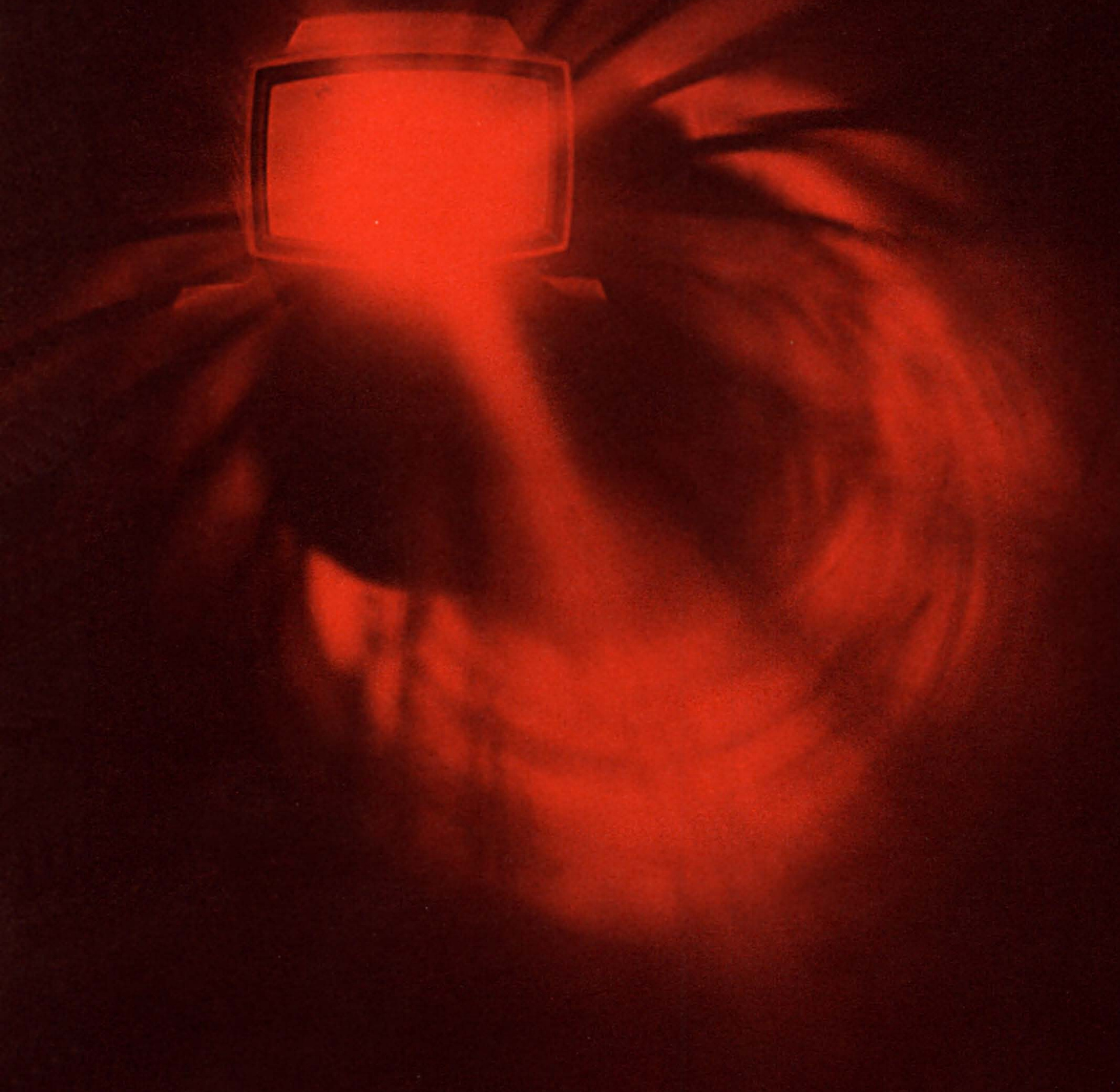
CALIBRATION OF A MACHINE TOOL

Laser Measurement System
Application Note 156-4



HEWLETT PACKARD

CALIBRATION OF A MACHINE TOOL
LASER MEASUREMENT SYSTEM

Application Note 156-4

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I. Introduction

Due to increasing demands for high productivity for machine tools, the machine tool industry has been forced to rely less on the skill of the machinist, placing more emphasis on the accuracy of the machine tool itself. Similarly, the large number of identical machining operations required for batch production led to increasing automation of machine tools, ultimately leaving the machine tool responsible for the quality of the finished part. This made it imperative that the builders and users of machine tools continuously study and improve their machine's operating characteristics.

One of the earliest problems associated with machine tool study or evaluation was the lack of a suitable length standard. Evaluation of positioning accuracy was commonly performed using a physical standard such as a scale or lug bar. These were available with sufficient accuracy in lengths up to about two feet, but longer standards were unwieldy and generally inaccurate. This meant that positioning accuracy of large machine tools had to be checked in short intervals by the method of "staging" which was an extremely long and tedious process. The results obtained were often non-repeatable and rarely were indicative of the accuracy of the machine tool under evaluation.

The development of the laser interferometer has provided the machine tool industry with a high accuracy length standard which can be used on machine tools of all sizes. The accuracy of the interferometer is determined by the laser wavelength, which for the HP 5526A Laser Measurement System is known to better than 0.5 parts per million. This value compares favorably with the best physical standards available, and is certainly acceptable for machine tool evaluation. In addition, the laser interferometer is easy to use allowing measurements to be made in minutes which had previously taken several hours or even days to perform.

Until recently the laser interferometer was used only to measure linear positioning errors in one, two or three coordinate axes. However, with the advent of the HP 5526A Laser Measurement System, the capability of measuring five of the six degrees of freedom of a machine tool with one instrument is now possible. Linear positioning, straightness in two planes, pitch, and yaw can all be measured by the 5526A Laser Measurement System by the use of the proper optical components. Since positioning errors resulting from unwanted angular motions or from out-of-straightness translations can potentially be larger than the linear positioning errors on a coordinate axis, all six degrees of freedom are of equal importance.

As a general rule, all of the basic six degrees of freedom of each coordinate axis of a machine tool (See Figure 1) should be measured during an accuracy calibration.

There are exceptions, notably tracer lathes. The tracer lathe is not very sensitive to straightness errors because the tracing mechanism will compensate, but the tracer lathe is very sensitive to angular motion because of the large Abbe' offset associated with the tracing system. Most numerically controlled machine tools, however, have requirements to measure all six degrees of freedom to be calibrated properly.

It is not enough to make a single measurement of these 6 parameters, but some reliability factor must also be assigned to the data. To do this the user should first satisfy himself that the non-repeatability of the machine tool is random and not due to systematic causes such as a temperature increase in the leadscrew. Then, multiple runs of data should be taken on an axis and a determination of a mean characteristic and a measure of the repeatability of the data should be performed. There are several recommendations available for calculating these parameters for linear positioning errors, notably the National Machine

The Six Degrees of Freedom

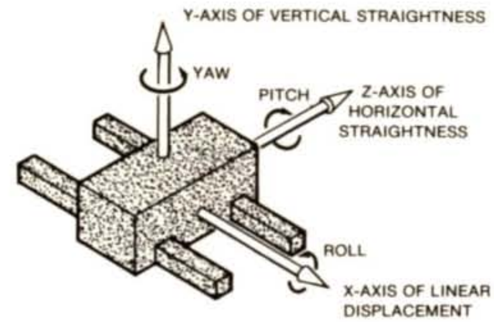


Figure 1 The drawing above illustrates the various degrees of freedom that a machine tool's saddle can experience as it slides along a pair of ways. As the saddle moves linearly in the X-axis direction there are six degrees of motion which will affect the final position of the saddle. Besides the positioning error along the X-axis which relates directly to the accuracy of the linear scale, the saddle can also experience angular rotations about the X, Y, and Z axes known as roll, yaw, and pitch, respectively. Pure translational motions in the Y and Z axes are identified as vertical and horizontal out-of-straightness movements respectively. In total, there are six degrees of freedom of motion which will affect the final position of the machine tool as we command it to move in the X direction. If one considers a typical 3-axis machine tool then there are 18 degrees of freedom (6 degrees of freedom per axis) plus errors introduced by out-of-squareness between axes, 21 potential error sources in all, which combine together to define the final position of the machine tool.

Tool Builder's Association's "NMTBA Definition and Evaluation of Accuracy and Repeatability for Numerically Controlled Machine Tools" in the United States, and the German VDI 3254 which is widely used in Europe. There are many other recommendations which pertain to linear positioning errors and some involve other errors, but almost all calculate a mean value and a repeatability value. The same approach can and should be used on measurements in all 6 degrees of freedom to determine machine tool accuracy in each degree of freedom.

After all of the data has been accumulated and the accuracy of each degree of freedom on each axis has been determined, it is necessary to calculate an overall accuracy for the machine tool. One proposal to accomplish this for the category of machine tools which are known as NC workcenters or machining centers is to define a mean work zone. This mean work zone is a cube which will enclose most of the workpieces being machined on the "workcenter". This approach gives a better interpretation of what accuracy can be expected in the workpieces but it still does not completely define workpiece accuracy.

Two approaches which go further in defining workpiece accuracy from the geometric accuracy of the machine tool are called integrated and accelerated tests. The integrated test is one which takes the measurement data for straightness, pitch, roll, yaw, linear displacement errors, and axis squareness and processes it in a computer to determine a worst case error for the machine tool. This approach has been implemented in a few instances, but is not in wide use because digital computers are a major investment to purchase, program, and maintain.

The second or accelerated approach involves the use of master parts which are traced on the machine tool. These are usually functional type tests and give a quick check that the machine tool is performing as expected. This type of test has also been combined with an integrated test to give both qualitative results and a determination of the individual geometric errors for the machine tool.

II. Calibration Measurements

A. Linear Measurements

A linear displacement measurement is the fundamental capability of the HP 5526A Laser Measurement System. The equipment required is:

5526A Laser/Display
Option 10 Linear Interferometer

Also, the HP 5510A Automatic Compensator and the HP 5526A Option 200 series Programmable Calculator/Plotter System are extremely useful in making the measurements and in reducing the data to determine linear displacement accuracy.

In making correct linear displacement measurements the following procedure should be used:

1. Set up the equipment in the correct position to make the measurements desired.
2. Align the laser beam to the axis of motion to alleviate cosine error.
3. Determine the correct compensation factor by measuring ambient temperature, air pressure, relative humidity, and material temperature. (OR use the HP 5510A Automatic Compensator).

The choice of the setup location of equipment is usually determined by what information is desired. If the Laser Measurement System is being used to check the accuracy of a feedback device on a machine tool slideway then the optical components should be as close as possible to the line of travel of the feedback sensor. However, if what is desired is tool path error, then the optics should be set up in a line as close as possible to the tool. It should be noted that due to Abbe' offset errors (See Section IIID) these two setups are not equivalent and in general will not yield the same results. On most machine tools the user must make some compromises to the theoretical setup location because of fixtures, splash shields, etc., but every effort should be made to minimize an undesired Abbe' offset error. Also, the setup should be chosen to minimize deadpath errors.

Once the setup is chosen the laser beam should be properly aligned to reduce the cosine error in the measurement (See Section IIIC). In all cases it should be possible to easily reduce the cosine error to less than 0.5 parts per million.

The third step in making linear measurements is to make the correct compensation for the changes in the wavelength of the laser light due to changes in the ambient conditions of the air, and compensation for expansion or contraction of the machine being calibrated. For machine shop environments the HP 5510A Automatic Compensator is the most effective way of determining the wavelength compensation because it has sensors to monitor air temperature, air pressure, relative humidity, and material temperature. The HP 5510A calculates a new compensation number and updates the compensation in the HP 5505A Laser Display continuously to correct for changes in the ambient conditions.

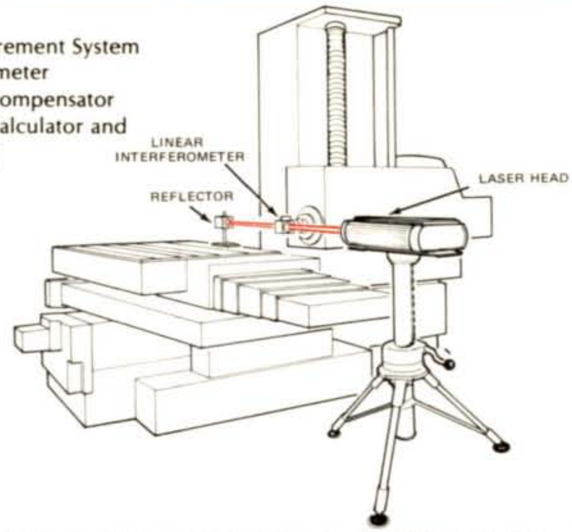
The compensation can be accomplished manually by determining the ambient conditions and material temperature and then using the compensation factor handbook to calculate the compensation number to be dialed into the thumbwheel switches on the HP 5505A Laser Display.

