# 10

# Precision Manufacturing




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International competition and ever improving technology have forced manufacturers to increase quality as well as productivity. Often the improvement of quality is realized via the enhancement of production system precision. This chapter discusses some of the basic concepts in precision system design including definitions, basic principles of metrology and performance, and design concepts for precision engineering.

This chapter is concerned with the design and implementation of high precision systems. Due to space limitations, only a cursory discussion of the most basic and critical issues pertaining to the field of precision engineering is addressed. In particular, this chapter is targeted at the area of precision machine tool design. These concepts have been used to design some of the most precise machines ever produced, such the Large Optics Diamond Turning Machine (LODTM) at the Lawrence Livermore National Laboratory which has a resolution of 0.1 μin. ($10^{-7}$ inches). However, these ideas are quite applicable to machine tools with a wide range of precision and accuracy. The first topic discussed is the Deterministic Theory, which has provided guidelines over the past 30 years that have yielded the highest precision machine tools ever realized and designed. Basic definitions followed by a discussion of typical errors are presented as well as developing an error budget. Finally, fundamental principles to reduce motion and measurement errors are discussed.

## 10.1 Deterministic Theory Applied to Machine Tools

The following statement is the basis of the Deterministic Theory: “Automatic machine tools obey cause and effect relationships that are within our ability to understand and control and that there is nothing random or probabilistic about their behavior" (Dr. John Loxham). Typically, the term random implies that the causes of the errors are not understood and cannot be eradicated. Typically, these errors are quantified statistically with a normal distribution or at best, with a known statistical distribution. The reality is that these errors are *apparently* nonrepeatable errors that the design engineers have decided to quantify statistically rather than completely understand. Using statistical approaches to evaluate results is reasonable when sufficient resources using basic physical principles and good metrology are not available to define and quantify the variables causing errors.[1] It must be understood that in all cases, machine tool errors that appear random are not random; rather, they have not been completely addressed in a rigorous fashion. It is important that a machine's precision and accuracy are defined early in the design process. These definitions are critical in determining the necessary depth of understanding that must be developed with respect to machine tools errors. For example, if it is determined that a machine needs to be accurate to 1 μm, then understanding its errors to a level of 1 nm may not be necessary. However, apparently, random errors of 1 μm are clearly unacceptable for the same machine.

Under the deterministic approach, errors are divided into two categories: repeatable or systematic errors and apparent nonrepeatable errors. Systematic errors are those errors that recur as a machine executes specific motion trajectories. Typical causes of systematic errors are linear slideways not being perfectly straight or improper calibration of measurement systems. These errors repeat consistently every time. Typical sources of apparent nonrepeatable errors are thermal variations, variations in procedure, and backlash. It is the apparent nonrepeatable errors that camouflage the true accuracy of machine tools and cause them to appear to be random. If these errors can be eliminated or controlled, a machine tool should be capable of having repeatability that is limited only by the resolution of its sensors. Figure 10.1 presents some of the factors affecting workpiece accuracy.[2]

## 10.2 Basic Definitions

This section presents a number of definitions related to precision systems. Strict adherence to these definitions is necessary to avoid confusion during the ensuing discussions. The following definitions are taken from ANSI B5.54.-1991.[5]

**Accuracy**: A quantitative measure of the degree of conformance to recognized national or international standards of measurement.

**Repeatability**: A measure of the ability of a machine to sequentially position a tool with respect to a workpiece under similar conditions.

**Resolution**: The least increment of a measuring device; the least significant bit on a digital machine.

The target shown in Figure 10.2 is an excellent approach to visualizing the concepts of accuracy and repeatability. The points on the target are the results of shots at the target's center or the bullseye. Accuracy is the ability to place all of the points near the center of the target. Thus, the better the accuracy, the closer the points will be to the center of the target. Repeatability is the ability to consistently cluster or group the points at the same location on the target. (Precision is often used as a synonym for repeatability; however, it is a nonpreferred, obsolete term.) Figure 10.3 shows a variety of targets with combinations of good and poor accuracy and repeatability. Resolution may be thought of as the size of the points on the target. The smaller the points, the higher the resolution.[3,4]

**Error**: The difference between the actual response of a machine to a command issued according to the accepted protocol of the machine's operation and the response to that command anticipated by the protocol.

**Error motion**: The change in position relative to the reference coordinate axes, or the surface of a perfect workpiece with its center line coincident with the axis of rotation. Error motions are specified as to location and direction and do not include motions due to thermal drift.

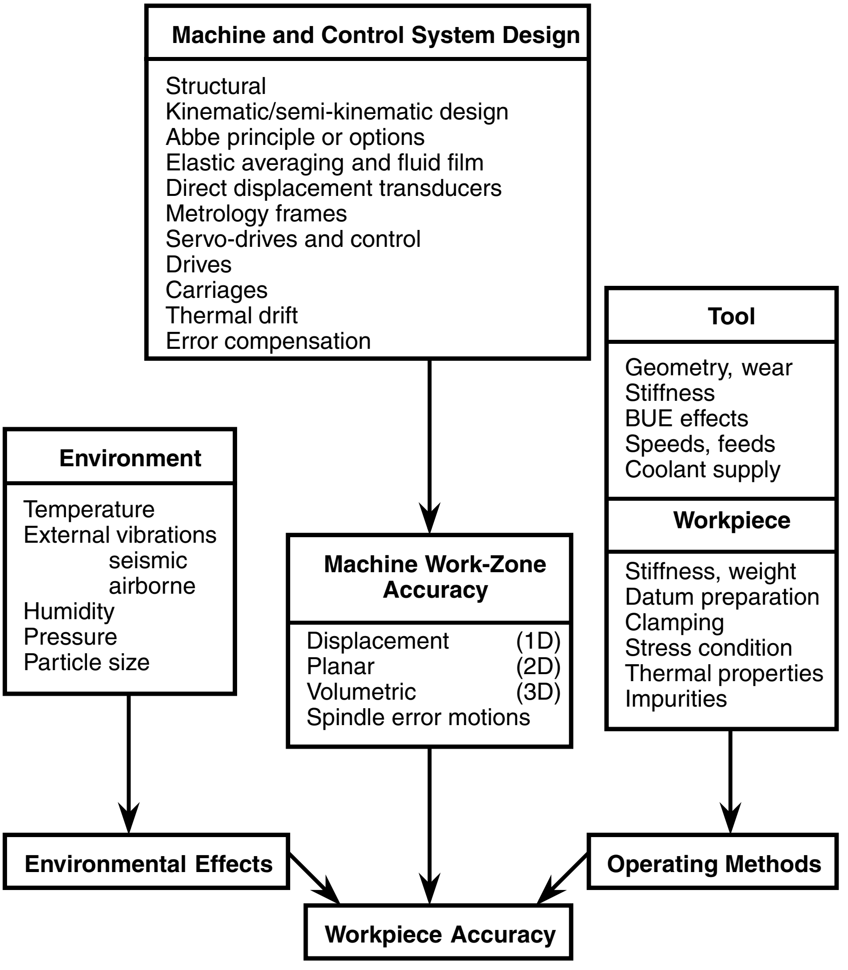


**FIGURE 10.1** Some of the factors affecting workpiece accuracy.

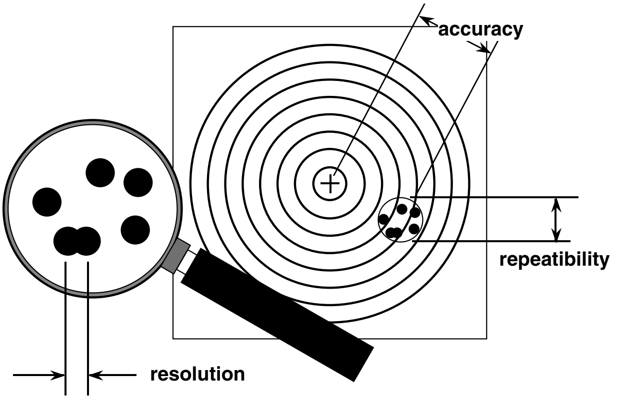


**FIGURE 10.2** Visualization of accuracy, repeatability, and resolution. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.*)*

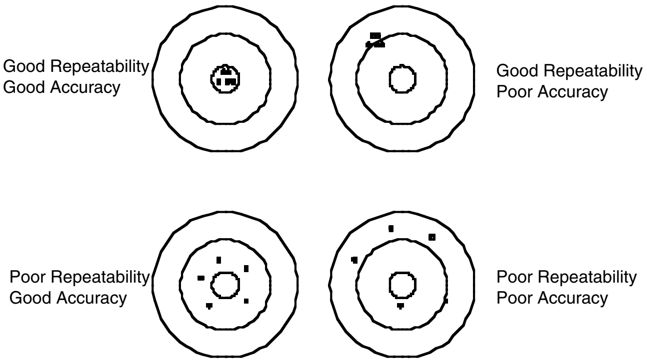


**FIGURE 10.3** A comparison of good and poor accuracy and repeatability.

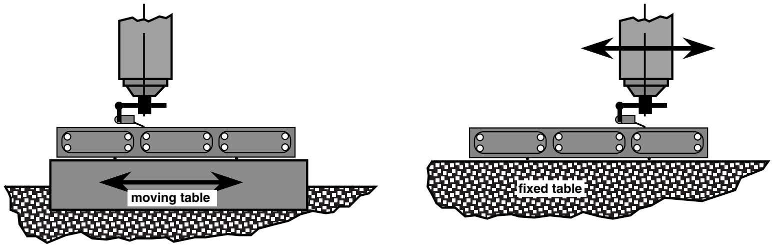


**FIGURE 10.4** Slideway straightness relationships. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

**Error motion measurement**: A measurement record of error motion which should include all pertinent information regarding the machine, instrumentation, and test conditions.

**Radial error motion**: The error motion of the rotary axis normal to the Z reference axis and at a specified angular location (see Figure 10.4).[5]

**Runout**: The total displacement measured by an instrument sensing a moving surface or moved with respect to a fixed surface.

**Slide straightness error**: The deviation from straight line movement that an indicator positioned perpendicular to a slide direction exhibits when it is either stationary and reading against a perfect straightedge supported on the moving slide, or moved by the slide along a perfect straightedge that is stationary.

