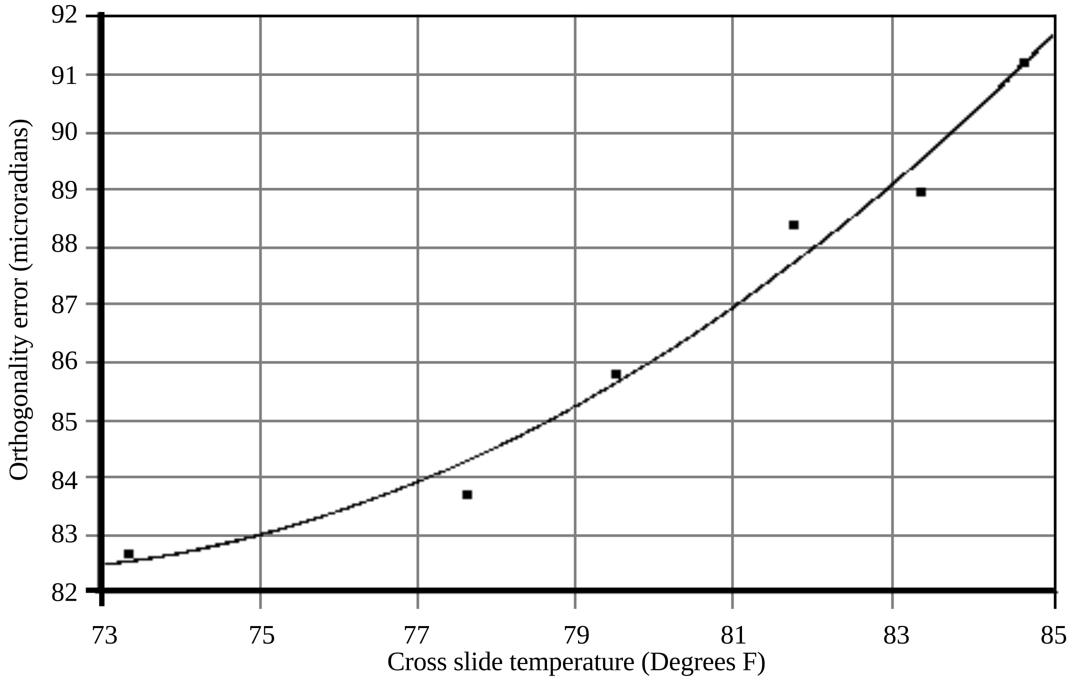


- **Calculated X straightness of the Z motion data for the reverse direction of the Z motion:**



- **Temperature did not have an appreciable effect on the straightness.**

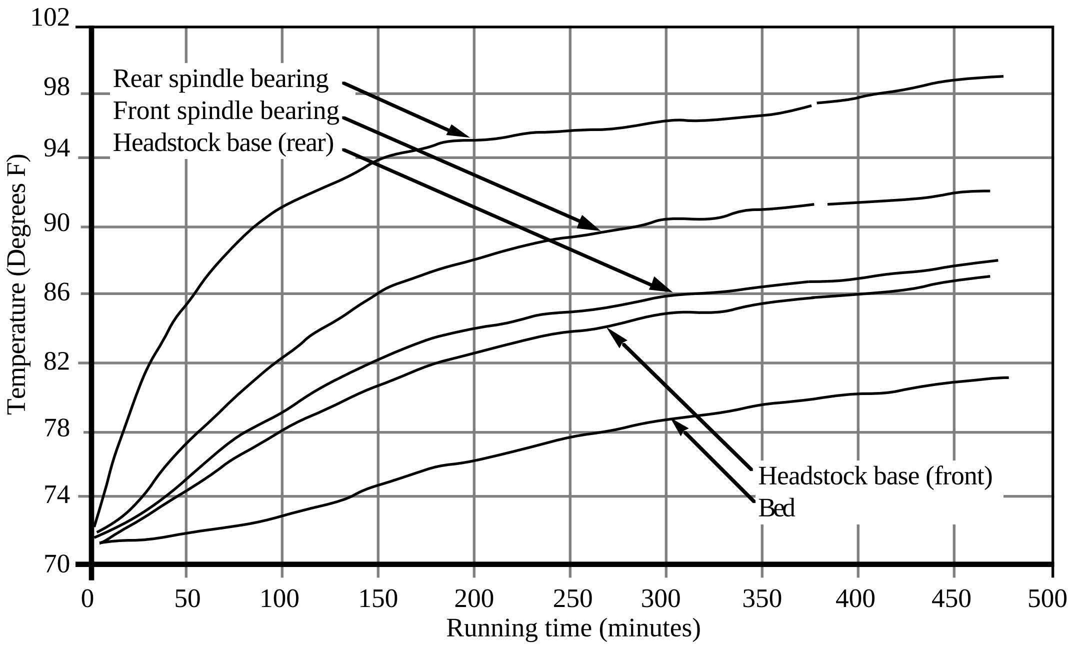
- **Orthogonality error between the X motion and the axis average line of spindle rotation as the machine warms up:**