Once the setup and alignment has been completed and the HP 5505A Laser Display is being compensated correctly, the system is ready to make linear measurements. When the data is taken on the displacement measurement, it can either be plotted manually or input directly into an HP Programmable Calculator using the HP 5526A Option 200 series Laser Measurement/Calculator Systems.

Equipment Used:

HP Model 5526A Laser Measurement System
Option 10 Linear Interferometer
HP Model 5510A Automatic Compensator
HP Programmable Desk-top Calculator and
Plotter for Data Processing

Set Up:



Description of Measurement:

The N/C machine tool was given a series of commands,using a 0.500 inch interval, to move in the X-axis. At each command point the reading on the 5526A Laser Measurement System was compared to the command position of the machine tool and the difference recorded as the positioning error. A graphical representation of this single run is given in Figure A.

This particular machine tool has a specification of being within ±.0005 inches at each positioning point in the mean work zone. The out-of tolerance position circled in the graph occurs at the X-axis command position of 19 inches.

In order to help isolate the reason for this out-of-tolerance position, the interval between 18.5 inches to 19.5 inches was expanded by decreasing the command interval. First, interpolation error of the linear scale on the machine tool was checked by stepping at a variety of intervals all of which were smaller than the null points of the position feedback device. This occured between command positions 18.5 - 19.5, and the error plot for this run is graphically displayed in Figure B below. The out-of-tolerance command points at 18.93, 18.95, and 19.02 inches were not caused by interpolation error of the feedback position device since the error did not show up as being cyclical over the entire interval. It was finally determined to be due to a flat spot on the lead screw.

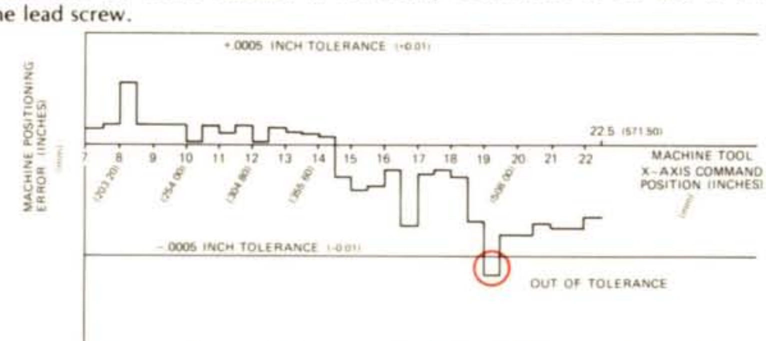


Figure A. Expanded Error Plot of Out-of-Tolerance Region on X-Axis

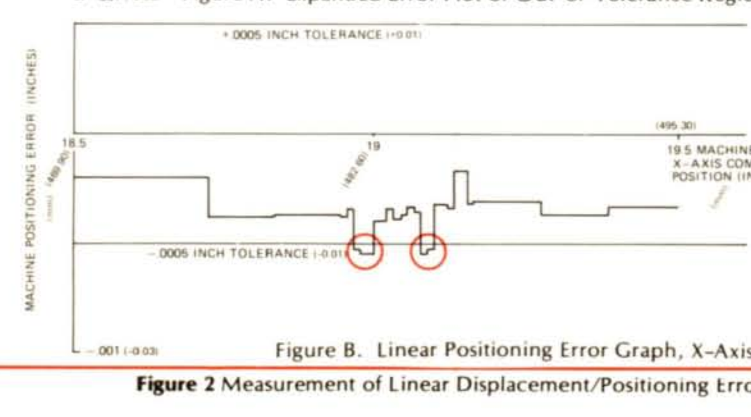


Figure B. Linear Positioning Error Graph, X-Axis

Figure 2 Measurement of Linear Displacement/Positioning Error

B. Angular Measurements

The equipment required to make pitch or yaw measurements with the HP 5526A Laser Measurement System is as follows:

5526A Laser/Display
Option 10 Linear Interferometer
Option 21 Angular/Flatness Add-on

Compensation is not necessary to make correct angular measurements since both the reference and the measurement paths will experience the same atmospheric changes, and the angular measurement device makes a differential measurement between the two paths. Also, alignment is not critical in angular measurements and cosine errors and Abbe' offset errors do not enter into these types of measurements.

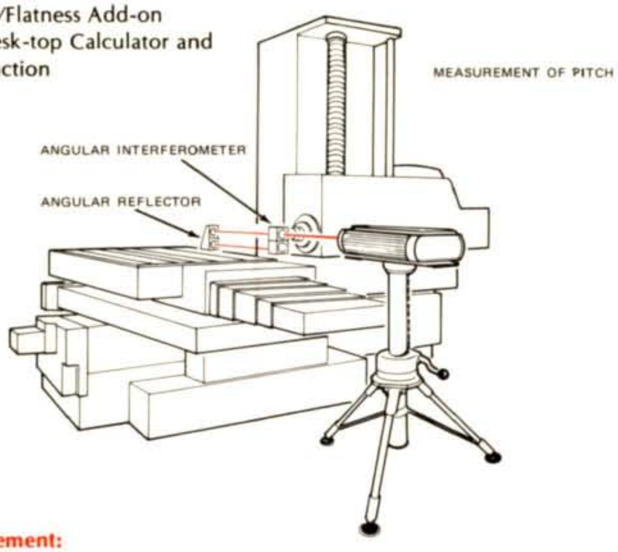
Unlike flatness measurments (see the HP Application Note 156-2 Rev.) pitch or yaw measurements do not require any special procedure to yield correct results. The HP 5505A Laser Display will read out the measured angular deviation of a moving member relative to a fixed member of a machine tool at any position of the movement.

Equipment Used:

HP Model 5526A Laser Measurement System
- Option 10 Linear Interferometer
- Option 21 Angular/Flatness Add-on

HP Programmable Desk-top Calculator and Plotter for Data Reduction

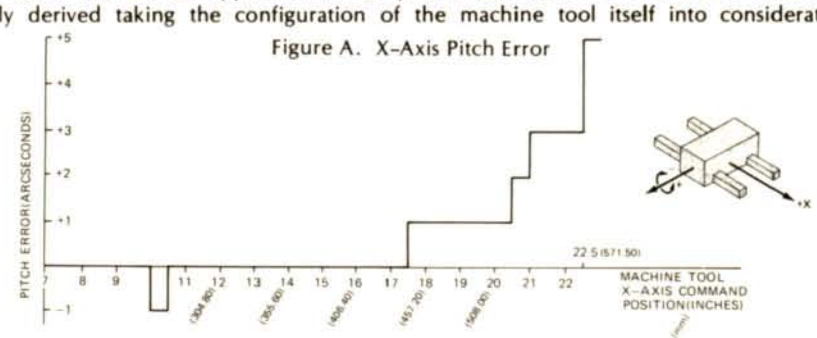
Set-up:



Description pf Measurement:

The N/C machine tool was given the same series of X-Axis commands as were used for measurement of the linear positioning error. The mean work zone was covered in a series of 5-inch command intervals. The first run was done with the optical components configured for measurement of pitch (see setup drawing). A second run was then made with the angular reflector and angular interferometer mounted at 90° to the pitch setup for measurement of yaw.

The question of how does one convert the angular error in arcseconds to the more familiar terminology of inches of error per inch of offset often arises. The conversion is simple if one remembers the rule of thumb which states that the error is approximately 5 microinches of error/inch of offset for each arcsecond. Therefore, if the workpiece is offset from the slide-ways of the machine by 20 inches, then at the X-axis command position of 21 inches, the error introduced by pitch in the X-axis is approximately 5 microinches/inch/arcsecond x 20 inches x 3 arcseconds = 300 microinches (.0003 inches). A more accurate estimate is: (distance of offset from pivot point of machine x $(\sin\theta)$ = amount of error. For the same example the error is (20 inches of offset from slideways pivot point) x (sin 3 arcseconds) = .000291 inches. This error value is an approximation only, and the actual value must be mathematically derived taking the configuration of the machine tool itself into consideration.



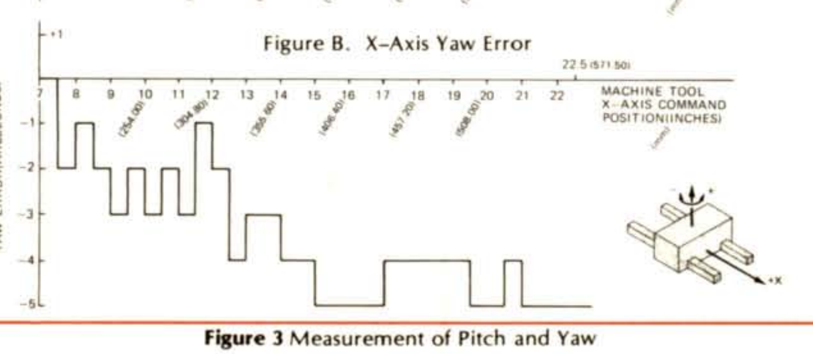


Figure 3 Measurement of Pitch and Yaw

C. Straightness and Squareness

The equipment required to measure straightness and squareness deviations with the HP 5526A Laser Measurement System is as follows:

5526A Laser/Display
Option 30, 31, or 32 Straightness Interferometers, and
Option 34 Optical Square
Option 35 Vertical Straightness Adaptor

Also, the 5526A Option 200 Series Calculator Systems are extremely helpful in straightness and squareness measurements.

There is much confusion today as to what a straightness deviation is and how it is to be measured. A straightness deviation is a linear displacement that occurs in either of two mutually perpendicular planes to the axis being inspected.

The straightness deviations incurred during the axis of motion are always reducible to deviations in these two mutually perpendicular planes.

To make a straightness measurement with the HP 5526A Laser Measurement System it is necessary only to obtain good alignment of the various components to the axis of measurement. Wavelength compensation is not a factor since the technique is similar to the angular measurement in that it is a differential measurement with both beams seeing the same atmospheric changes. Cosine error does not affect the straightness errors as such, but misalignment will cause the data to be superimposed on a line whose slope is directly proportional to the misalignment. This can be alleviated by either manually aligning the components to give a zero reading on the HP 5505A Laser Display at each endpoint or by using the HP 5526A Option 200 series Calculator to remove the slope from the input data.

The setup configuration is very important in straightness/squareness measurements. The Straightness Reflector should always be configured so that it undergoes the same type of translations that the workpiece makes. If the tool is held stationary and the workpiece moves on a table, then the Straightness Reflector should be positioned on the table; but, if the workpiece is stationary and the tool moves, then the Straightness Reflector should be positioned such that it is stationary. It is essential that a straightness measurement on a machine tool be analyzed very carefully to ensure that the measured deviation is that which is desired.

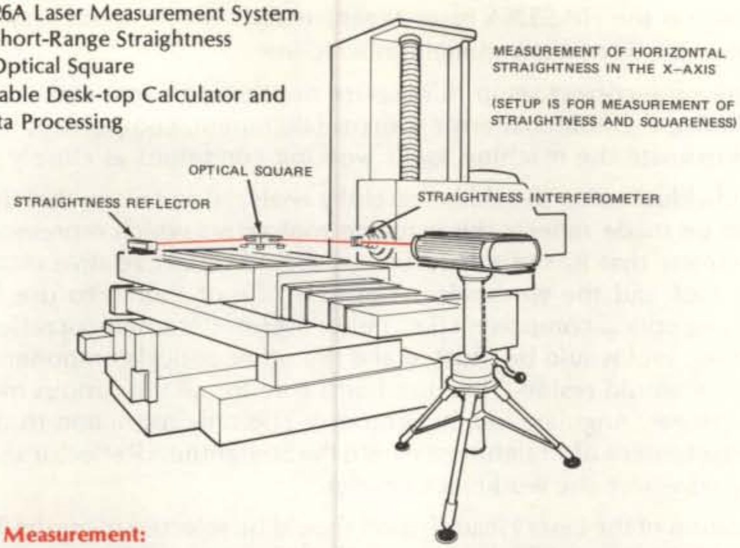
The Straightness Reflector should always be fixtured to the section of the machine tool which holds the workpiece and the Straightness Interferometer should always be placed at the tool tip position regardless of whether the workpiece, tool tip, or both move.

Equiptment Used:

HP Model 5526A Laser Measurement System
- Option 30 Short-Range Straightness
- Option 34 Optical Square

HP Programmable Desk-top Calculator and Plotter for Data Processing

Set-up



Description of Measurement:

The optical configuration for measurement of horizontal straightness and squareness in the X and Z axis was set up as shown. The numerically controlled machine tool was positioned first in the X-axis using a series of .5 inch incremental movements and the horizontal straightness information recorded.