## 10.3 Motion

This chapter treats machine tools and their moving elements (slides and spindles) as being completely rigid, even though they do have some flexibility. Rigid body motion is defined as the gross dynamic motions of extended bodies that undergo relatively little internal deformation. A rigid body can be considered to be a distribution of mass rigidly fixed to a rigid frame.[6] This assumption is valid for average-sized machine tools. As a machine tool becomes larger, its structure will experience larger deflections, and it may become necessary to treat it as a flexible structure. Also, as target tolerances become smaller, compliance must be considered. For example, modern ultra-rigid production class machine tools may possess stiffnesses of over 5 million pounds per inch. While this may appear to be large, the simple example of a grinding machine that typically applies 50 lbs. of force can demonstrate that compliance can cause unacceptable inaccuracies. For this example, the 50 lbs. of force will yield a 10 μin. deflection during the grinding process, which is a large portion of the acceptable tolerance of such machine tools. These deflections are ignored in this section. Presented in this section is a fundamental approach to linking the various rigid body error motions of machine tools.

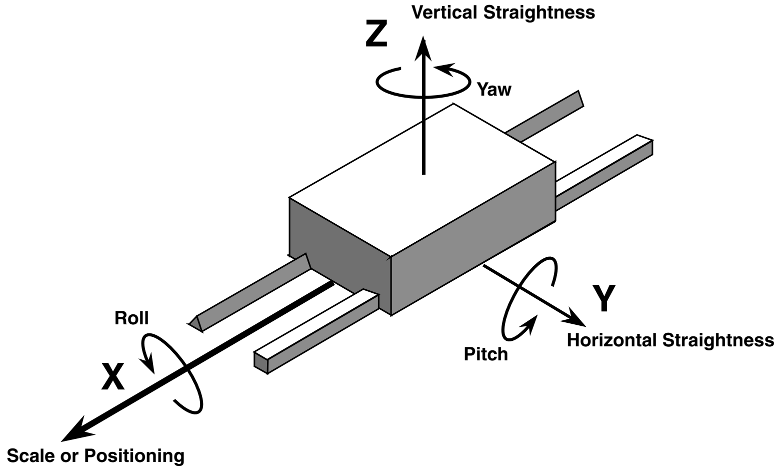


**FIGURE 10.5** Slide and carriage rigid body relationships. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

### 10.3.1 Rigid Body Motion and Kinematic Errors

There are six degrees of freedom defined for a rigid body system, three translational degrees of freedom along the X, Y, and Z axes, as well as three rotational degrees of freedom about the X, Y, and Z axes. Figure 10.5 depicts a linear slide that is kinematically designed to have a single translational degree of freedom along the X axis. The other five degrees of freedom are undesired, treated as errors, and often referred to as kinematic errors.[7]

There are two straightness errors and three angular errors that must be considered for the slide and carriage system shown in Figure 10.5. In addition, the ability of the slide to position along its desired axis of motion is measured as scale errors. These definitions are given below:

**Angular errors**: Small unwanted rotations (about the X, Y, and Z axes) of a linearly moving carriage about three mutually perpendicular axes.

**Scale errors**: The differences between the position of the read-out device (scale) and those of a known reference linear scale (along the X axis).

**Straightness errors**: The nonlinear movements that an indicator sees when it is either (1) stationary and reading against a perfect straightedge supported on a moving slide or (2) moved by the slide along a perfect straightedge which is stationary (see Figure 10.5).[5] Basically, this translates to small unwanted motion (along the Y and Z axes) perpendicular to the designed direction of motion.

While slides are designed to have a single translational degree of freedom, spindles and rotary tables are designed to have a single rotational degree of freedom. Figure 10.6 depicts a single degree-of-freedom rotary system (a spindle) where the single degree of freedom is rotation about the Z axis. As with the translational slide, the remaining five degrees of freedom for the rotary system are considered to be errors.[8] As shown in Figure 10.6, two radial motion (translational) errors exist, one axial motion error, and two tilt motion (angular) errors. A sixth error term for a spindle exists only if it has the ability to index or position angularly. The definitions below help to describe spindle error motion:

**Axial error motion**: The translational error motion collinear with the Z reference axis of an axis of rotation (about the Z axis).

**Face motion**: The rotational error motion parallel to the Z reference axis at a specified radial location (along the Z axis).

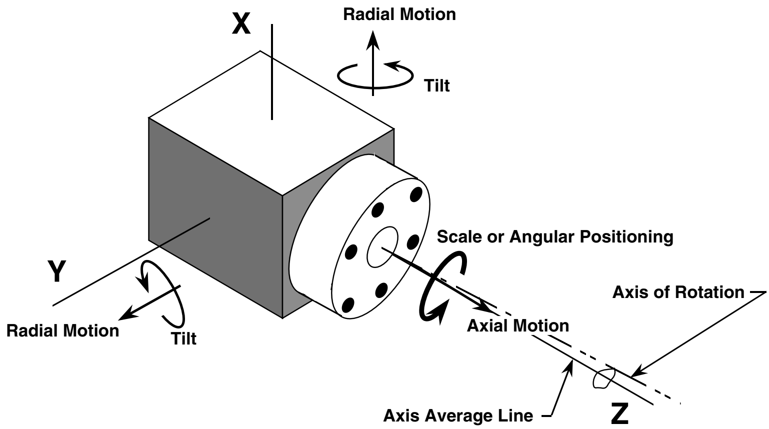


**FIGURE 10.6** Spindle rigid body relationships. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

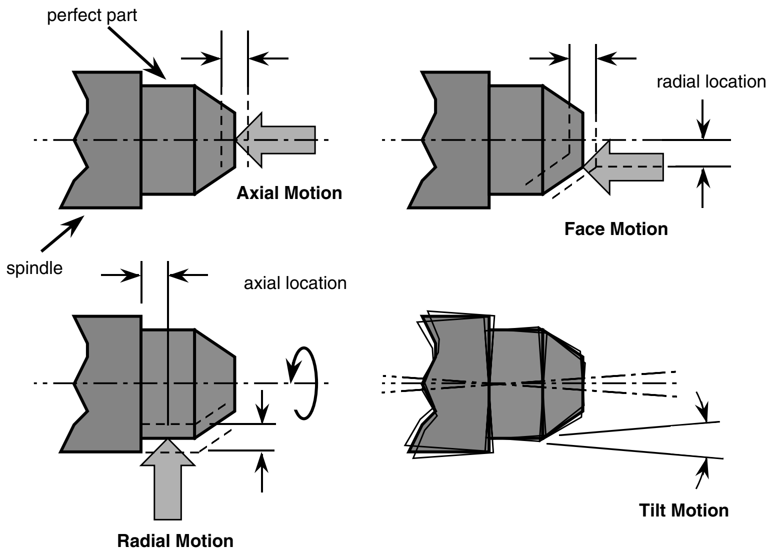


**FIGURE 10.7** Spindle error motion. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

**Radial error motion**: The translational error motion in a direction normal to the Z reference axis and at a specified axial location (along the X and Y axes).

**Tilt error motion**: The error motion in an angular direction relative to the Z reference axis (about the X and Y axes).

Figure 10.7 is a plan view of a spindle with an ideal part demonstrating the spindle errors that are discussed. Both the magnitude and the location of angular motion must be specified when addressing radial and face motion.[9]

As previously stated, runout is defined as the total displacement measured by an instrument sensing against a moving surface or moved with respect to a fixed space. Thus, runout of the perfect part rotated by a spindle is the combination of the spindle error motion terms depicted in Figure 10.7 and the centering error relative to the spindle axis of rotation.[9]

Typically, machine tools consist of a combination of spindles and linear slides. Mathematical relationships between the various axes of multi-axis machine tools must be developed. Even for a

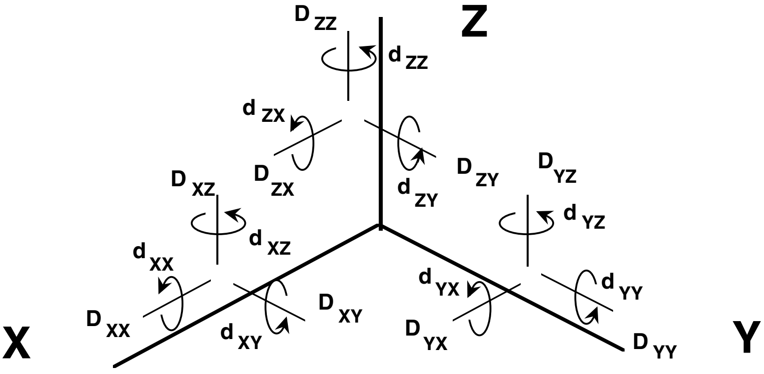


**FIGURE 10.8** Error terms for a machine tool with three orthogonal axes. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

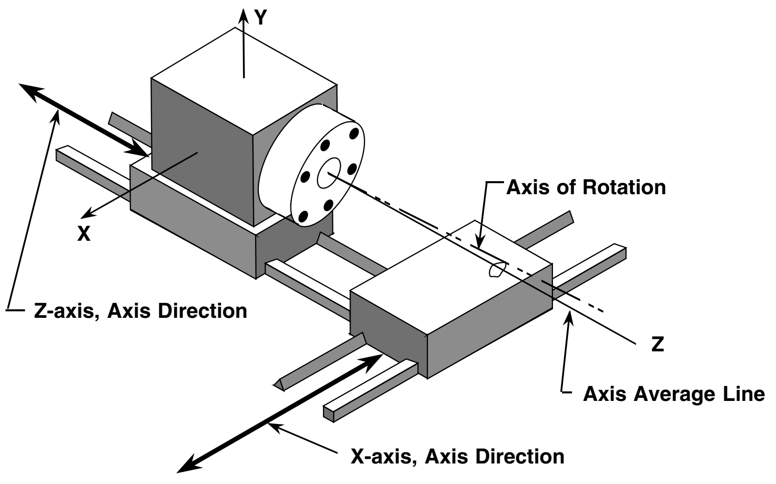


**FIGURE 10.9** Typical machine tool with three desired degrees of freedom, the lathe. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

simple three-axis machine, the mathematical definition of its kinematic errors can become rather complex. Figure 10.8 presents the error terms for positioning a machine tool (without a spindle) having three orthogonal linear axes. There are six error terms per axis totaling 18 error terms for all three axes. In addition, three error terms are required to completely describe the axes relationships (e.g., squareness) for a total of 21 error terms for this machine tool. Figure 10.9 shows a simple lathe where two of the axes are translational and the third is the spindle rotational axis.

The following definitions are useful when addressing relationships between axes:

**Squareness**: A planar surface is "square" to an axis of rotation if coincident polar profile centers are obtained for an axial and face motion polar plot at different radii. For linear axes, the angular deviation from 90° measured between the best-fit lines drawn through two sets of straightness data derived from two orthogonal axes in a specified work zone (expressed as small angles).