- **The temperature dependence is mild which indicates the machine expands fairly uniformly.**
  - **Only a few arc-seconds of error are due to the temperature change.**

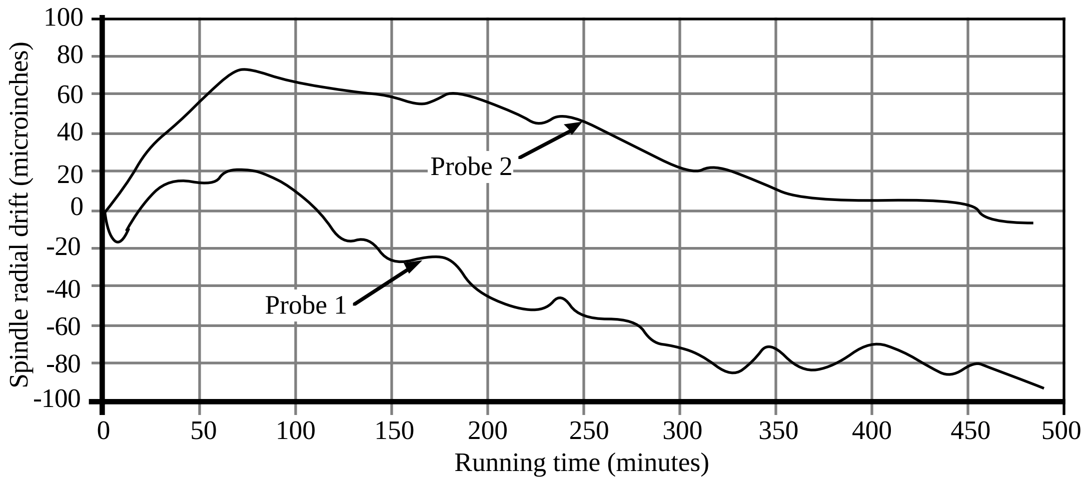
- **Temperature profiles during spindle drift measurements at 2000 rpm.**