The straightness interferometer was then repositioned between the straightness reflector and optical square for measurement in the Z-axis. The N/C machine tool was commanded to move in .5 inch increments along the Z-axis with the horizontal straightness information recorded at each command position. With the straightness data from both axes it is a simple matter to calculate the out-of-squareness value between the X and Z axis. A graphical representation of each axis and the squareness value is presented in Figure A. The 0.3 arcsecond out-of-squareness value shows that the X-axis to Z-axis angle is 90° plus 0.3 arcseconds.

By turning the straightness reflector 90° and repositioning it to where the optical square sits in the setup sketch, it is possible to make a measurement of vertical out-of-straightness along the X-axis. Again, the N/C machine tool was commanded to move in 0.5-inch increments along the X-axis and each vertical out of straightness data point recorded. A graphical representation of the vertical measurement is presented in Figure B.

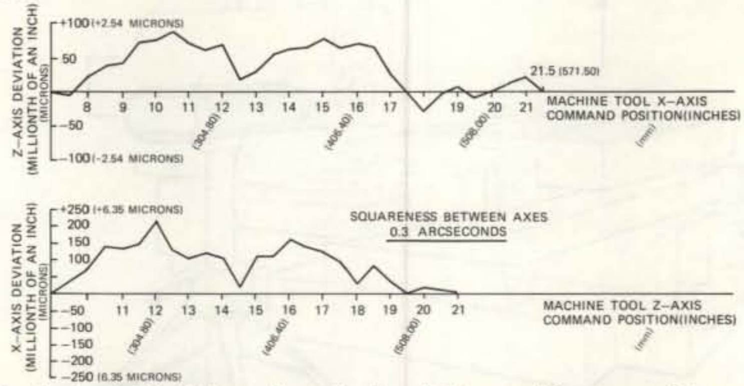


Figure A. Horizontal Straightness Along the X and Z Axes and Squareness Between Them

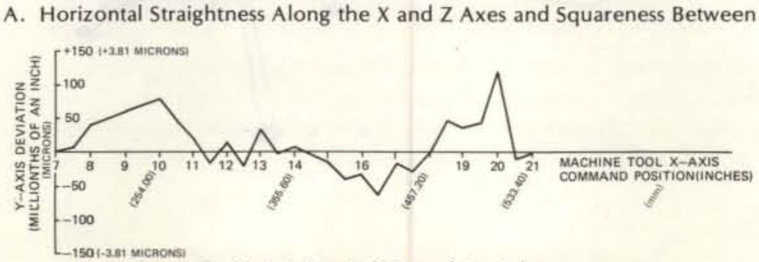


Figure B. X-Axis Vertical Out-of-Straightness

Figure 4 Measurement of Horizontal and Vertical Straightness Plus Squareness

D. Setup Samples

In setting up the HP 5526A Laser Measurement System to calibrate a machine tool there are three basic guidelines to follow:

1) Choose the correct setup to measure the desired parameter.
2) Minimize the potential error sources (alignment, compensation, etc.)
3) Approximate the machine tool's working conditions as closely as possible.

Each individual setup should be carefully analyzed to ensure that the measurement to be made reflects the machine tool errors which represent the workpiece errors; that is, the measurement should reflect relative motions of the cutting tool and the workpiece. The best rule of thumb to use is to always mount one optical component (i.e., either the interferometer or reflector) where the cutting tool would be situated and the other optical component where the workpiece would reside. This rule holds true for all the various measurement setups (Linear, Angular, and Straightness). The only restriction to this being in the measurement of straightness where the Straightness Reflector should always be located where the workpiece resides.

The location of the Laser Head/Tripod should be selected to maximize the number of measurements which can be made without repositioning the Laser Head/Tripod. In the example setups described below this criterion is illustrated showing as many measurements from a single Laser Head/Tripod setup as possible.

In Figure 5 a typical machining center with its defined coordinate system is shown.

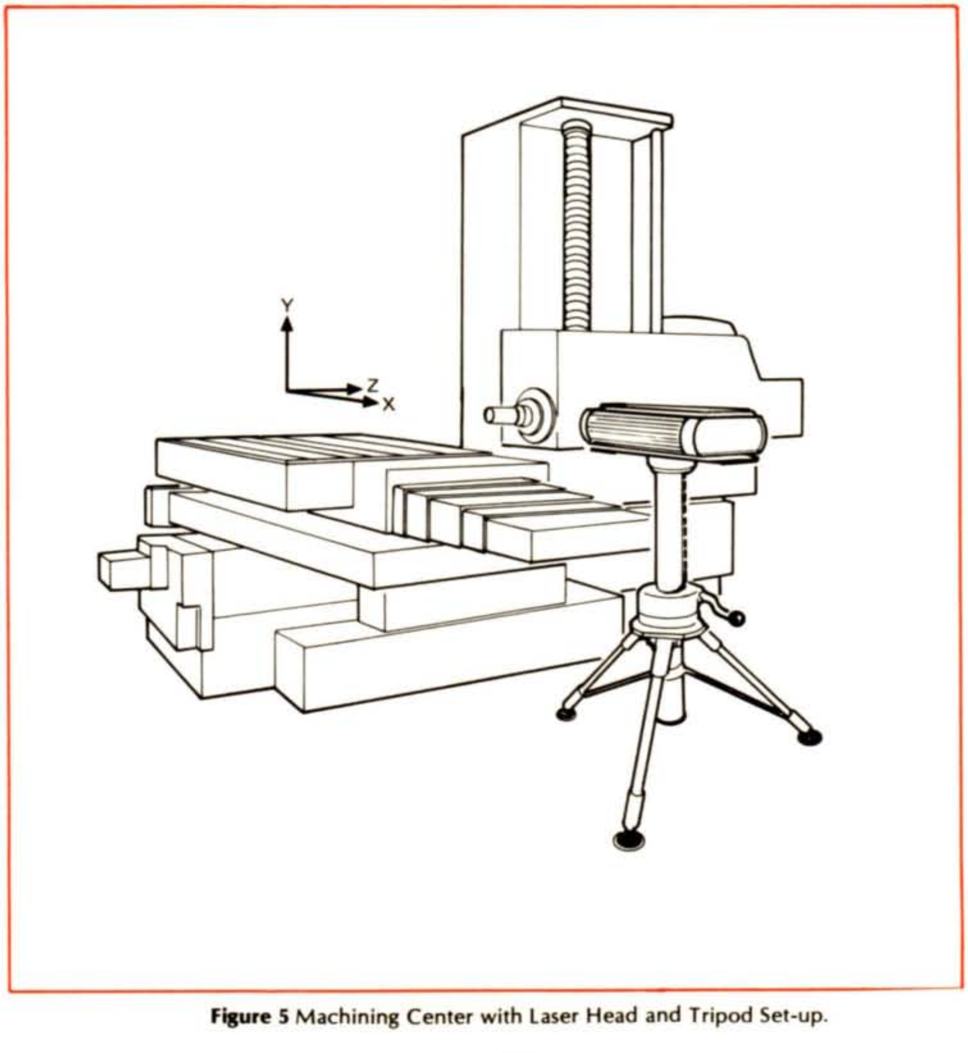


Figure 5 Machining Center with Laser Head and Tripod Set-up.

The configuration of this machining center is such that the workpiece is fixed to a two-axis table (X and Z) and the tool spindle moves vertically for the third (Y) axis. The Laser Head/Tripod is set up to measure linear positioning error in the X, Y, and Z axes, pitch and yaw angular errors in the X and Y axes, horizontal and vertical straightness error in the X axis, and horizontal straightness error in the Y axis plus squareness between the X and Y axes.

Figures 6, 7, and 8 below show the optical configuration for measurement of linear positioning error in the three axes.

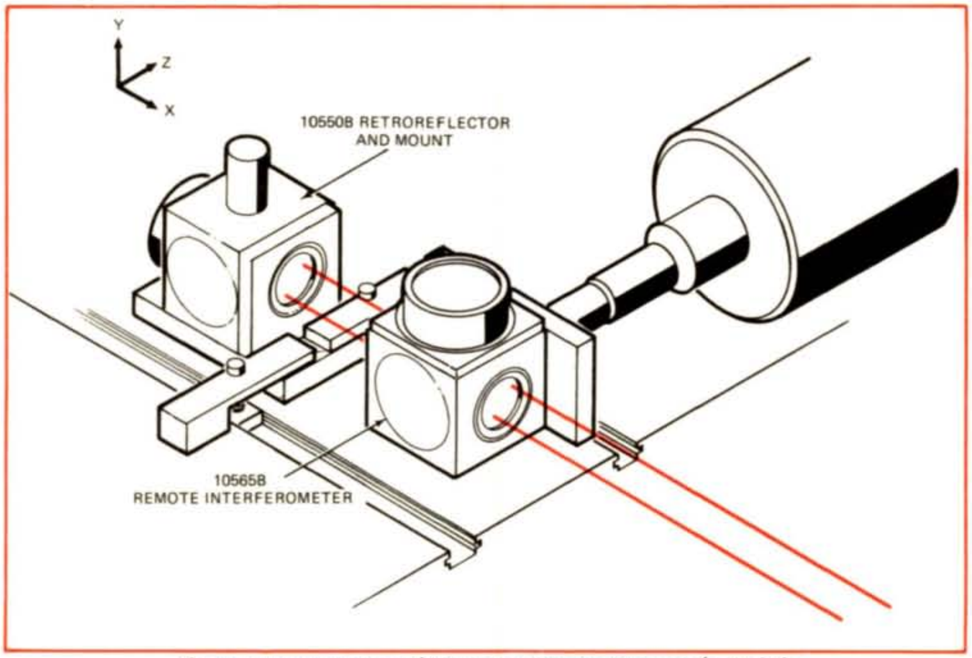


Figure 6 Measurement of Linear Positioning Error in the X-Axis

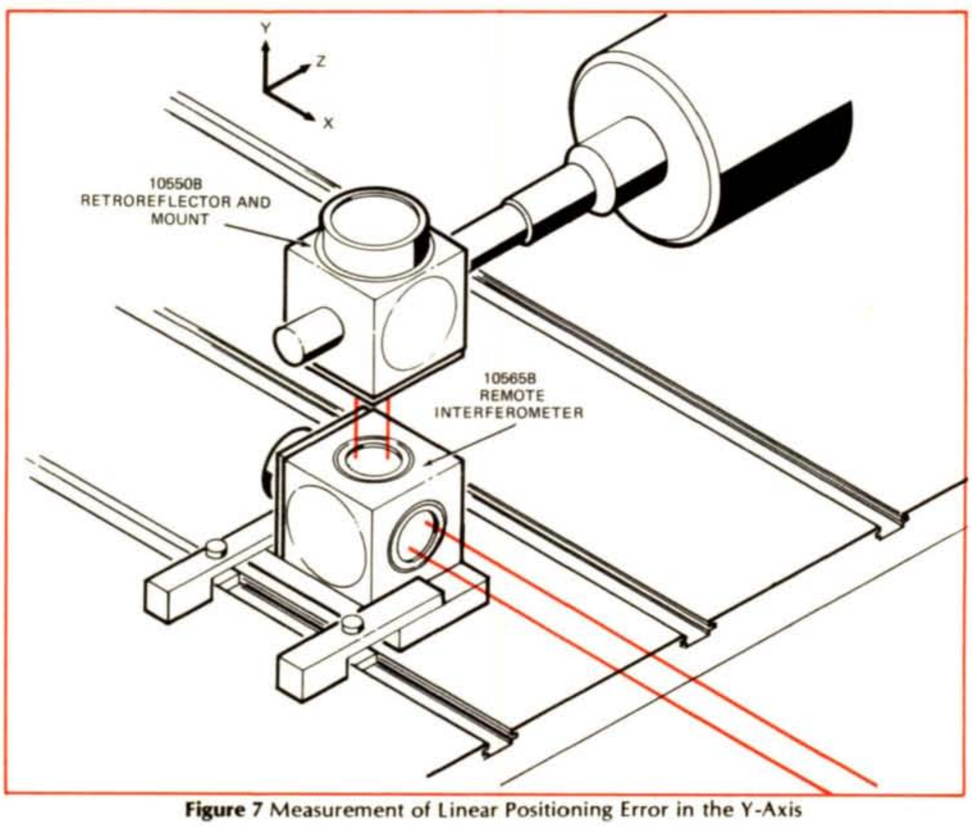


Figure 7 Measurement of Linear Positioning Error in the Y-Axis

By converting the linear optics into an angular configuration and using the same Laser Head/Tripod position, angular pitch and yaw errors in the X axis (Figures 9 and 10) and Y axis (Figures 11 and 12) can be measured.