**Parallelism**: The lack of parallelism of two or more axes (expressed as a small angle).

For machines with fixed angles other than 90°, an additional definition is used:

**Angularity**: The angular error between two or more axes designed to be at fixed angles other than 90°.

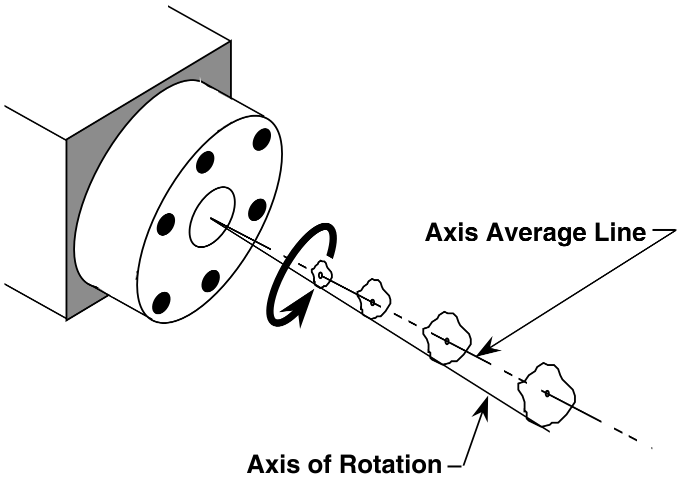


**FIGURE 10.10** Determination of axis average line. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

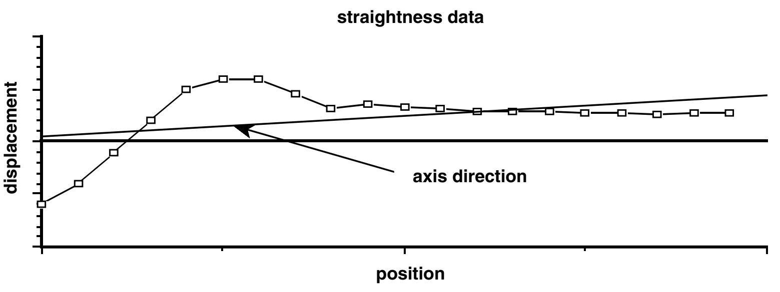


**FIGURE 10.11** Determination of axis direction. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

The rotor of a spindle rotates about the average axis line as shown in Figure 10.7. Average axis line (shown in Figure 10.10) as defined in ANSI B5.54-1992[5] is

**Average axis line**: For rotary axes it is the direction of the best-fit straight line (axis of rotation) obtained by fitting a line through centers of the least-squared circles fit to the radial motion data at various distances from the spindle face.

The actual measurement of radial motion data is discussed later in this chapter.

Just as spindles must have a defined theoretical axis about which they rotate, linear slides must have a specific theoretical direction along which they traverse. In reality, of course, they do not track this axis perfectly. This theoretical axial line is the slide's equivalent of the average axis line for a spindle and is termed the axis direction:

**Axis direction**: The direction of any line parallel to the motion direction of a linearly moving component. The direction of a linear axis is defined by a least-squares fit of a straight line to the appropriate straightness data.

The best fit is necessary because the linear motion of a slide is never perfect. Figure 10.11 presents typical data used in determining axis direction in one plane. The position indicated on the horizontal scale is the location of the slide in the direction of the nominal degree of freedom. The displacement on the vertical scale is the deviation perpendicular to the nominal direction. The axis direction is the best-fit line to the straightness data points plotted in the figure. It should be noted

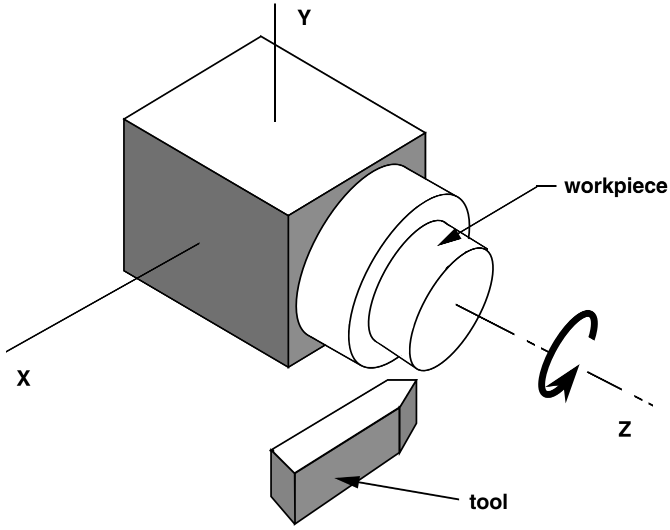


**FIGURE 10.12** Sketch of a lathe configuration. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

that these data are plotted for two dimensions; however, three-dimensional data may be used as well (if necessary). Measurement of straightness data is discussed later in this chapter.

## 10.3.2 Sensitive Directions

Of the six error terms associated with a given axis, some will affect the machine tool's accuracy more than others. These error terms are associated with the sensitive directions of the machine tool. The other error terms are associated the machine's nonsensitive directions. Although six error terms are associated with an individual axis, certain error components typically have a greater effect on the machine tool's accuracy than others. Sensitivities must be well understood for proper machine tool design and accuracy characterization.

The single-point lathe provides an excellent example of sensitive and nonsensitive directions. Figure 10.12 and 10.13 depict a lathe and its sensitive directions. The objective of the lathe is to turn the part to a specified radius, R, using a single point tool. The tool is constrained to move in the X–Z plane of the spindle. It is clear that if the tool erroneously moves horizontally in the X–Z plane, the error will manifest itself in the part shape and be equal to the distance of the erroneous move. If the tool moves vertically, the change in the size and shape of the part is relatively small. Therefore, it can be said that the accuracy is sensitive to the X and Z axes nonstraightness in the horizontal plane but nonsensitive to the X and Z nonstraightness in the vertical plane (the Y direction in Figure 10.12). The error, S, can be approximated for motion in the vertical (nonsensitive) direction by using the equation:

$$S \approx \frac{1}{8}\frac{\varepsilon^2}{R}; \quad \varepsilon << R$$

Sensitive directions do not necessarily have to be fixed. While the lathe in Figure 10.13 has a fixed sensitive direction, other machine tools may have rotating sensitive directions. Figure 10.14 depicts a lathe which has a fixed sensitive direction (fixed cutting tool position relative to the spindle) and a milling machine with a rotating cutting tool that has a rotating sensitive direction. Because the sensitive direction of the mill rotates with the boring bar, it is constantly changing directions.[3,4]

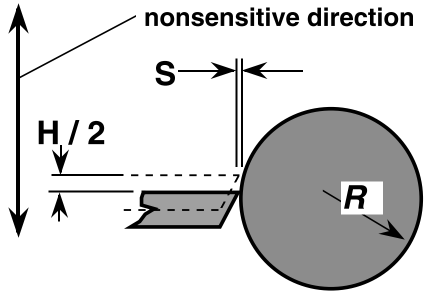


**FIGURE 10.13** Sensitive direction for a lathe. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

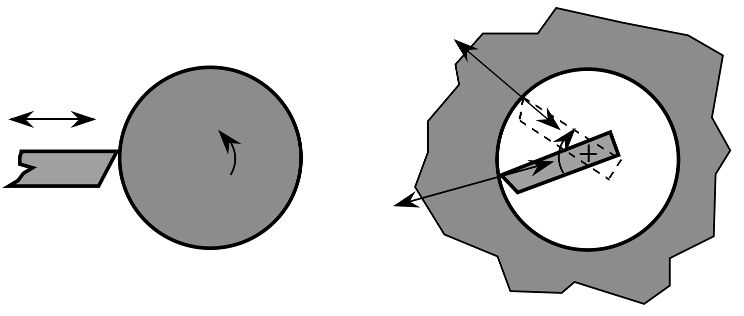

**FIGURE 10.14** Fixed and rotating sensitive directions. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

## 10.3.3 Amplification of Angular Errors, The Abbe Principle

One of the most common errors affecting a machine's ability to accurately position a linear slide is Abbe error. Abbe error is a result of the slide's measuring scales (used for position feedback) not being in line with the functional point where positioning accuracy is desired. The resulting linear error at the functional point is caused by the angular motion of the slide that occurs due to nonstraightness of the guide ways. The product of the offset distance (from the measuring system to the functional point) and the angular motion that the slide makes when positioning from one point to another yields the magnitude of the Abbe error. Dr. Ernst Abbe (a co-founder of Zeiss Inc.) was the first person to mention this error.[10] He wrote, "If errors in parallax are to be avoided, the measuring system must be placed coaxially with the axis along which the displacement is to be measured on the workpiece." This statement has since been named "The Abbe Principle." It has also been called the first principle of machine tool design and dimensional metrology. The Abbe Principle has been generalized to cover those situations where it is not possible to design systems coaxially. The generalized Abbe Principle reads: "The displacement measuring system should be in line with the functional point whose displacement is to be measured. If this is not possible, either the slideways that transfer the displacement must be free of angular motion or angular motion data must be used to calculate the consequences of the offset."[11]

While the Abbe Principle is straightforward conceptually, it can be difficult to understand at first. However, a variety of examples exist that clearly show the effects of Abbe error. An excellent illustration of the Abbe Principle is to compare the vernier caliper with the micrometer. Both of these instruments measure the distance between two points, and are thus considered two point measurement instruments. Figure 10.15 shows these two instruments measuring a linear distance, D. The graduations for the caliper are *not* located along the same line as the functional axis of measurement. Abbe error is generated if the caliper bar is bent causing the slide of the caliper to

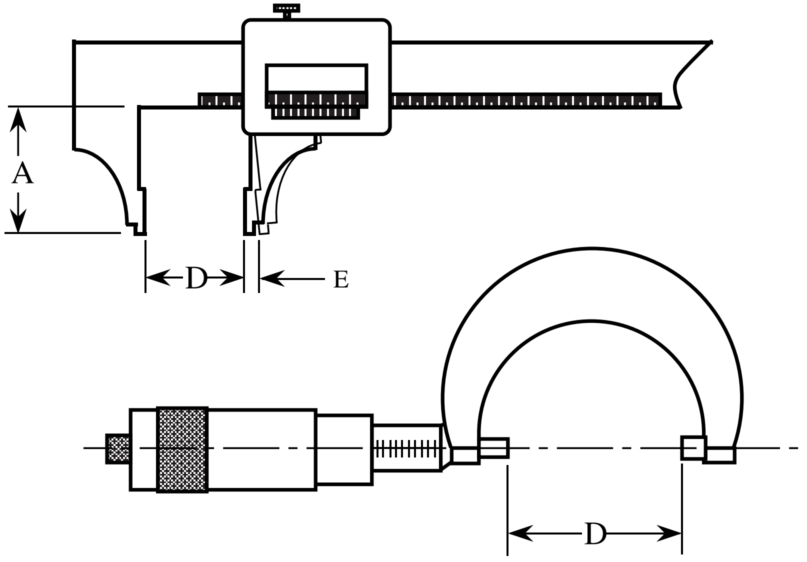


**FIGURE 10.15** Micrometer and caliper comparison for Abbe offsets and errors. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

move through an angle θ when measuring D as shown in Figure 10.15. The distance, A, between the measurement graduations and the point of measurement is called the Abbe offset. In general, the Abbe error, E, is given by

$$E = A\sin(\theta)$$

Since the angle, θ, will be very small for most situations, the Abbe error can be accurately approximated as the product of the Abbe offset and the angle expressed in radians. Since most angular errors are measured in arc seconds, it is perhaps easier to remember that 1 arc sec is equal to approximately 4.8 μin/inch so the calculation becomes:

$$Abbe\ \ error\ (\mu in) = [Abbe\ \ offset\ \ (in)] \bullet [angular\ \ error\ \ (\text{sec})] \bullet [4.8(\mu in/in)]$$

The screw and graduated drum used in a micrometer are coaxially located to the distance being measured. Therefore, angular errors will have no effect on the measured distance, as the Abbe offset is zero. Thus, the micrometer obeys the Abbe Principle and is typically considered more accurate than the caliper.