- **At 4000 rpm, the upper bound approaches 180ºF:**

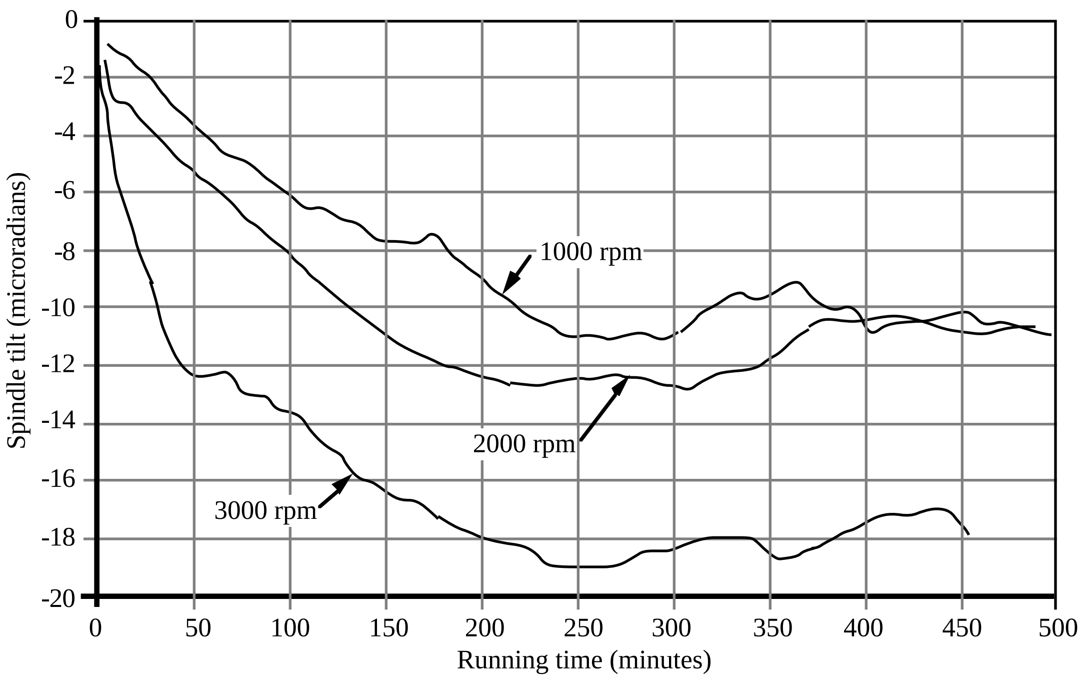


- **Because the spindle is large and has a large heat source:**
    - **Time-dependant boundary conditions may make mapping spindle housing thermal growth errors very difficult.**

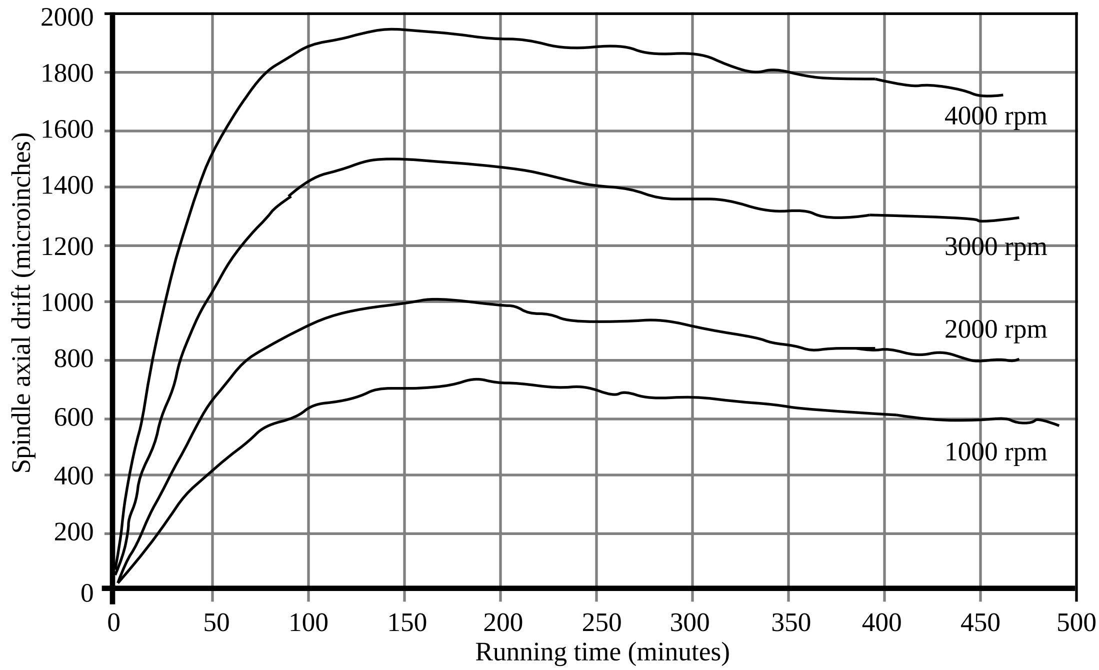
- **Spindle radial thermal drift @ 2000 rpm:**