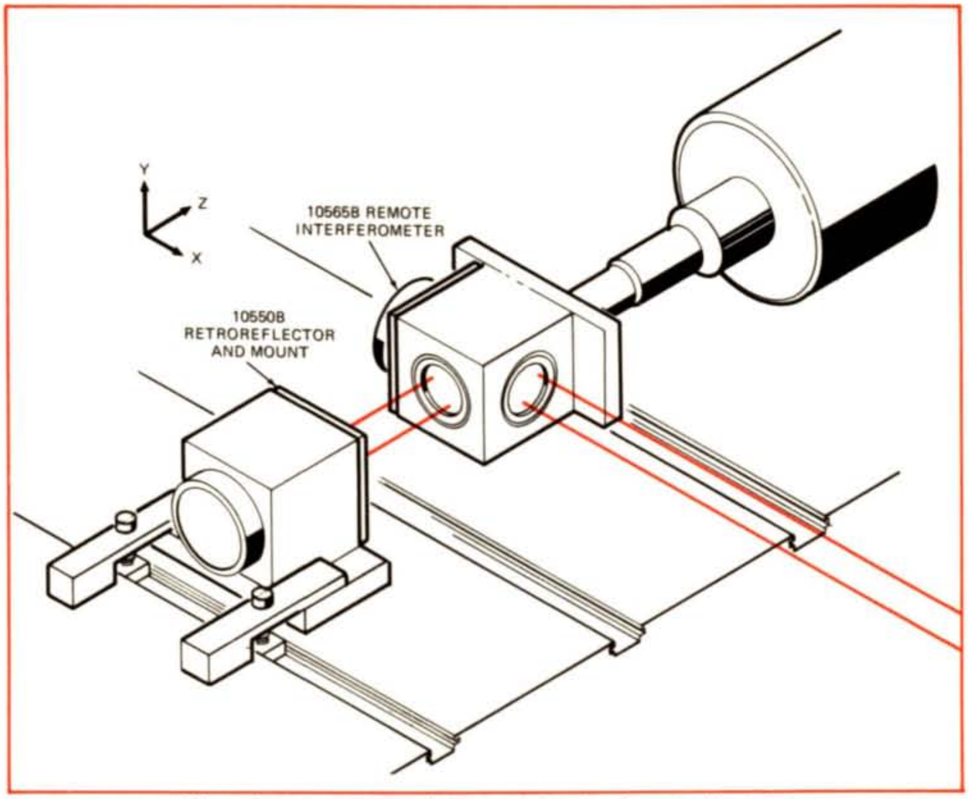


Figure 8 Measurement of Linear Positioning Error in the Z-Axis

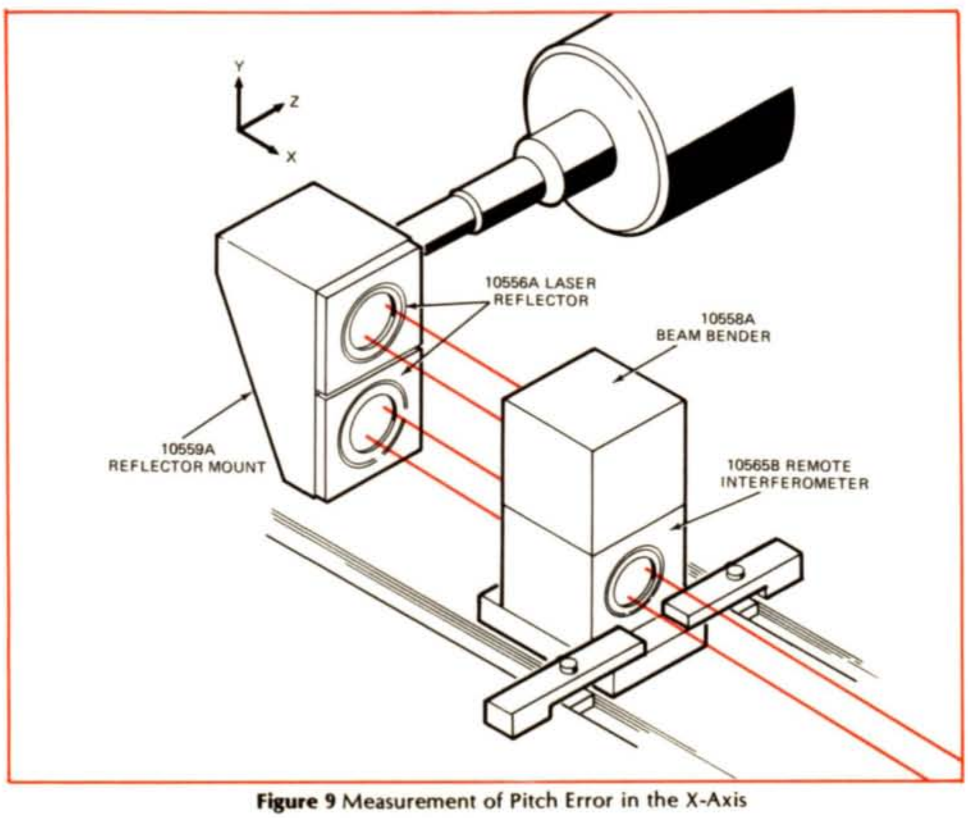


Figure 9 Measurement of Pitch Error in the X-Axis

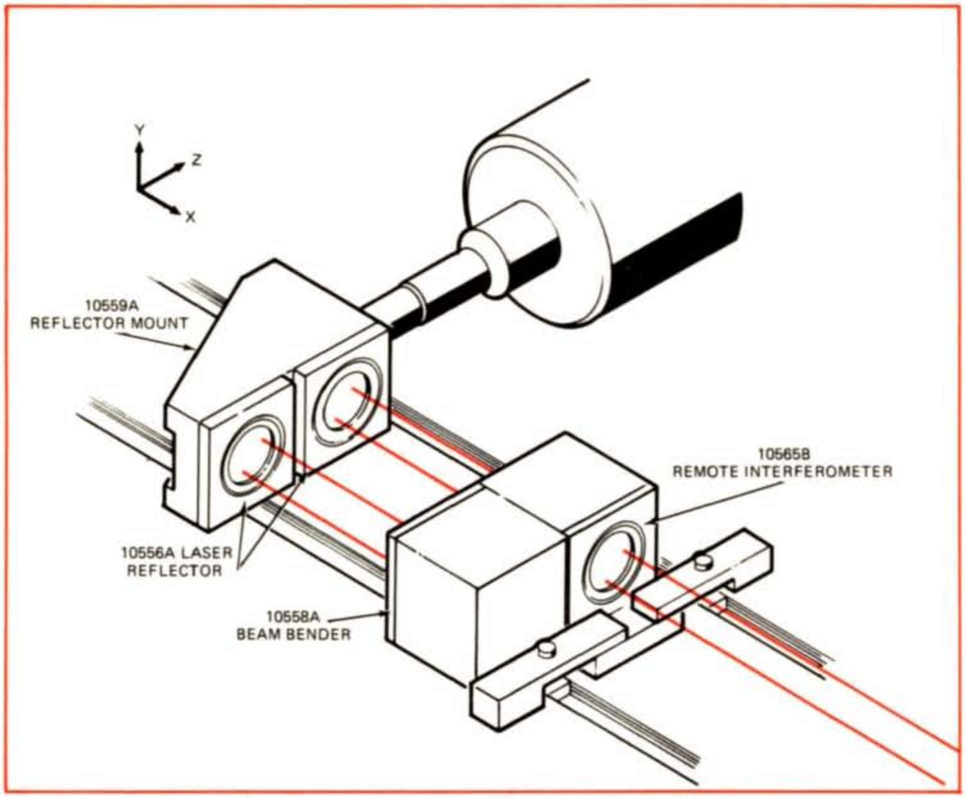


Figure 10 Measurement of Yaw Error in the X-Axis

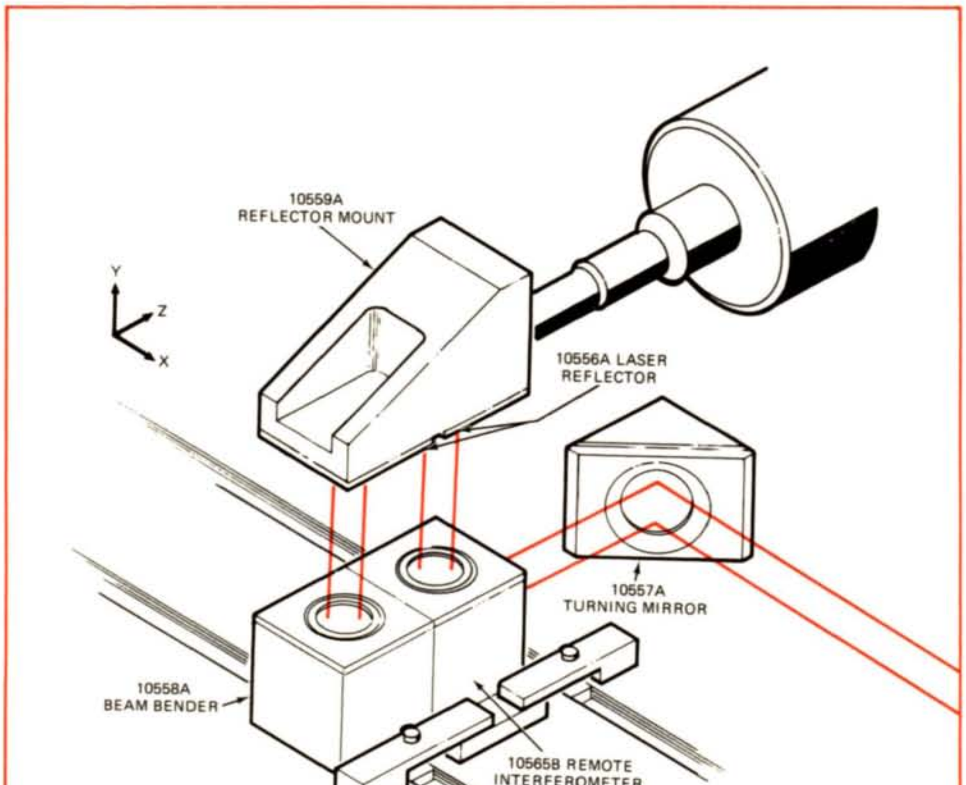


Figure 11 Measurement of Pitch Error in the Y-Axis

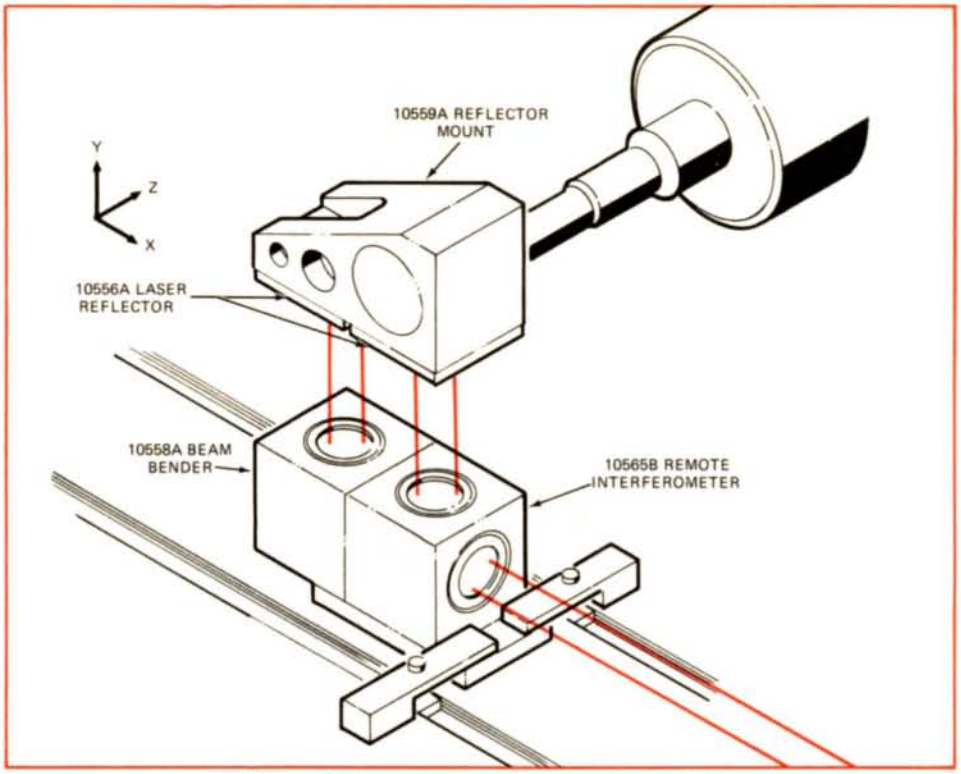


Figure 12 Measurement of Yaw Error in the Y-Axis

Switching to the straightness optics and again using the same Laser Head/Tripod setup the vertical straightness error in the X-axis can be measured (Figure 13).