Another excellent example of Abbe error is the height gauge shown in Figure 10.16. Here the slide of the gauge has a uniform angular motion of 10 arc sec error (that is exaggerated in the figure). This is the equivalent of a 100 μin. nonstraightness over the length of the slide. The probe arm of length 10 in. amplifies and transforms this angular error into a linear error in the height measurement by the following relationship

$$E = A\sin(\theta) = [10(in)] \bullet \sin[10(\text{sec})] = [10(in)] \bullet \sin[10(\text{sec})] = 0.000485\,in$$

Using the approximate relationship that 1 arc sec is equal to approximately 4.8 μin/inch, the error may also be computed as

$$E = [10\,(in)] \bullet [10\,(\text{sec})] \bullet [4.8(\mu in/in)] = 480\,\mu in = 0.000480\,in$$

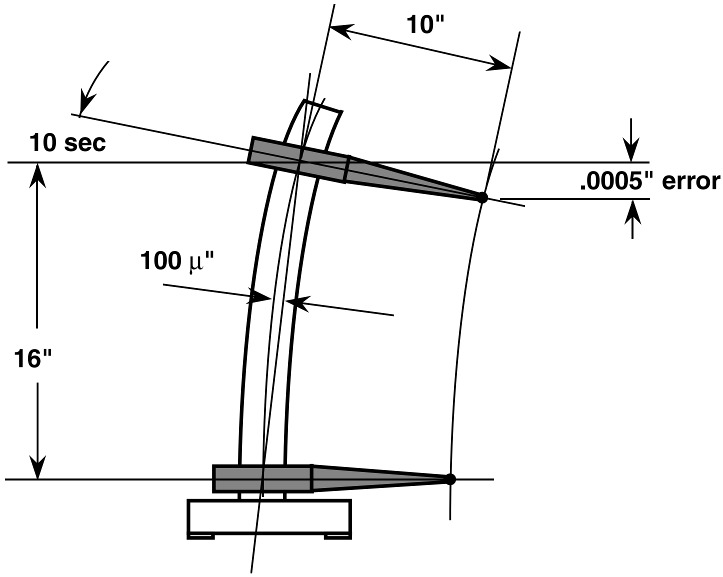


**FIGURE 10.16** Abbe error for a height gauge. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

Thus, an error of approximately 485 μin is realized due to the angular motion error of the probe arm as it traverses the length of the height gauge slide.[3]

#### 10.3.3.1 Reducing Abbe Error

There are three methods that may be used to reduce the effects of Abbe error. The first is to reduce the Abbe offset as much as possible. For example, placing measurement instrumentation coaxially with the points being measured, or placing templates for tracer lathes in the plane of the tool motion. Such modifications will eliminate Abbe error completely.

In many cases, machine designers are forced to place measurement devices at some distance from the functional measurement axis. The retro-fitting of machine tools with glass scales is an excellent example. In the retro-fit case, the replacement of the wheel gauge s (with typical resolutions of 0.0001 in.) on a machine tool with glass scale linear encoders that have an order of magnitude better resolution may cause the machine's positioning accuracy to be worse than the original design due to larger Abbe offsets for the glass scales. Such a retro-fit does not obey the Abbe Principle; however, the engineers effecting the retro-fit may not have an alternative to increasing the Abbe offset since it may be difficult to find a location to mount the linear scales that is close to the working volume.

Besides reducing the Abbe offset, designers may employ the two other methods to reduce the effects of Abbe error: (1) use slideways that are free of angular motion, or (2) use angular motion data to calculate the consequences of the offset (map out the Abbe error). Either of these two methods may be used to correct for Abbe error. However, slideways will never be completely free of angular motion, and tighter angular motion specifications can be expensive. Using angular motion data to correct the Abbe errors requires more calculations in the machine controller; however, with modern controllers these additional calculations are easily executed. Still, the best option is to minimize Abbe offsets before attempting to correct for them.[11]

#### 10.3.3.2 The Bryan Principle

There is a corollary to the Abbe Principle that addresses angular error when determining straightness, known as the Bryan Principle. The Bryan Principle states that "The straightness measuring system should be in line with the functional point whose straightness is to be measured. If this is not possible, [two options are available] either the slideways that transfer the straightness must be

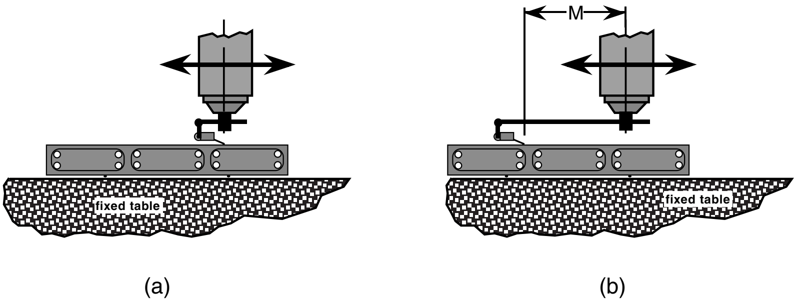


**FIGURE 10.17** Visualization of the Bryan Principle for straightness measurements. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

free of angular motion or angular motion data must be used to calculate the consequences of the offset."[11] Either of these two options may be used to improve straightness measurements; however, they may require expensive modifications to the machine tool and its controller. As with the Abbe Principle, it is always best, if possible, to comply with the Bryan Principle and design machines with zero offsets.[11] Figure 10.17 demonstrates this principle with a fixed table straightness test. The set-up presented in Figure 10.17(a) obeys the Bryan Principle since the probe tip is located in line with the spindle axis. However, Figure 10.17(b) does not obey the Bryan Principle since the probe tip is at a distance, M, from the spindle axis.

## 10.4 Sources of Error and Error Budgets

As stated in the previous section, before any advanced mapping or control techniques should be employed to improve a machine tool's accuracy and repeatability, the designer should attempt to design the best machine possible. Of course, time, economic constraints, and physics will prevent the design engineer from achieving perfection and at best, the various error that a machine possesses will be greatly reduced. An error budget is the realization that a perfect machine without error cannot be constructed. The error budget is an attempt to separate and quantify a machine tool's errors into its basic components. These error components are then budgeted such that the combination of the various acceptable errors does not exceed the total desired error of the machine tool.

The error budget is developed before the machine is designed, and may be modified during the design process if the target accuracies cannot be achieved by redistributing the error components until a technically feasible and economically viable design is reached. By redistributing the errors, the design team can still maintain the target acceptable while allowing the contributions of the various individual errors to change. The error budget is both a guideline when designing a machine and a tool to determine the machine's final accuracy when the design process is complete. The error budget provides a set of goals to the design team and identifies the errors that are the most significant and those on which the most resources must be expended. This section briefly describes some of the major considerations in developing an error budget. The process is a long and tedious one as every component of error must be identified and quantified either precisely or statistically.

### 10.4.1 Sources of Errors

Generally, the sources of errors may be broken into four categories: geometric errors, dynamic errors, workpiece effects, and thermal errors. This section presents a brief discussion of these errors providing some insight into their causes and possible methods to reduce their effects.[4]

#### 10.4.1.1 Geometric Errors

Geometric errors manifest themselves in both translational and rotational errors on a machine tool. Typical causes of such errors are lack of straightness in slideways, nonsquareness of axes, angular errors, and static deflection of the machine tool. Angular errors are, perhaps, the least understood and most costly of the various geometric errors. They are enhanced and complicated by the fact that they are typically amplified by the linear distance between the measurement device and the point of measurement (Abbe error). They are also the errors that can result in the largest improvement with simple design modifications like reducing the Abbe offset. With proper procedures, instrumentation and careful metrology, many errors can be identified, predicted and held within the desired level of the error budget.

#### 10.4.1.2 Dynamic Errors

Dynamic errors are typically caused by machine tool vibration (or chatter). They are generated by exciting resonances within the machine tool's structure. Current research is investigating the prediction of vibrations in machine tools; however, from a practical perspective, this is quite difficult. Usually, a machine tool is built and its resonant frequencies are determined experimentally. The machine's controller can then be programmed to avoid combinations of feeds and speeds that may excite its various resonances. Typically, the best one can do during the design phases of machine tools is to design a structure that is stiff, light weight, and well damped.

#### 10.4.1.3 Workpiece Effects

The workpiece can affect a machine tool's accuracy and precision in two manners: deflection during the cutting process and inertial effects due to motion. Deflection may be addressed by reducing the overall compliance of the machine tool. This is a relatively simple and well understood solution. It should be noted that most machine tool's are quite rigid by design, and it is usually the fixturing that provides the largest amount of compliance. For example, a lathe is typically a massive machine with an extremely rigid bed. However, the cutting tool or tool holder are often held in place by only a few small screws. Clearly, the stiffness of these components is small in comparison to the lathe bed, and are thus the weak point in the machine's structural loop. It is typically these weak points that yield the largest amount of stiffness increase with the least effort and design modification (i.e., it is easier to change a tool holder design, and typically more beneficial, than changing the design of the machine bed).[12]

Inertial effects of the workpiece, however, are not as simple to address. They become more pronounced with the increased speed that is associated with higher production rates. They are one of the critical limiting factors in high speed machining and typically their severity increases nonlinearly with respect to speed. Inertial effects may manifest themselves in several manners including asymmetry about a rotating axis and overshoot on a linear slide. If the part is asymmetric and is being turned on a lathe, the asymmetry may cause periodic spindle deviations reducing accuracy. A typical solution to these rotary problems is to balance the spindle with the workpiece mounted on it. For high speed spindles operating at over 200,000 rpm, balance levels under 3 mg are necessary for precision grinding operations. Other inertial effects are seen as large parts are moved rapidly in high production rate machines. Because of the high velocities and large masses of the workpieces, the machine tools may overshoot their target point. Basically, the machine's brakes are not powerful enough to stop the part at the desired position without overshooting that position. Proper design of servo systems as well as reasonable trajectories (smooth acceleration and velocity profiles) can substantially reduce inertial errors. Also, position probes used in conjunction with the machine tool can inform the controller if the workpiece is, indeed, tracking the proper trajectory.