- **Spindle tilt thermal drift:**



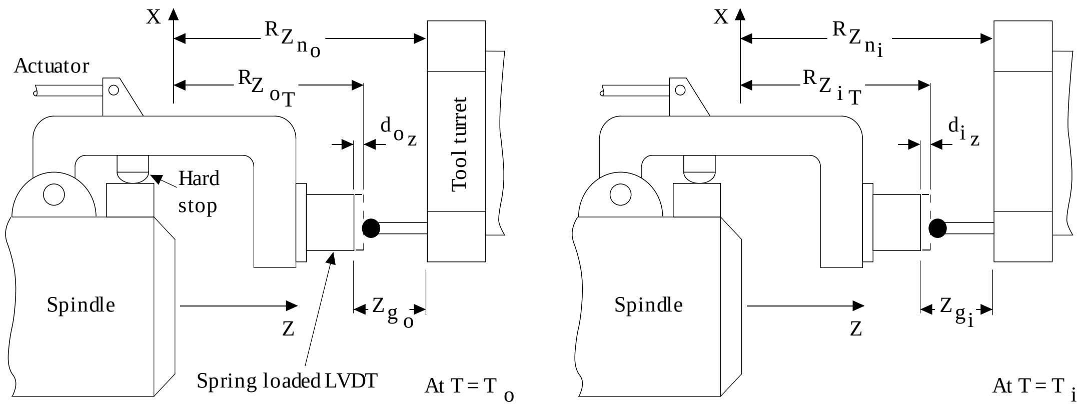
- **Spindle axial thermal drift:**



- **Because of all the variables in spindle thermal error, and the time-dependent boundary conditions:**
    - **Mapping spindle thermal drift error as a function of measured temperature is very difficult.**
- **Practically, in order to obtain an accurate prediction of spindle thermal growth:**
    - **The bearing outer race temperature must be measured.**
        - **This allows the axial expansion of the spindle shaft to be determined to the 10-20 μm level.**
        - **This method is used by Giddings & Lewis to reduce spindle axial growth errors by an order of magnitude.**

Compensating for the measured errors:

- **The tool-setting station for measuring relative position of the tool and the spindle to obviate thermal errors:**



- **Used to obtaining the machine reference and the tool dimension offsets.**

Cutting tests:

- **Error in diameter (nominal diameter: 1.605"):**

Compensated (μin.)	Uncompensated (μin.)	Improvement (ratio)
650	1300	2.00
530	1050	1.98
270	1030	3.81
-130	1470	11.31
-150	2230	14.87

- **Error in length (nominal length: 3.44"):**

Compensated (μin.)	Uncompensated (μin.)	Improvement (ratio)
-150	570	3.80
390	4410	11.31
-250	5240	20.96
- 90	-480	5.33
450	6390	14.20

- **Error in taper (1.605" diameter, along 2.7" length):**

Compensated (μrad)	Uncompensated (μrad)	Improvement (ratio)
26	85	3.27
18	88	4.89
-44	95	2.16
- 8	-7	0.88
4	17	4.25

- **Error in squareness (on 1.99" radius):**

Compensated (μrad)	Uncompensated (μrad)	Improvement (ratio)
33.5	44.1	1.32
39.5	8.7	0.22
25.7	36.8	1.43
54.3	78.6	1.45
32.0	58.2	1.82

- **Increasing improvement of the dimensional accuracy was the result of the machine tool warming up.**

- **Angular error improvement was less because the machine expanded more uniformly as it warmed up (good!).**

- **Need help, call Dr. Alkan Donmez at NIST (301) 975 6618!**