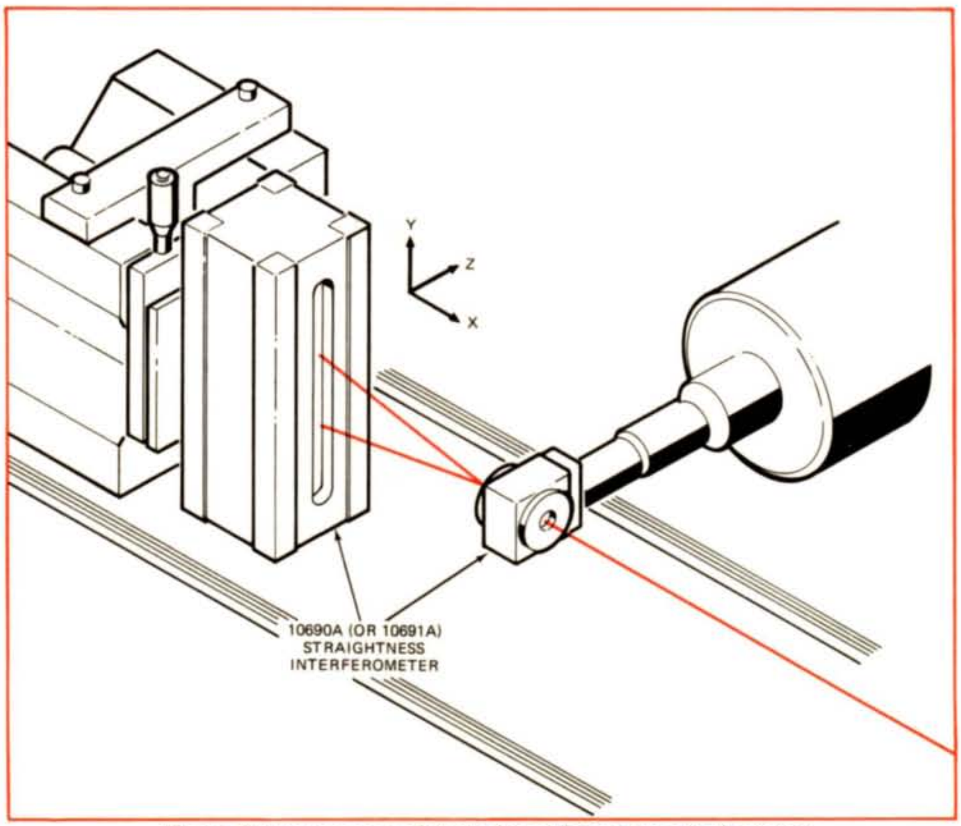


Figure 13 Measurement of Vertical Straightness Error in the X-Axis

By adding the squareness optics, measurement of horizontal straightness error in the Y-axis and squareness error between the X and Y axes can be found (Figure 14). Rearranging the straightness optics will yield the horizontal straightness error in the X-axis (Figure 15).

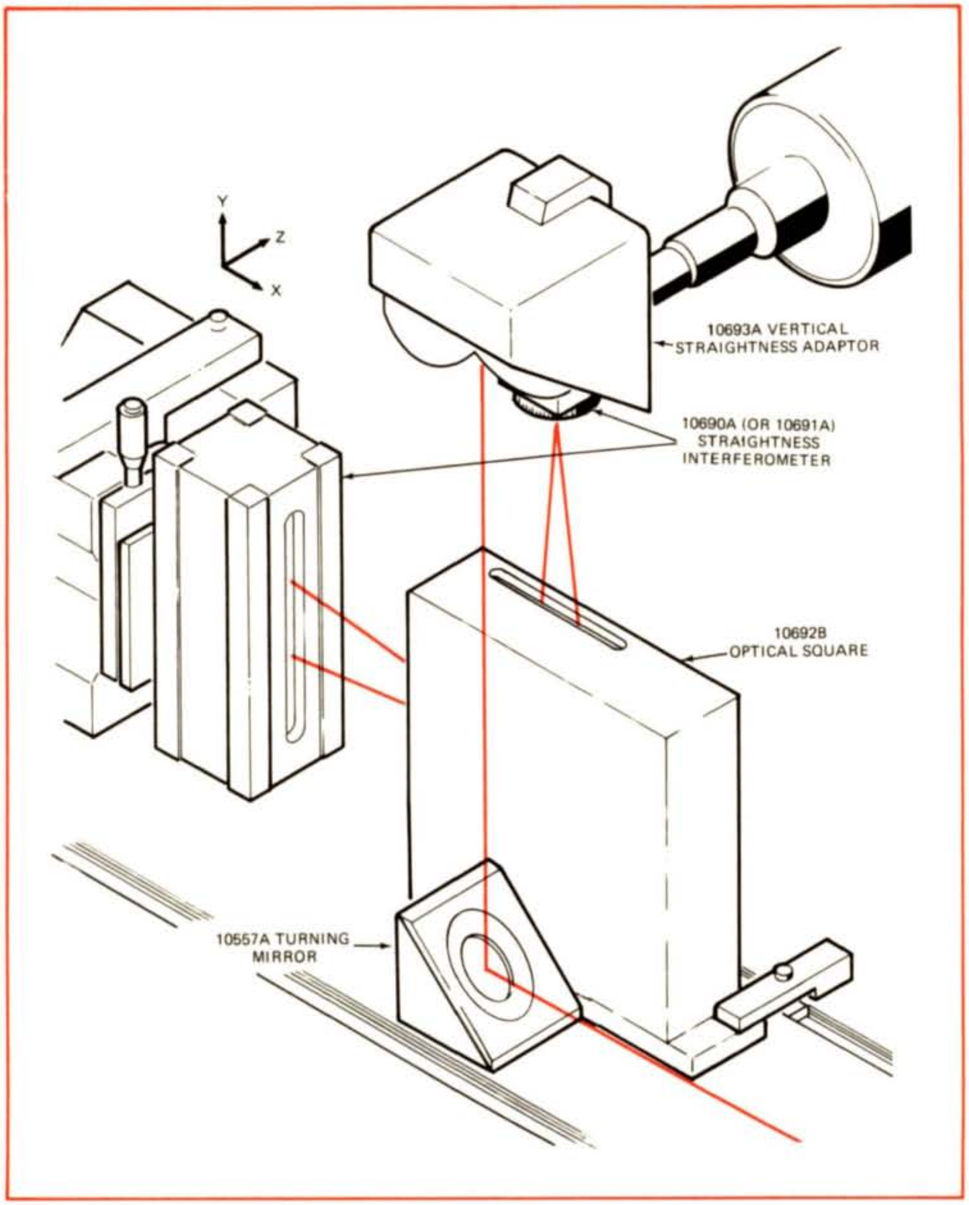


Figure 14 Measurement of Horizontal Straightness Error in the Y-Axis and the Squareness Error Between the Y and X Axis

Movement of the Laser Head/Tripod to the front of the machining center allows the remaining measurements to be performed. The measurement of horizontal straightness error in the Z-axis and the squareness error between the Z and X axes is illustrated in Figure 16. The remaining setups for vertical straightness error in the Z and Y axes and the squareness error between them are shown in Figures 17 and 18.

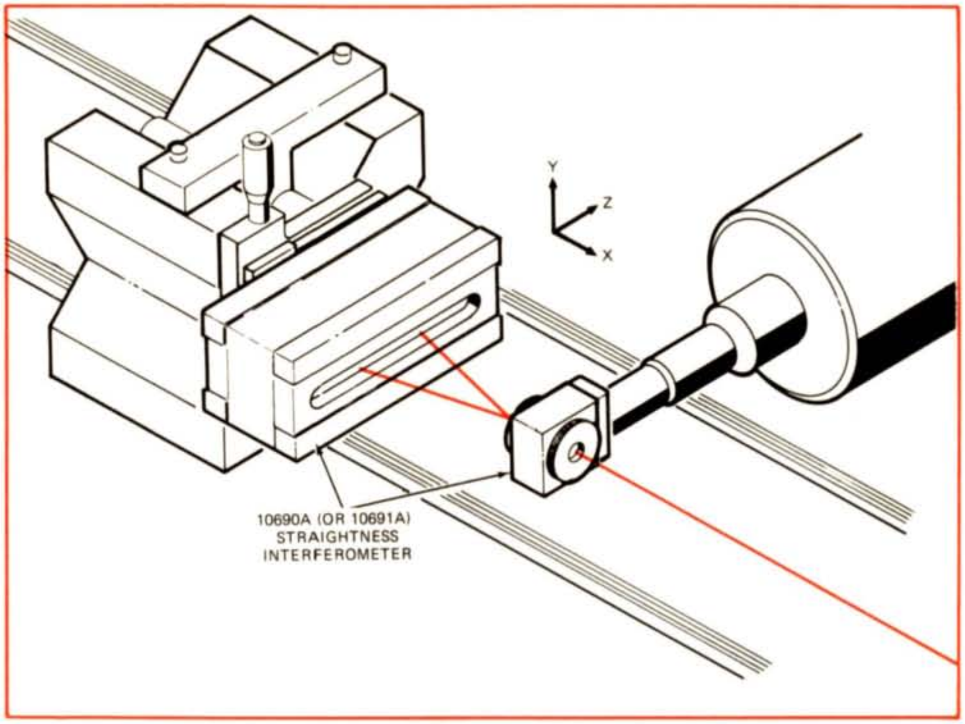


Figure 15 Measurement of Horizontal Straightness Error in the X-Axis

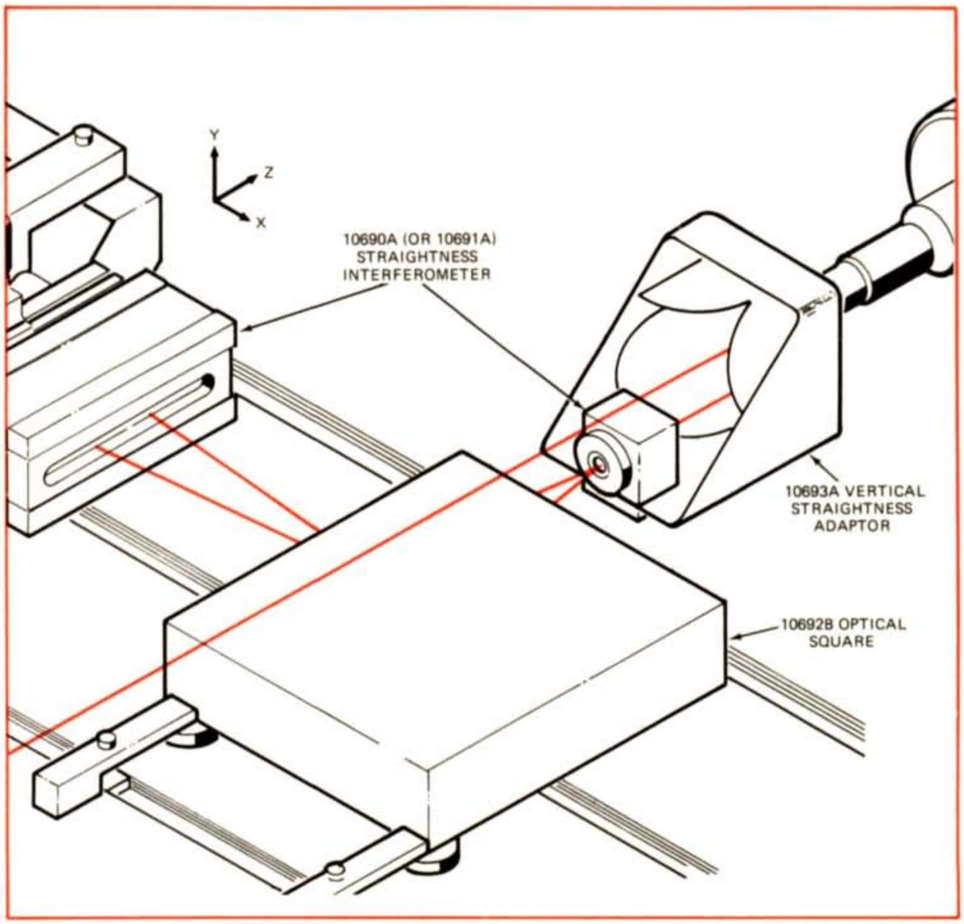


Figure 16 Measurement of Horizontal Straightness Error in the Z-Axis and the Squareness Error Between the Z and X Axis