#### 10.4.1.4 Thermal Errors

Thermal errors are probably the most significant set of factors that cause apparent nonrepeatable errors in a machine tool. These errors result from fluctuating temperatures within and around the machine tool. They also result from nonfluctuating conditions at constant temperatures other than 20°C. Although deviations in machine tool geometry from thermal causes may be theoretically calculated, in practice such an analysis is difficult at best to successfully achieve even in the simplest of machine tools. Thus, proper thermal control is required.

For typical machine tools, thermal errors may be caused by a wide variety of fluctuating heat sources including motors, people, coolant, bearings, and the cutting process. Furthermore, variations in the temperature of the environment may cause substantial thermal errors. For example, temperatures in a machine shop may vary from 95° F in the summer to 65° F or cooler in the winter. For higher precision machine tools, sources such as overhead lighting and sunlight may substantially contribute to thermal errors. Even windows or skylights in a machine shop may permit sunlight to shine on such machines during a specific time of day causing them to expand more than the tolerances that they are supposed to hold.

Thermal errors may be reduced substantially by proper procedure and design. For example, errors due to motors and bearings heating-up during use are reduced by warming-up the machine tool before it is used. Typically, high precision machine tools such as grinders are not shut down unless they are not being used for a substantial period of time. The grinding wheels for such grinders are kept spinning at their operational speed continuously, even when the machine is idle. This insures that the grinder's spindle motor and bearings as well as the grinding wheel are at a constant temperature. To further eliminate thermal effects, coolant temperature as well as environmental temperature should be controlled. The target temperature for the machine tool's environment and coolant is typically 20°C (68°F) which is the national (and international) temperature at which all distance measurements are made.[13]

Finally, there are several design techniques that may be employed to reduce thermal effects, including reducing the thermal capacitance of the machine tool. This permits the entire machine tool to thermally equilibrate rapidly rather than have thermal gradients, thus reducing the amount of time required for the system to warm-up. The use of materials with similar coefficients of thermal expansion ($C_{te}$), or the kinematic isolation of materials with different $C_{te}$ will reduce thermally induced stresses in the system. For example, glass scales having a low $C_{te}$ are often fixed at both ends to steel machines having a higher $C_{te}$. When the temperature of the machine varies, the steel structure will deform more from the thermal variations than the glass scale. Since the scale is significantly less rigid than the steel structure, the scale may undergo deformation as scale and structure deform at different rates. This could generate an error in the measurement system. A solution to this problem is to fix the scale at one end, and mount the other end of the scale such that there is compliance in the scale's sensitive direction. When the two bodies change size at different rates the stresses are then mostly absorbed by the compliant mount.[3,14]

### 10.4.2 Determination and Reduction of Thermal Errors

The environment in which the machine tool operates has a significant effect on the performance of the machine tool. Typically, in high precision applications thermal effects are the largest single source of errors (Bryan, 1968).[15] Figure 10.18 is a block diagram depicting various sources of thermal disturbances that influence machine tools. As stated in ANSI B5.54, "Thermally caused errors due to operating a machine tool in a poor environment cannot be corrected for by rebuilding the machine tool, nor are they grounds for rejection of a machine tool during acceptance test unless the machine is specified to operate in that particular environment."[5] Furthermore, thermal error cannot be completely eliminated by enhanced control algorithms or the addition of sensors. The reality is that it is simpler and more cost effective to limit thermal effects than to attempt to compensate for them. This section briefly discusses basic concepts of thermal behavior characterization, and simple methods to limit errors caused by varying thermal conditions.

To quantify the effects of thermal errors on a machine tool's performance, the Thermal Error Index (TEI) is used. The TEI is the summation, without regard to sign, of the estimates of all thermally induced measurement errors, expressed as a percentage of the working tolerance or total permissible error. The TEI and its computation are thoroughly explained in ANSI B89.6.2-1973.[13] The computational procedures account for uncertainties in the quantification of various parameters such as expansion coefficients and the differential expansions of various materials when machines

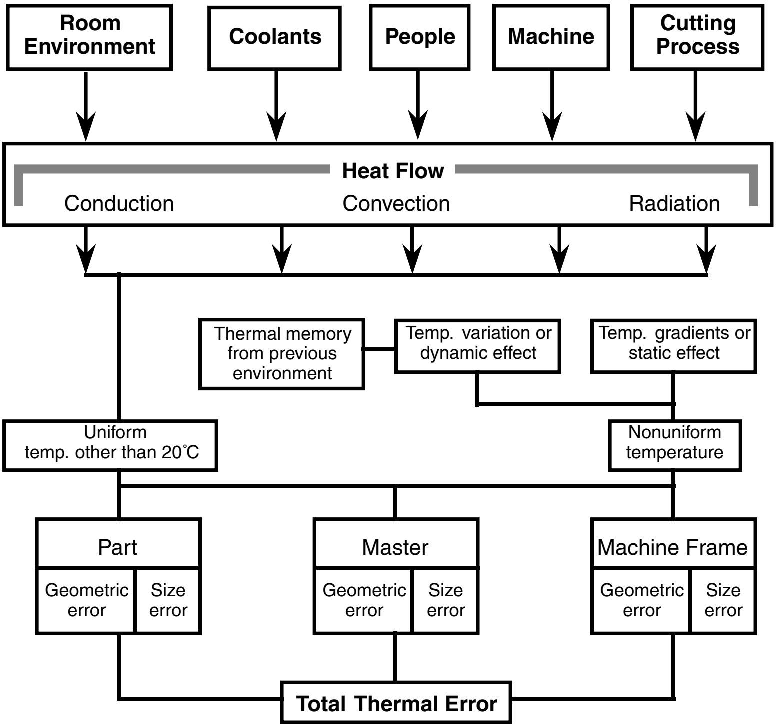


**FIGURE 10.18** Factors thermally affecting machine tool environment. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

are operated at temperatures other than 20°C. The ANSI standard B5.54-1992[5] provides a method of using the TEI to develop contractual agreements for the purchasing and selling of machine tools and manufactured parts. It states that calibration, part manufacture and part acceptance procedures are valid if all pertinent components of the system are at 20°C, or it can be shown that the TEI is a reasonable and acceptable percentage of the working tolerance.

An important value used in the computation of the TEI is the temperature variation error (TVE). The TVE is the maximum possible measurement error induced solely by the deviation of the environment from average conditions. In particular this applies to repeatability, linear displacement accuracy and telescoping ball bar performance measurement results. The TVE may be determined from measurements using a standard drift test. Figure 10.19 presents a schematic for a three-axis drift test using three orthogonally positioned air bearing LVDTs (linear variable differential transformer).[5] Once the set-up in Figure 10.19 is established, the LVDT signals are sampled and recorded over an extended time period (typically 24 hours). The results are used to quantify the amount of error motion that is generated along three orthogonal directions via thermal drift over a long period in time. The error recorded in a drift test is often used to provide a bound on the repeatability of a machine tool since a machine's repeatability clearly cannot be smaller amount of drift that it experiences.

There are several factors that must be considered if the machine tool and environment are to be thermally controlled. The first is the temperature of the machine's environment. The defined standard temperature at which machine tools should be calibrated is 20°C (68°F). Proper temperature control of the ambient air around the machine tool is critical in high precision operations. This includes temperature control of the environment as well as providing sufficient circulation to remove any excess heat generated by the system. Even seemingly small heat sources such as lights and sunlight can substantially add to thermal errors.

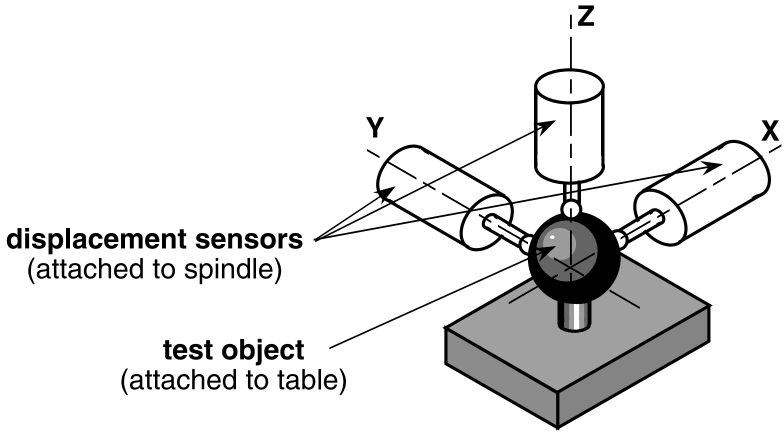


**FIGURE 10.19** Three-axis drift test. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

It is also critical to control the temperature of the coolant. Variations of coolant temperature of more than 30°F are typical in many plants depending on the time of the year and even the time of the day, in particular if a central coolant system is used. Furthermore, a constant flow rate of coolant should be supplied to the machine tool to eliminate any type of time dependent thermal gradients in the machine. In fact, some machine tools are *oil showered* specifically to engulf the machine tool in temperature controlled oil. Even the composition of the coolant is critical for temperature control. Water based coolants will evaporate, cooling the machine more than expected depending on environmental conditions. This will cause changing thermal gradients over time and yield thermal errors in the machine tool (Bryan et al., 1982).[16] However, water-based coolants are currently preferred over oil-based ones because they are not as harmful (toxic) the environment and are not nearly as flammable. Thus, evaporation effects of water-based coolant should be considered if it becomes necessary to use them in high precision operations.

Clearly, thermal gradients will exist in a machine tool; however, it is important that these gradients remain constant with respect to time. For example, a large electric motor on a lathe will generate heat. Ideally, it is best to remove this heat. However, in reality sections of the machine tool that are nearest to the motor will have a higher temperature. Thus, from a spatial perspective, thermal gradients exist. However, as long as those gradients do not change in a temporal fashion, the machine tool's repeatability will not be significantly affected by the thermal gradients.[3]

### 10.4.3 Developing an Error Budget

The error budget is based on the behavior of individual components of the machine tool as well as their interactions with other components. Since no machine is perfect, error exists in positioning the cutting tool relative to the workpiece. This error is called the tool positioning error (TPE). The error budget is concerned with determining the effect of system variations (systematic and non-systematic) on the TPE. The error budget should contain as many of the sources of error as possible. The effects of each source of error on the TPE must also be well understood. Large error components that are in highly sensitive directions (thus, contributing greatly to the TPE) should be primary concerns. Other error components with lower sensitivities may be too small to be considered until larger TPE components have been reduced.