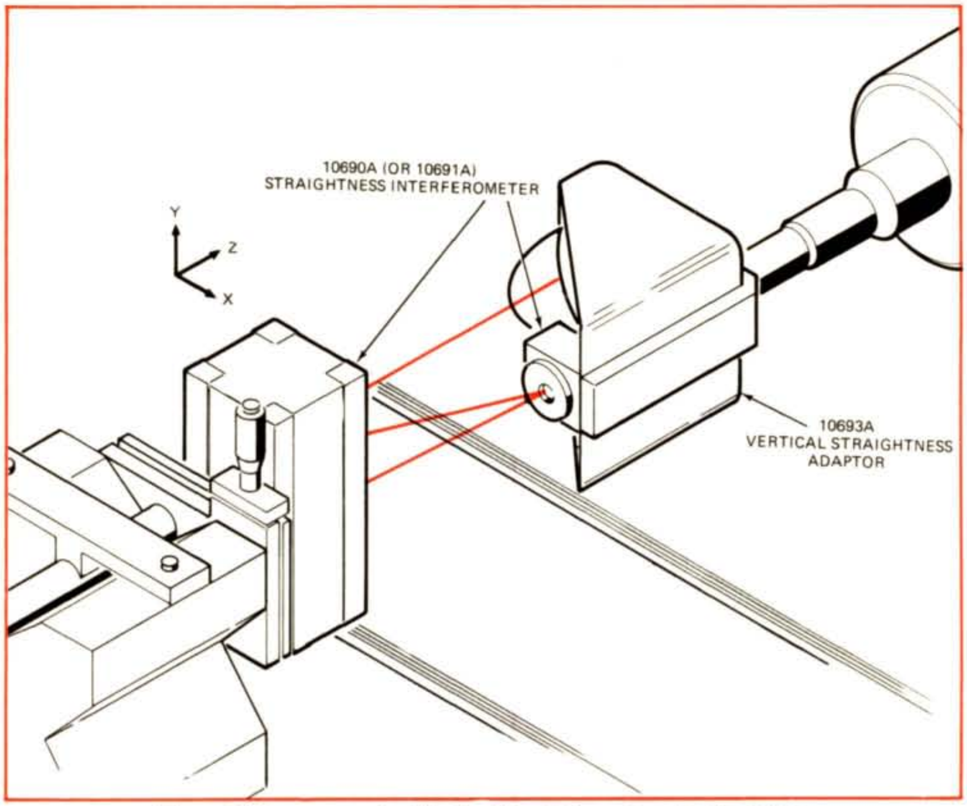


Figure 17 Measurement of Vertical Straightness Error in the Z-Axis

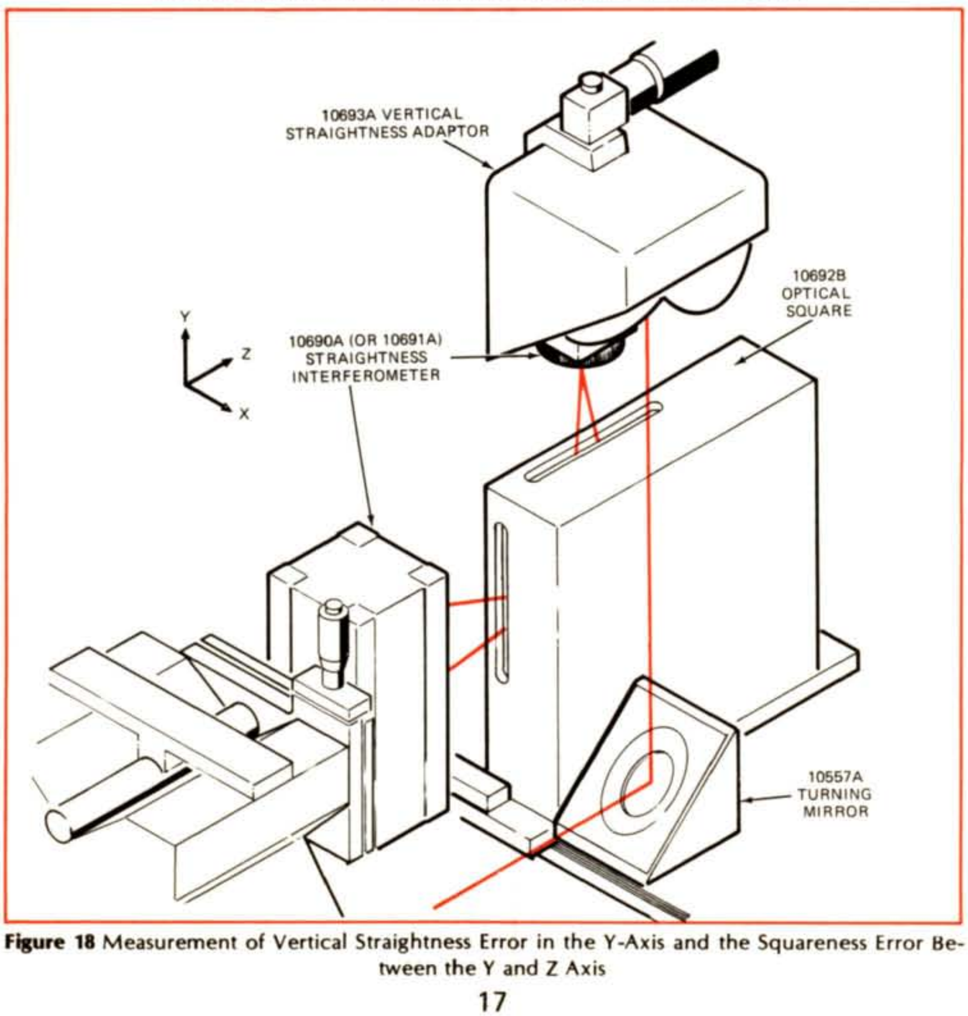


Figure 18 Measurement of Vertical Straightness Error in the Y-Axis and the Squareness Error Between the Y and Z Axis

Converting back to the angular optics, the remaining measurements of pitch error in the Z-axis (Figure 19) and yaw error in the Z-axis (Figure 20) can be performed.

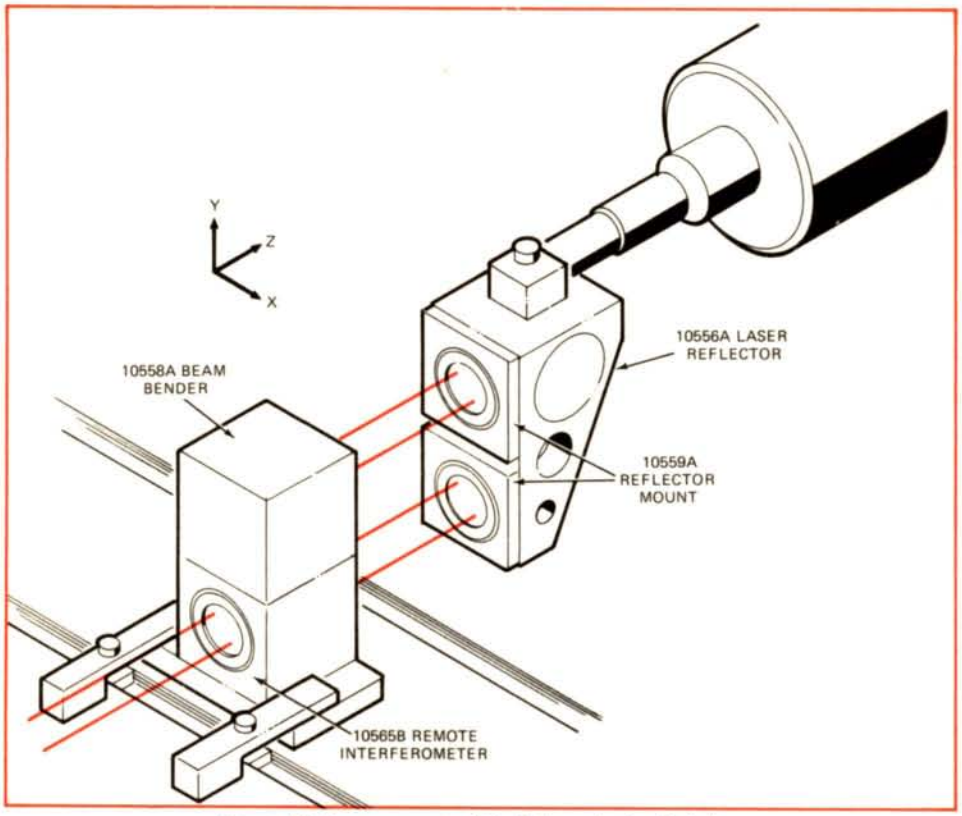


Figure 19 Measurement of Pitch Error in the Z-Axis

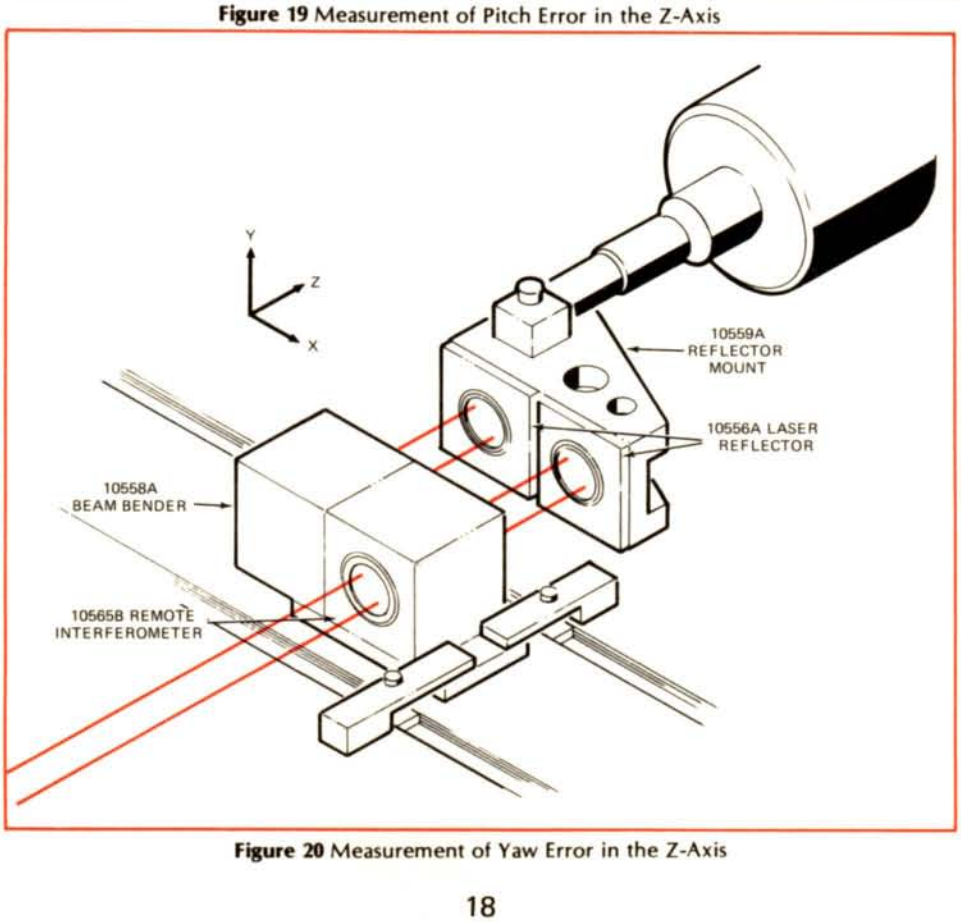


Figure 20 Measurement of Yaw Error in the Z-Axis

In all of these setup sketches the measurement performed reflects the relative motions between the cutting tool and workpiece. This criterion is met because one optical component (either the interferometer or reflector) is always mounted where the cutting tool resides (i.e., in the spindle) and the other optical component is situated where the workpiece normally resides (i.e., on the table). Please note that the straightness measurements are all set up with the Straightness Reflector mounted on the table of the machining center and the Straightness Interferometer is located in the spindle.

For the lathe and its defined coordinate system (Figure 21), the workpiece is fixed in the spindle and the tool moves on a two-axis table (or carriage). The Laser Head/Tripod setup shown will allow measurement of the linear positioning error in the X and Z axes (Figures 22 and 23) and the pitch and yaw angular errors in the Z-axis (Figure 24 and 25).

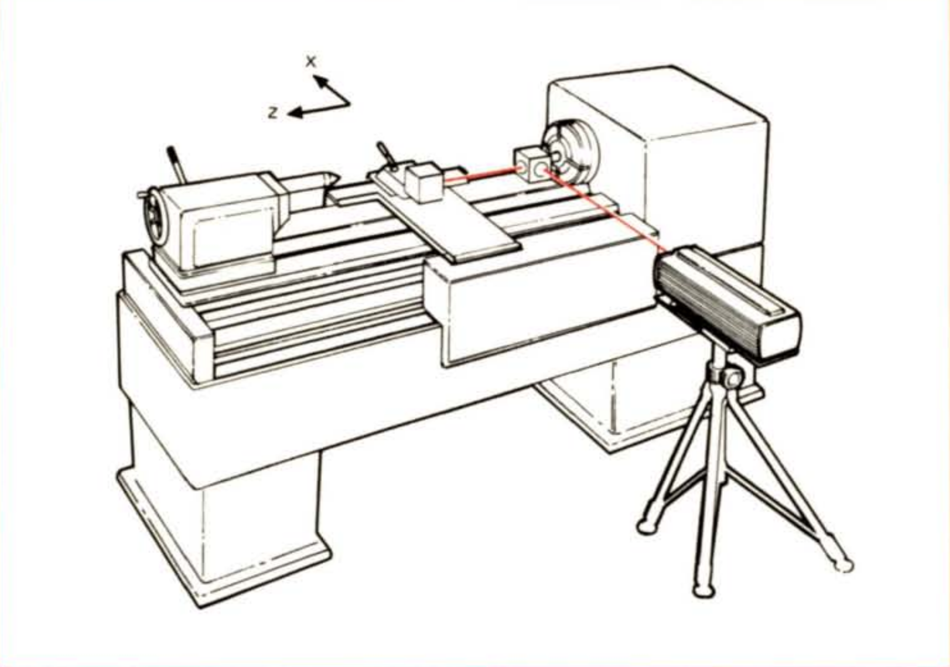


Figure 21 Lathe with Laser Head and Tripod Set-up

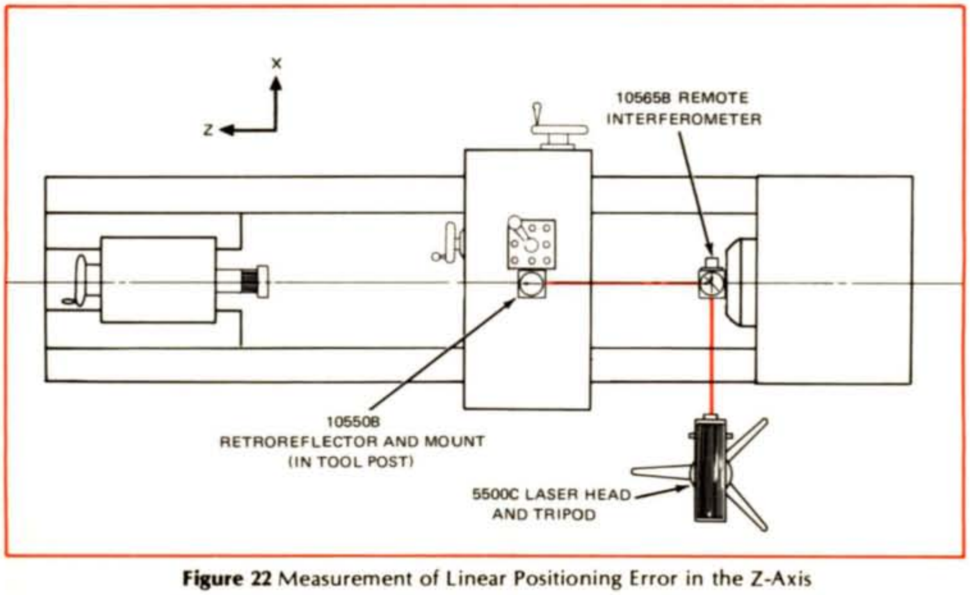


Figure 22 Measurement of Linear Positioning Error in the Z-Axis

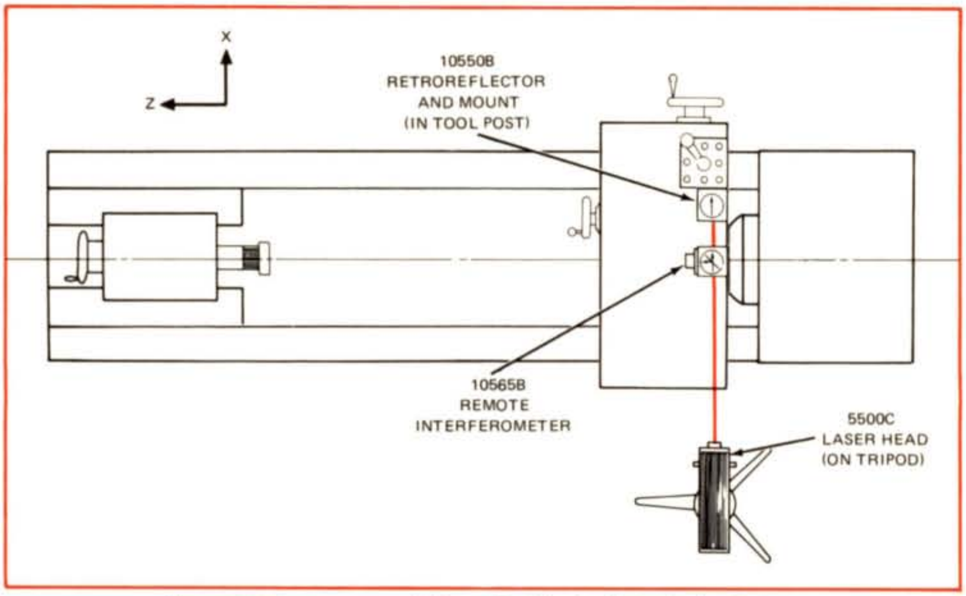


Figure 23 Measurement of Linear Positioning Error in the X-Axis

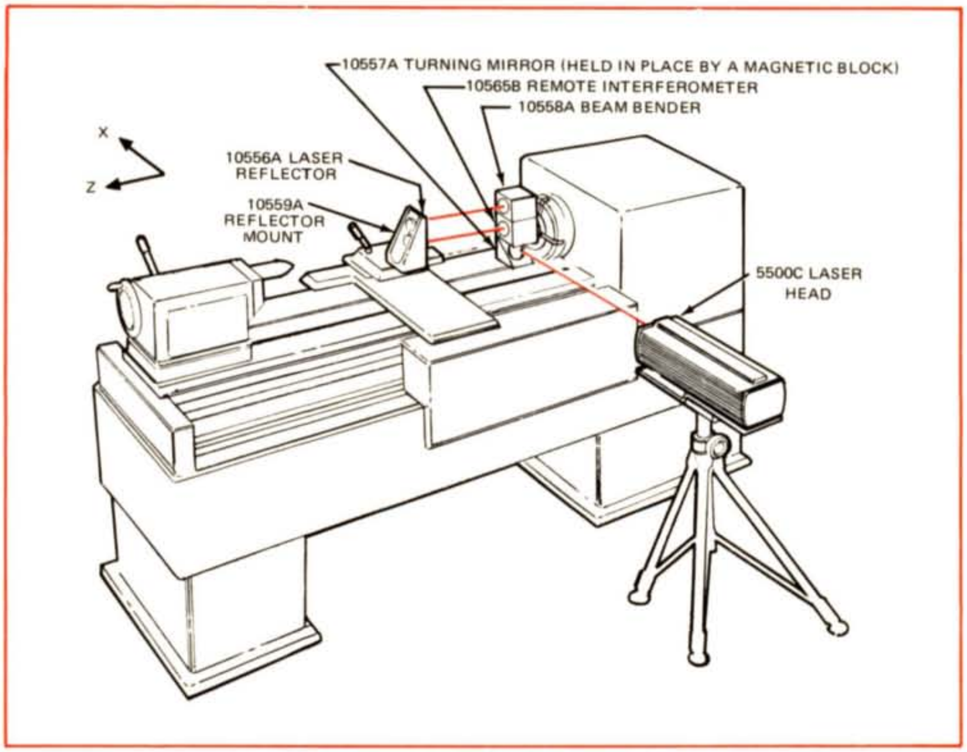


Figure 24 Measurement of Pitch Error in the Z-Axis

Movement of the Laser Head/Tripod to the position in Figure 26 allows the measurement of horizontal straightness error in the Z-axis and parallelism error of the axis of rotation of the spindle to the travel of the tool carriage (Figure 26), horizontal straightness error in the X-axis and the squareness error between the X and Z axes (Figure 27), and vertical straightness error in the X and Z axes (Figures 28 and 29).

Measurement of relative errors between the carriage and workpiece is again assured by mounting the optical components at the location of the cutting tool and workpiece. Again, the straightness measurement setups require that the Straightness Reflector be mounted in the spindle where the workpiece normally resides.

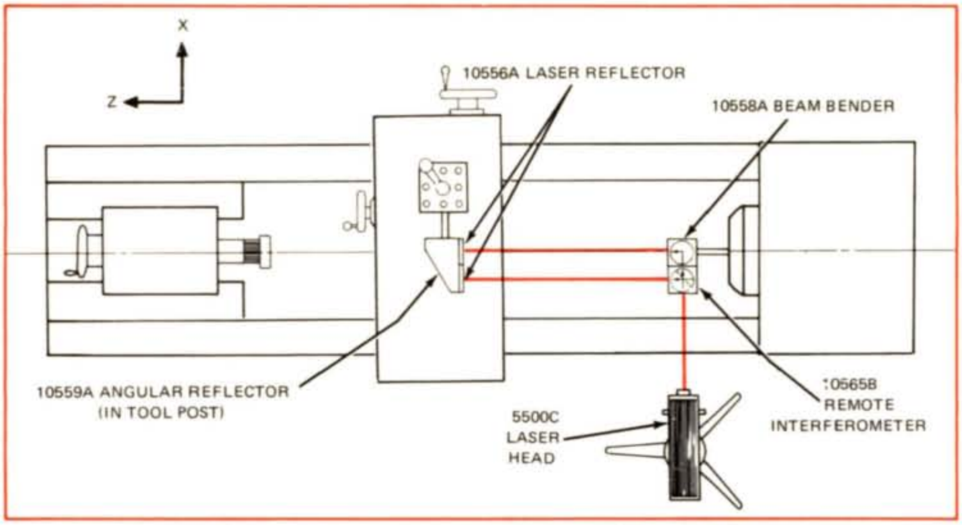


Figure 25 Measurement of Yaw Error in the Z-Axis

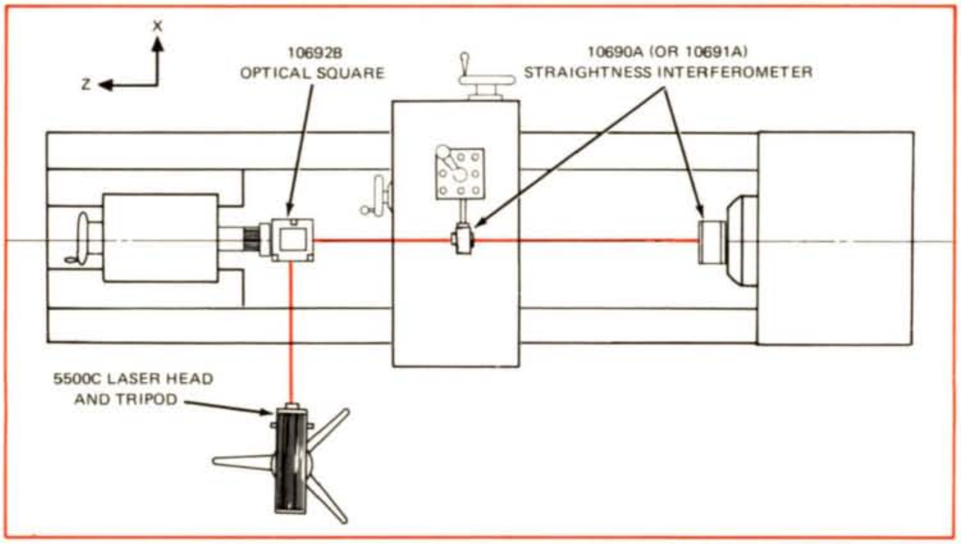


Figure 26 Measurement of Horizontal Straightness Error in the Z-Axis and Parallelism Error of the Axis of Rotation of the Spindle to the Tool Carriage Travel

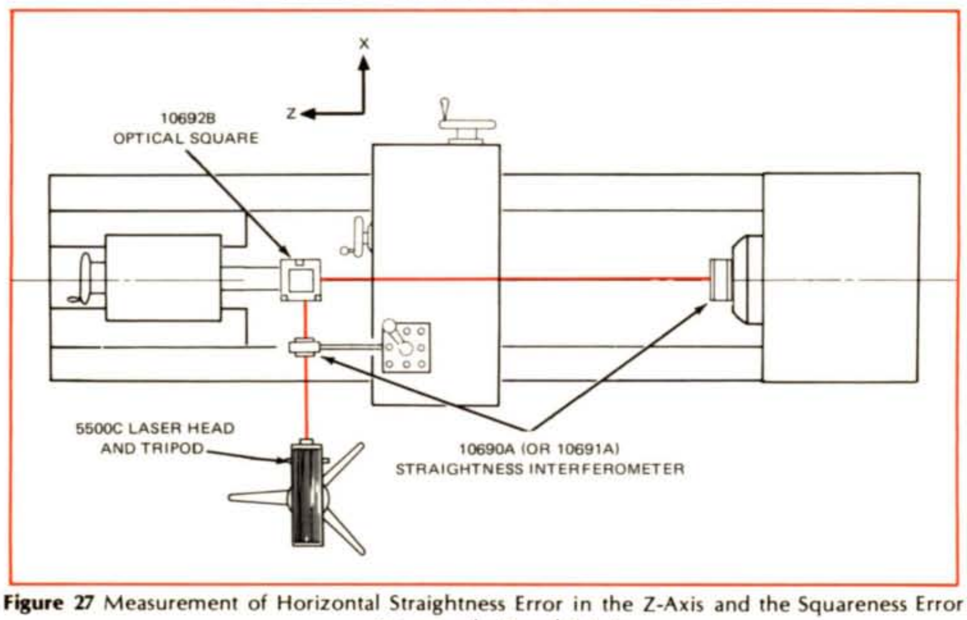


Figure 27 Measurement of Horizontal Straightness Error in the Z-Axis and the Squareness Error Between the X and Z Axis