To properly use an error budget, two tasks must be undertaken:

1. Determine the sources of error within the machine tool and its environment.
2. Determine how those sources of error combine to affect the TPE.

This chapter is limited to a brief discussion on the identification and combination of errors that affect the machine tool. However, extensive research has been conducted on these issues, and it is recommended that an engineer be familiar with the literature before using an error budget.[4] This section is concerned with combining error components that affect a machine tool to yield their overall effect on the TPE in a particular direction.

The errors discussed in the previous section may be placed into three categories when developing an error budget:

1. Random, which under apparently equal conditions at a given position, does not always have the same value and can only be expressed statistically.
2. Systematic, which always has the same value and sign at a given position and under given circumstances. (Wherever systematic errors have been established, they may be used for correcting the value measured.)
3. Hysteresis is a systematic error (which in this instance is separated out for convenience). It is usually highly reproducible, has a sign depending on the direction of the approach, and a value partly dependent on the travel. (Hysteresis errors may be used for correcting the measured value if the direction of the approach is known and an adequate pretravel is made.)[17]

Systematic errors, $e_{sys}$, may be considered vector quantities possessing both magnitude and direction that may be added in a vector sense. That is to say that all systematic errors of a machine tool along a particular axis may be summed together to yield the total systematic error. Because the errors do possess direction (positive or negative in a specified direction), individual errors may either increase the total system error or actually reduce the error via cancellation.

Random errors, however, must be treated via a statistical approach. The portions of an error budget that represent random errors are *always* additive. That is to say they will always make the error larger because the sign of their direction as well as the magnitude of the error is a random quantity. The assumption here is that nature will work against the machine designer and generate error components that increase the overall machine error. One cannot assume that one will be lucky and have a random error component reduce the overall system error.

Root mean square (RMS) error is often used to quantify random errors where the random errors tend to average together. The combined random RMS error is computed as the geometric sum of the individual RMS errors. Thus, for N random error components, the total RMS error is given by

$$\left(RMS_{tot}\right)_i = \sqrt{\left(\sum_{j=1}^{N}\left(RMS_j\right)^2\right)}$$

where $RMS_j$ is the $j^{th}$ component of random error in the $i^{th}$ direction. This results in a total overall error of

$$\left(e_{RMS}\right)_i = \left|\sum\left(e_{sys}\right)_i + \sum\left(e_{hyst}\right)_i\right| + \left(RMS_{tot}\right)_i$$

where $(e_{sys})_i$ and $(e_{hyst})_i$ are the systematic error and hysteresis error of the system along the $i^{th}$ axis. The absolute values about the systematic and hysteresis error make them positive quantities which are added to the always positive quantity of the random error. This reflects the fact that random error can only increase the total error; however, systematic errors may cancel each other.

Quite often, random errors are described in terms of a total peak-to-valley amplitude, PV. $PV_j$ may be considered the separation of two parallel lines containing the $j^{th}$ error signal. $PV_j$ is related to $RMS_j$ by the following equation

$$PV_j = \left(K_j\right)\left(RMS_j\right)$$

where $K_j$ is a scalar quantity that depends on the error signal's probability distribution. The values of $K_j$ for uniform and ±2σ Normal (Gaussian) distributions are 3.46 and 4, respectively. Typically, the value for the uniform distribution ($K_j = 3.46$) is used, since individual error traces are not generally normally distributed. If there are some central tendencies for the distribution, the uniform assumption will be conservative.[18] Using the relationship for $PV_i$ given above, the total random error generated by combining N random error components in the $i^{th}$ direction is given by

$$\left(e_{PV,rand}\right)_i = \frac{1}{2\sqrt{3}}\left[\sum_{j=1}^{N}\left(PV_j\right)^2\right]_i$$

The total error in the $i^{th}$ direction for the peak-to-valley scenario is

$$\left(e_{PV}\right)_i = \left|\sum\left(e_{sys}\right)_i + \sum\left(e_{hyst}\right)_i\right| + \left(e_{PV,rand}\right)_i$$

It should be noted that these error values are based on a probabilistic estimation. Therefore, the actual error may be smaller or larger than the estimated value. Depending on the value that is used for $K_j$, the designer may estimate the probability of the error estimate being either too small or too large. It must be remembered that the above equations only provide for an estimation of the error and cannot provide a precise quantity, only a bound with a given probability. However, using these relationships with a $K_j$ for a uniform distribution is the procedure that is practiced by many designers.

## 10.5 Some Typical Methods of Measuring Errors

Multi-axis machine tools have a wide variety of parametric error sources that may be determined using a broad spectrum of approaches. This section presents a few of the most common and important techniques for addressing scale errors, straightness errors, and radial motion of a spindle (or rotary table). The techniques discussed are not the only techniques available to qualify machine tools; however, they are a set of powerful tools that are relatively easy to implement and quite useful.

Before the various procedures for error measurement are described, it is worth while to discuss the laser measurement system, one of the most versatile measurement systems available to the metrologist. The laser measurement system may be used to measure linear displacement, angular displacement, straightness, squareness, and parallelism. The laser measurement system, often referred to as a laser interferometer, consists of the following components:

1. The laser head that is the laser beam's source.
2. A tripod or stand on which the laser head is mounted.
3. An air sensor to measure the temperature, humidity, and barometric pressure of the ambient air.
4. A material sensor to measure the temperature of the machine tool's measurement system.
5. A linear interferometer that actually performs the interference measurements.
6. A linear retro-reflector (or measurement corner cube) to reflect the laser beam off of the point being tracked.
7. A reference corner cube to split and recombine the beam generating the beam interference needed for the interferometer.

Figure 10.20 is a drawing of a laser interferometer and its components set-up for a linear displacement test.

Figure 10.21 is a schematic of the basic operational configuration of a laser measurement system. The beam originates in the laser head and is sent through the reference corner cube where it is

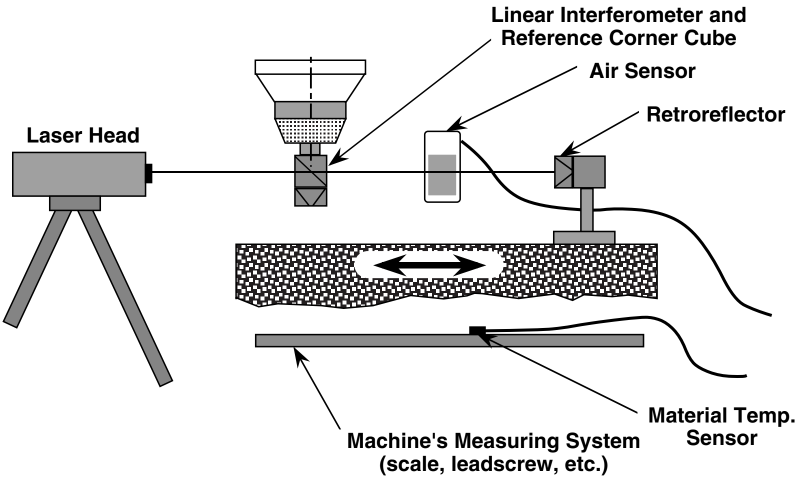


**FIGURE 10.20** Laser interferometer set-up for linear displacement test. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

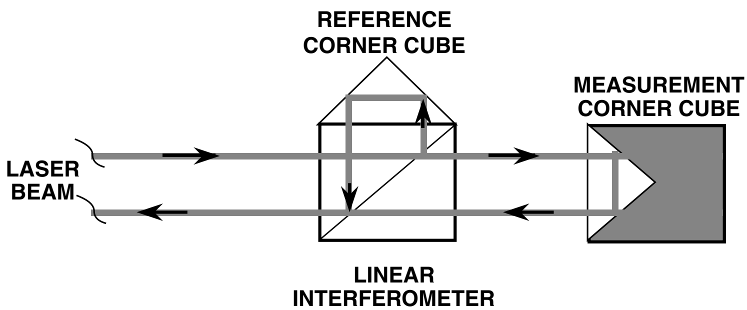


**FIGURE 10.21** Laser path.

split. Part of the beam continues to the measurement corner cube where it is reflected back towards the reference corner cube. The two beams are then recombined in the reference corner cube where they may combine (interfere) in a constructive or destructive manner. The combined beam then continues to the interferometer. The interferometer measures the amount of interference between the two beams, and determines the distance traveled between the initial location of the measurement corner cube and its current position.

Laser interferometers typically use either a single or multiple frequency Helium-Neon gas laser. The interferometer simply counts the number of wavelengths that the slide traverses between two points. Thus, the laser interferometer can only measure relative displacements as opposed to absolute distances. It can only inform the operator as to the number of wavelengths of light between two points. The wave length of the laser is typically stabilized and known to better than 0.05 parts per million.

There are three basic guidelines in setting-up the laser measurement system:

1. Choose the correct set-up to measure the desired parameter (e.g., distance) and verify the directional signs (±) of the system.
2. Approximate the machine tool's working conditions as closely as possible. For example, make sure that the machine tool is at its operational temperature. Machine tool scales may be made of material that will change length as their temperature varies. This change in length directly affects their position output.
3. Minimize potential error sources such as environmental compensation, dead path, and alignment.

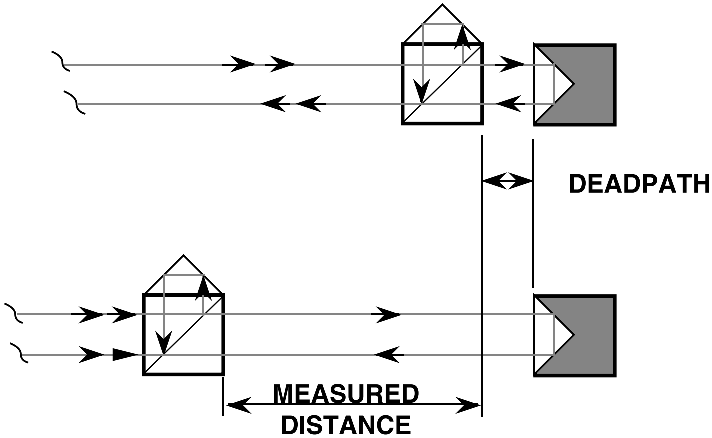


**FIGURE 10.22** Laser interferometer dead path. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

The potential error sources from the environment are variations in air temperature, humidity, and barometric pressure. These affect the wavelength of light in the atmosphere. The wavelength of the laser light will vary one part per million for each

1°C (2°F) change in air temperature
2.5 mm (0.1 inch) Hg change in absolute barometric pressure
30% change in relative humidity

As a comparison, if the machine's scales are made of steel they will expand or contract one part per million for every 0.09°C (0.16°F). The accuracy of the laser interferometer is directly determined by how accurately the ambient conditions are known.

Typically, laser interferometers come equipped with environmental measurement systems that are capable of tracking the temperature, barometric pressure, and humidity during a test. This information is used to electronically alter the displacement values, compensating for the change in the velocity of light in air under the measured conditions. Thus, proper compensation can eliminate most environmental effects on the system. There is, however, an area known as the dead path where compensation for the velocity of light error is not applied. The dead path, shown in Figure 10.22, is the distance between the measurement corner cube and the reference corner cube when the laser interferometer is nulled or reset. The compensation for the velocity of light error is applied only to the portion of the path where displacement is measured as shown in Figure 10.22. To minimize the dead path error, the unused laser path must be minimized by placing the reference corner cube as close to the measurement corner cube as possible. The interferometer should then be reset, and the set of distance measurements made by moving the reference corner cube away from the measurement corner cube. Changes in the ambient environmental conditions during the measurement will only be considered for the measured distance and not for the dead path. However, if the dead path is small and the measurements are made over a short time period, the ambient conditions typically will not change enough to generate significant velocity of light errors. Dead path error may be further reduced by having a well controlled environment.

Misalignment of the laser beam to the linear axis of motion of the machine tool will result in an error between the measured distance and the actual distance. This error is typically called cosine error and is depicted in Figure 10.23. If the axis of motion is misaligned with the laser beam by an angle, θ, then the measured distance, $L_{measured}$, is related to the actual machine distance, $L_{machine}$ by the following equation

$$L_{measured} = L_{machine} \cos(\theta)$$

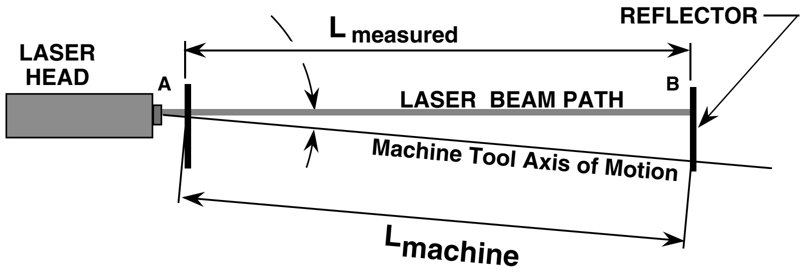


**FIGURE 10.23** Geometry for cosine error. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

Cosine error will always result in the measured value being less than the actual machine value when the machine and the reference are perfect ($L_{measured} < L_{machine}$).

The significant advantage in using the laser measurement system is that it is dependent only on a well-calibrated wavelength of its laser source for measurement. That is to say, its measurement standard is related directly to fundamental characteristics defined in physics. Linear measurement devices such as micrometers, are typically calibrated to gauge blocks that are calibrated against other gauge blocks that eventually can be traced back to a formal calibration at a calibration laboratory such as the one at NIST (National Institute of Standards and Technology). Thus, the traceability of an individual measurement can be established. However, the laser measurement system need only be traced back to the wavelength of light; thus, it is a powerful tool in the metrologists' arsenal. When properly used, the laser measurement system is a powerful tool that is useful for determining many types of errors. It is very important to understand the basic theory of the laser measurement system's operation and the correct procedures before using it. If employed improperly, it can easily generate erroneous results that may not be at all obvious.

## 10.5.1 Linear Displacement Errors

As previously stated the linear displacement error is the difference between where the machine's scale indicates that a carriage is and where the carriage is actually located. To determine linear displacement error an accurate external reference device for measuring travel distance must be used. Typically, a laser measurement system is employed for this task. This section is concerned with the use of the laser measurement system to measure linear displacement.

The determination of linear displacement errors is accomplished by a simple comparison of the linear scale output to that of the laser interferometer at different locations along a particular machine tool slideway. The set-up for such a measurement is shown in Figure 10.20. The laser measurement system should be set-up in accordance with the procedures previously outlined, minimizing errors such as dead path errors, cosine errors, and environmental errors. The table of the machine tool is then moved in increments of a given amount along the length of the slideway. At each interval, the table is brought to a stop, and the distance traveled is computed from data gathered from the machine's scales. The scale distance is compared to the distance measured using the laser interferometer. The difference between the two distances is the linear displacement error. These measurements and comparisons are repeated several times along the entire length of the slideway, mapping the scale errors for the slideway. It should be noted that the linear displacement error includes not only the machine's scale errors, but the Abbe errors due to angular motion of the carriage.

## 10.5.2 Spindle Error Motion — Donaldson Reversal

As was discussed earlier, when a spindle or rotary table rotates, it has some error motion in the radial direction termed radial motion. It is important to measure the amount of radial motion in order to characterize spindle performance and understand the amount of error contributed by the

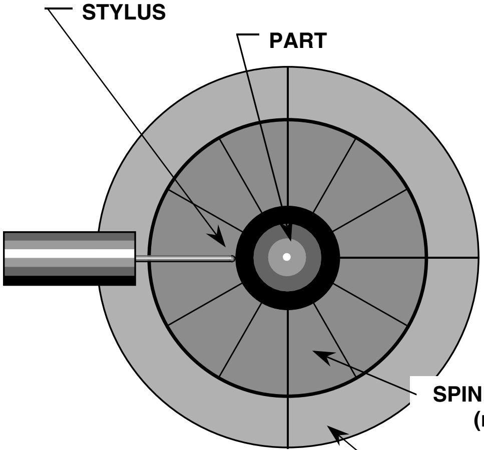


**FIGURE 10.24** Radial motion set-up. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

spindle or rotary table to the machine tool's total error. To measure the radial motion of a spindle or rotary table, a precision ball is centered on the axis of rotation of the table and rotated. A probe is placed on the surface of the ball and radial deviations of the probe tip are recorded (see Figure 10.24). If the precision ball was perfect and it was perfectly centered, the signal from the probe would be the radial motion of the table.

Unfortunately, the precision ball is not a perfect sphere and the resulting probe signal is a combination of the radial motion of the spindle and the imperfections in the ball. Donaldson developed a method for completely separating gauge ball nonroundness from spindle radial motion.[19] This method has been termed Donaldson ball reversal. All that is needed for ball reversal is:

1. A spindle with radial motion that is approximately an order of magnitude less than the value of roundness desired (this is a rule of thumb).
2. An accurate indicator (preferably electronic).
3. Recording media (polar chart or a computer).

The following assumptions are made:

1. The radial motion is repeatable.
2. The indicator accurately measures displacement.

There are two set-ups for ball reversal that are shown in Figure 10.25. In the first set-up, the ball is mounted on the spindle with point B of the ball located at point A on the spindle. The stylus of the probe is located at point B on the ball. The spindle is then rotated 360° and the motion of the stylus is recorded. The signal from the stylus, $T_1(\theta)$ is given by the sum of the nonroundness of the gauge ball, $P(\theta)$, and the radial motion of the spindle, $S(\theta)$

$$T_1(\theta) = P(\theta) + S(\theta)$$

The spindle is then rotated back 360° and the gauge ball is relocated on the spindle such that point B is rotated 180°, and is at a position opposite to point A on the spindle. The probe is also positioned opposite point A and brought into contact with the gauge ball at point B. The spindle is once again rotated 360° and the data from the probe are recorded. The signal from the probe, $T_2(\theta)$ is

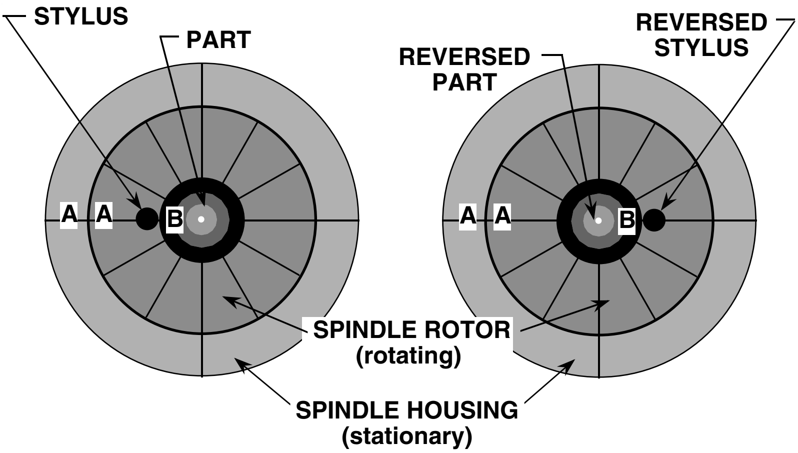


**FIGURE 10.25** Donaldson ball reversal set-up. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

$$T_2(\theta) = P(\theta) - S(\theta)$$

From the two data sets, $T_1(\theta)$ and $T_2(\theta)$, the spindle radial motion may be computed as

$$S(\theta) = \frac{T_1(\theta) - T_2(\theta)}{2}$$

and the gauge ball nonroundness may be computed as

$$P(\theta) = \frac{T_1(\theta) + T_2(\theta)}{2}$$

This set of simple linear combinations of $T_1(\theta)$ and $T_2(\theta)$ provides information on both the ball and the spindle without using secondary or intermediate standards. The method is also independent of the errors in either the precision ball or the spindle. Thus, it is considered a self-checking method.[19]

If the spindle does not use rolling elements (e.g., an air aerostatic or hydrostatic bearing) then the spindle does not need to be rotated backwards 360° degrees between the two set-ups. Rotating the spindle back 360° between set-ups is necessary to insure that all of the rolling elements exactly repeat the same motions each time the data are taken. Furthermore, if the spindle is being used as a rotary axis, then is should only be used for the 360° measured by the reversal method. If the use of a rotary table with rolling element bearings exceeds the test rotation range, then the measured radial motion of the table, $S(\theta)$, will not correctly represent the radial motion of the table outside of the original 360° range. If more rotation than 360° is necessary, then the reversal should be done for the entire range of rotation that will be used.

### 10.5.3 Straightness Errors — Straight Edge Reversal

As was discussed earlier, when a machine table moves along a slideway, it experiences straightness errors along the slide perpendicular to the axis of travel. The straightness errors must be measured to determine the amounts and directions of error that the slideway nonstraightness is contributing to the overall machine tool error. To measure the nonstraightness of a slideway, a straight edge is placed on the machine table parallel to the axis direction. A probe is placed normal to the surface of the straight edge and deviations of the probe tip are recorded (see Figure 10.26). The resulting

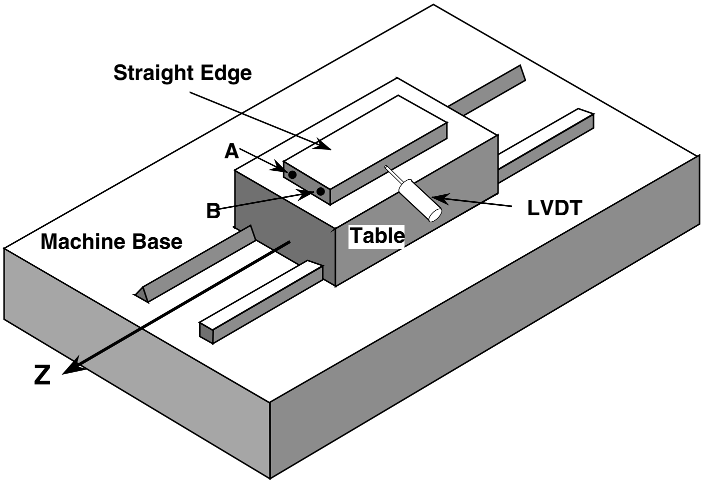


**FIGURE 10.26** Nonstraightness measurement (first set-up). (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

probe signal is the nonstraightness of the slideway, the nonstraightness of the straight edge, and the nonparallelism of the straight edge to the axis. (If the slideway was perfectly straight and the straight edge was also perfect, the signal from the probe would be a straight line.)

In a fashion similar to Donaldson ball reversal, a method termed straight edge reversal can be used to separate the nonstraightness of the straight edge from the nonstraightness of the slideway. All that is needed for straight edge reversal is:

1. A straight edge that has a length equal to the length of the slideway to be measured.
2. An accurate indicator (preferably electronic).
3. Recording media (strip chart or a computer).

The following assumptions are made:

1. The slideway straightness error is repeatable.
2. The indicator accurately measures displacement.

There are two set-ups for straight edge reversal. The first is shown in Figure 10.26, and the second is shown in Figure 10.27. In the first set-up, the straight edge is mounted on the table with a three point kinematic mount. Point B of the straight edge is located at the front of the table and point A at the rear of the table. The stylus of the probe is located on the side of the straight edge nearest to point B. The table is then moved along the entire length of the slideway and the motion of the stylus is recorded. The signal from the stylus, $T_1(Z)$ is given by the sum of the nonstraightness of the straight edge, P(Z), and the nonstraightness of the slideway, S(Z)

$$T_1(Z) = P(Z) + S(Z)$$

The table is then positioned back to its original starting point and the straight edge is relocated (flipped) on the table such that point B is at the rear of the table and point A is at the front of the table as shown in Figure 10.27. The probe is also moved to the rear of the table such that it is in contact with the side of the straight edge that is nearest point B. The table is once again moved along the entire length of the slideway and the data from the probe are recorded. The signal from the probe, $T_2(Z)$ is

$$T_2(Z) = P(Z) - S(Z)$$

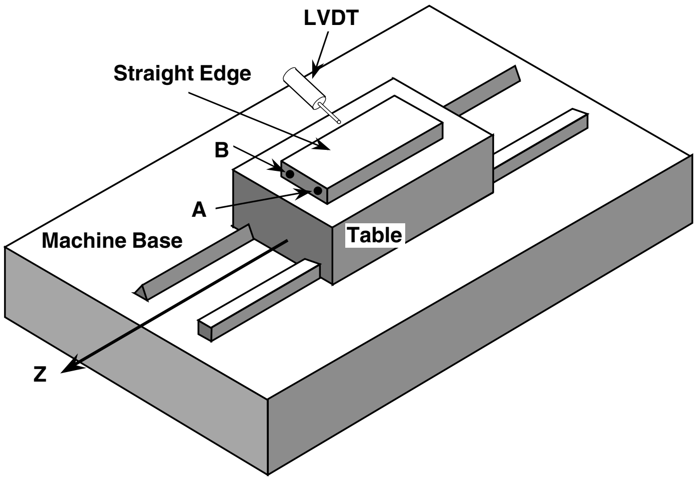


**FIGURE 10.27** Second set-up for straight edge reversal. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

From the two data sets, $T_1(Z)$ and $T_2(Z)$, the slideway nonstraightness error may be computed as

$$S(Z) = \frac{T_1(Z) - T_2(Z)}{2}$$

and the straight edge nonstraightness error may be computed as

$$P(Z) = \frac{T_1(Z) + T_2(Z)}{2}$$

This set of simple linear combinations of $T_1(Z)$ and $T_2(Z)$ provides information on both the straight edge and the slideway without using secondary or intermediate standards. The method is also independent of the errors in either the straight edge or the slideway. Thus, it is considered a self-checking method.[20]

### 10.5.4 Angular Motion — Electronic Differential Levels

The angular motion about axes may be determined using a variety of tools including laser measurement system, autocollimator, and electronic differential levels. This section presents angular motion measurement using a set of electronic levels. This technique is simple and the levels are relatively inexpensive in comparison to a laser measurement system or autocollimator. Since electronic levels use gravity as a reference, they are limited to angular motion about axes in a horizontal plane. Thus, roll and pitch errors may be determined for axes in the horizontal plane, and pitch and yaw may be determined for vertical axes.

The electronic level is an instrument that measures small angles using the direction of gravity as a reference. A typical set-up for determining the pitch of an axis is shown in Figure 10.28. The two levels, A and B, are used differentially in one plane yielding the angular motion of one level relative to the other level. Level A is located in the tool location, and level B is located where the workpiece is mounted. These locations insure that the angular motions computed will be those that are experienced between the workpiece and the tool. To perform the measurement, the table is moved along its entire length, stopping at fixed distances along the length of the slideway. It is important that the table is brought to a complete stop at each point where the readings are taken. This permits the levels to stabilize so that accurate data can be recorded. The two levels are then read and

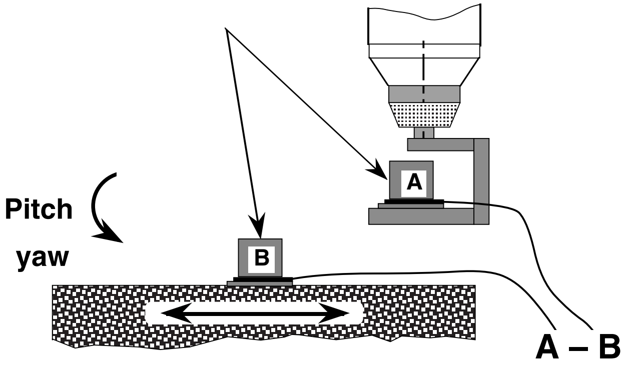


**FIGURE 10.28** Pitch measurement set-up using electronic levels. (From Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

the value from B is subtracted from A resulting in the relative angular motion between the two levels. The table is then moved to the next location where another reading is taken. This procedure is repeated until the angular motion for the entire axis is mapped. The roll of the slide may be measured by simply rotating the two levels 90° about the vertical axis and repeating the procedure. Yaw measurement requires the use of either a laser angular interferometer or an autocollimator.

## 10.6 Conclusion

Precision manufacturing is continuously changing as technological advances and consumer demands push machine accuracy, resolution, and repeatability to ever improving levels. This chapter has presented some of the basic ideas, principles, and tools used to design high precision manufacturing systems. There are a plethora of other concepts available to engineers designing precision machine tools or metrology systems, and the reader is encouraged to make use of the references provided throughout this chapter. In conclusion, adherence to fundamental principles and the combination of good design, metrology, and practice are necessary to realize machine tools of the highest precision.

## 10.7 Terminology

**Accuracy** is formally defined as quantitative measure of the degree of conformance to recognized national or international standards of measurement.

**Angular errors** are small unwanted rotations (about X, Y, and Z axes) of a linearly moving carriage about three mutually perpendicular axes.

**Angularity** is the angular error between two or more axes designed to be at fixed angles other than 90°.

**Average axis line** for rotary axes is the direction of the "best fit" straight line (axis of rotation) obtained by fitting a line through centers of the least squared circles fit to the radial motion data at various distances from the spindle face.

**Axial error motion** is the translational error motion collinear with the Z reference axis of an axis of rotation (about the Z axis).

**Axis direction** is the direction of any line parallel to the motion direction of a linearly moving component. The direction of a linear axis is defined by a least squares fit of a straight line to the appropriate straightness data.[5]

**Error** is defined as the difference between the actual response of a machine to a command issued according to the accepted protocol of the machine's operation and the response to that command anticipated by the protocol.

**Error motion** is the change in position relative to the reference coordinate axes, or the surface of a perfect workpiece with its center line coincident with the axis of rotation. Error motions are specified as to location and direction and do not include motions due to thermal drift.

**Error motion measurement** is a measurement record of error motion which should include all pertinent information regarding the machine, instrumentation, and test conditions.

**Face motion** is the rotational error motion parallel to the Z reference axis at a specified radial location (along the Z axis).

**Parallelism** is the lack of parallelism of two or more axes (expressed as a small angle).

**Radial error motion** is the error motion of rotary axis normal to the Z reference axis and at a specified angular location (see Figure 10.5).[5]

**Radial error motion** is the translational error motion in a direction normal to the Z reference axis and at a specified axial location (along the X and Y axes).

**Repeatability** is formally defined as a measure of the ability of a machine to sequentially position a tool with respect to a workpiece under similar conditions.

**Resolution** is the least increment of a measuring device; the least significant bit on a digital machine.

**Runout** is the total displacement measured by an instrument sensing a moving surface or moved with respect to a fixed surface.

**Scale errors** are the differences between the position of the readout device (scale) and that of a known reference linear scale (along the X axis).

**Slide straightness error** is the deviation from straight line movement that an indicator positioned perpendicular to a slide direction exhibits when it is either stationary and reading against a perfect straight edge supported on the moving slide, or moved by the slide along a perfect straight edge which is stationary.

**Squareness** is a plane surface that is "square" to an axis of rotation if coincident polar profile centers are obtained for an axial and face motion polar plot at different radii. For linear axes, the angular deviation from 90° measured between the best fit lines drawn through two sets of straightness data derived from two orthogonal axes in a specified work zone (expressed as small angles).

**Straightness errors** are the nonlinear movements that an indicator sees when it is either (1) stationary and reading against a perfect straightedge supported on a moving slide or (2) moved by the slide along a perfect straight edge which is stationary (see Figure 10.5).[5] Basically, this translates to small unwanted motion (along the Y and Z axes) perpendicular to the designed direction of motion.

**Tilt error motion** is the error motion in an angular direction relative to the Z reference axis (about the X and Y axes).

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