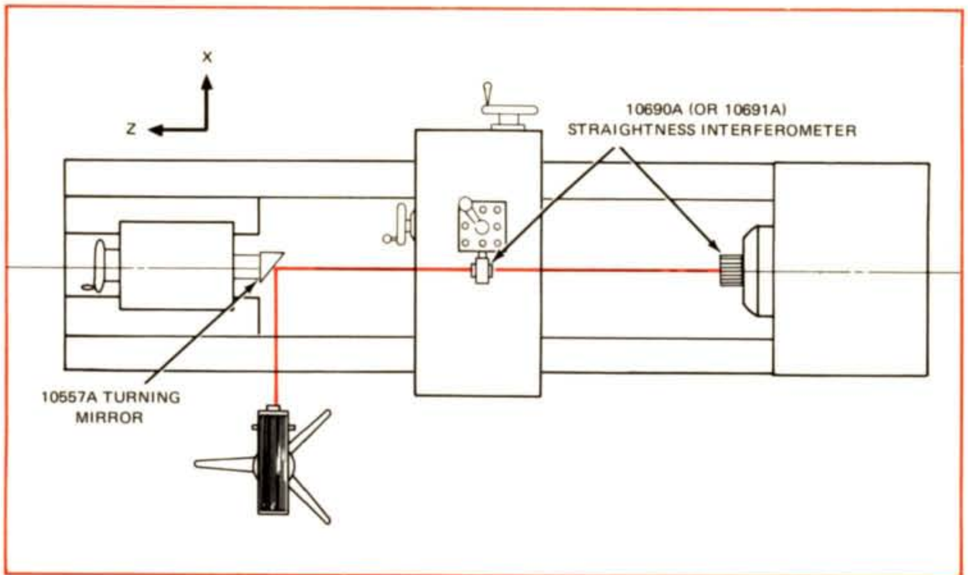


Figure 28 Measurement of Vertical Straightness Error in the Z-Axis

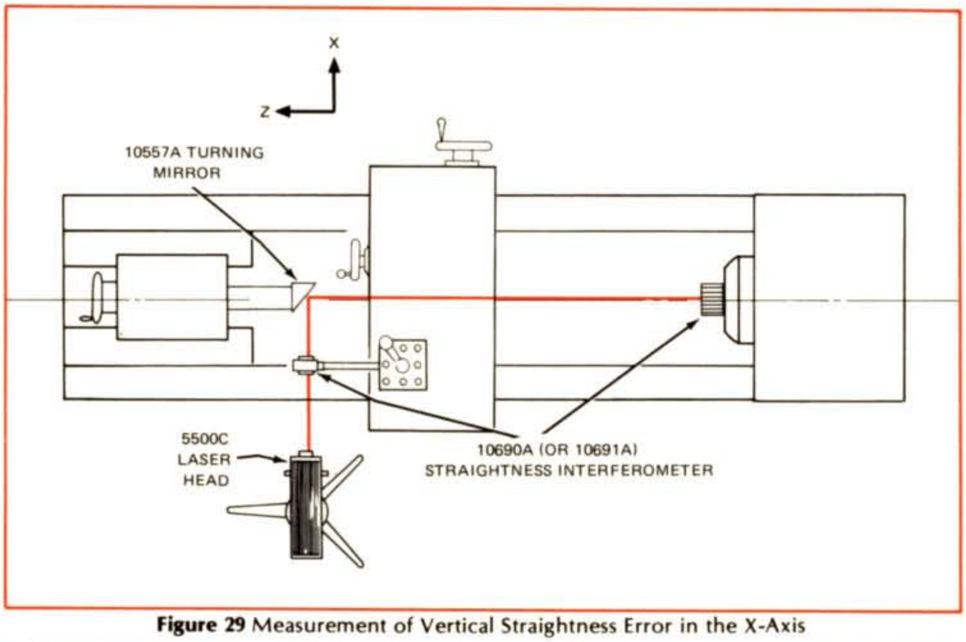


Figure 29 Measurement of Vertical Straightness Error in the X-Axis

Although these two examples do not cover all machine tools, they are representative of a great number and, as such, they should be studied very closely. There is no one set method for setting up the various measurement optics since every machine tool with a different geometric configuration will require different optical paths. Therefore, the best technique to learn the various setups is to completely familiarize oneself with the optical components and how they can bend the laser beam. A good training exercise is to sketch up on a piece of paper the optical path proposed for a particular measurement setup before the actual configuration is attempted. After several sketches the operator will gain enough familiarity with the various optical components so that he can mentally draw a picture of all the measurement setups required before he starts the actual machine tool calibration. This developed ability will provide for a shorter amount of time required for a machine tool calibration by reducing the initial setup time of the equipment. Thus, a systematic approach to machine tool calibration will be adopted which will yield more consistent results from machine to machine.

III. Sources of Errors

A. Environmental and Material Temperature Effects
Velocity-of-Light Compensation

Initial attempts at machine tool evaluation using the Laser Interferometer yielded results very quickly, but again, the results were often non-repeatable and were not always indicative of machine tool positioning accuracy. The machine tool industry had, at last, a standard whose accuracy was at least one order of magnitude better than required; a standard similar to the one accepted by most of the standards organizations of the world, the wavelength of light. Why, then, was industry still obtaining misleading and non-representative data using such a length standard?

One reason, oddly enough, concerns the wavelength of the laser itself. The wavelength in a vacuum is known to within 1 part in 10 million, but the wavelength in air is somewhat shorter than the vacuum wavelength since the velocity of light in air is less than in a vacuum. In addition, the velocity of light in air is not constant but is a function of air composition, temperature, and barometric pressure. It is therefore necessary to accurately determine all of these factors in order to define the wavelength of the laser in air. For this reason the HP 5526A Laser Measurement System has provisions for determining barometric pressure, temperature, and relative humidity either via manual input or automatically through the HP 5510A Automatic Compensator.

Wavelength Compensation

The frequency of the light emitted by the laser is quite stable with time and changes in ambient conditions. However, the wavelength of this light in air (used as the standard in the distance measurement) depends directly on the velocity of light in air, which in turn depends upon air temperature, pressure, and relative humidity. Air that is less dense (for example, low pressure, high temperature air) results in a higher velocity of light, and thus, a longer laser wavelength.

The distance shown on the laser display at any time is equal to the product of the laser wavelength (in units of inches or millimeters) times the number of wavelengths of motion counted since RESET was last pressed. In practice, this product operation is done in two steps. First, the number of wavelengths counted is multiplied by the ratio of the wavelength in air to the wavelength in a vacuum, and this result is then multiplied by the vacuum wavelength of the laser light (in appropriate units). That is:

$$\text{distance} = (\text{wavelengths of motion}) \times \frac{\text{air wavelength}}{\text{vacuum wavelength}} \times (\text{vacuum wavelength})$$

The absolute accuracy of the Laser Interferometer is directly determined by how accurately the ambient conditions are known; and as a guide, it can be stated that an error of approximately one part per million will be incurred for each error of 2°F (1°C) in ambient temperature, 0.1 in (2.5 mm) Hg. in absolute pressure, and 30% in relative humidity. In general, the HP 5510A Automatic Compensator is intended to be used in machine shop environments for calibration purposes. If measurements are made in an environment where the ambient conditions are very stable, such as in a metrology lab, the ultimate accuracy can be attained by manually determining and inputting the compensation number. This can remove most of the uncertainty of the sensors and the 0.5 parts per million accuracy of the instrument can be realized.

Absolute Pressure Vs. Barometric Pressure

Barometric pressure as defined here is the absolute pressure which would exist in a given area if the same weather conditions prevailed and if that area were at sea level rather than its particular altitude. For example, weather reports in Denver might give the barometric pressure on a certain day as 30.00 inches Hg. But the absolute pressure there on that same day would be closer to 25 inches Hg, because the altitude is about 5,000 feet. To measure pressure then, the user needs an absolute pressure indicator, which is equivalent to a barometer that has not been corrected at sea level. When no pressure indicator is readily available, a reasonable approximation to absolute pressure can be found by decrementing barometric pressure obtained from the nearest weather station, 0.1 inches Hg for each 100-feet of altitude. That is:

$$\text{absolute pressure} - \text{barometric pressure} = \frac{h}{100} \times 0.1$$

where h is the altitude in feet (sea level = 0) of the measurement location.

Material Temperature Compensation

The most significant source of error in interferometric machine tool evaluation, or in any other calibration procedure, is the effect of temperature on the machine tool itself. For machine tools which use a steel leadscrew to determine carriage position, this effect represents an expansion of approximately six micro-inches per inch for a one degree Fahrenheit rise in the leadscrew temperature. If the total carriage travel is 50 inches, this effect represents a change in the leadscrew length of 300 micro-inches per degree Fahrenheit change in temperature. Further compounding the difficulty is the fact that the leadscrew operates in an extremely poor thermal environment. During operation, the leadscrew is faced on all sides with heat sources such as the driving motor, bearings, and drive nut.

During the first few hours of machine operation, the leadscrew temperature will increase to some value well above ambient. Its final temperature, however, is not only a function of the ambient temperature but is also dependent on how the machine is operated during warmup. For example, if the carriage is cycled on fast speed through its entire travel the leadscrew temperature will stabilize at a higher value than would result during normal operation. It is therefore important that the conditions under which a machine tool evaluation is made be well controlled and well defined.

A machine tool evaluation should be conducted under conditions which best approximate operational conditions under which the machine tool will be used.

An additional temperature effect occurs in the machined part itself. Part temperature is affected by part material, feed rates, type of coolant used, type of tool, depth of cut, and tool condition. It cannot be assumed that the machined part will remain at ambient temperature, its dimensions will change due to thermal expansion or contraction when it is removed from the machine. This effect is not directly applicable to machine tool evaluation since it is not a fault of the machine, but it must be understood by the machine tool user if he wishes to obtain optimum machine tool performance and relate performance to calibration.

Part Temperature Compensation

In addition to wavelength compensation, the material of the part being measured must be compensated for, due to expansion and contraction with temperature changes. Most materials expand with increases in temperature. If a part is measured at two different temperatures, two different size determinations will result, and the difference can easily be as great as a part in 10^4. There is, thus, a significant ambiguity about the "true" size of the part. (There is no "true" size, all objects change with temperature.) To remove this ambiguity, a reference temperature must be established. The size of the part is then defined as the measured size when the part is at the reference temperature. Usually, metrologists and others use a reference temperature of 68°F (20°C). This reference temperature will be assumed in the discussions to follow, but the concepts discussed will apply equally well to any chosen reference.

Material Temperature Compensation is the most critical part of a machine tool calibration. There are basically two functions which can be performed with material temperature compensation. The first is to use the material temperature sensors to monitor the machine temperature and to use this temperature to determine the material temperature compensation. This procedure should be followed in most cases and will give a calibration of the machine tool which will be indicative of the positioning accuracy if the machine was at 68°F (20°C). **While this approach does give a calibration of the machine tool positioning accuracy, it does not necessarily indicate the accuracy of the parts which will be generated on the machine.**

The second function is one which can be used to determine workpiece thermal errors. The following analysis will demonstrate the workpiece errors which would be generated if the machine tool and the workpiece have different coefficients of expansion and the calibration data was compensated for machine expansion.

Let α = Coefficient of Expansion.

ΔT = Temperature difference from 68°F (20°C)

$L_{machine} = L_{command} \times (1 + \alpha_{machine} \times \Delta T)$

$L_{workpiece} = L_{command} \times (1 + \alpha_{workpiece} \times \Delta T)$

The net effect of expansion on the machined part is:

$\Delta L = L_{machine} - L_{workpiece};$

$\Delta L = L_{command} \times (\alpha_{machine} - \alpha_{workpiece}) \times \Delta T;$

$\Delta L = L_{command} \times \Delta\alpha \times \Delta T$

This says that if $\alpha_{workpiece} > \alpha_{machine}$ and $\Delta T > 0$, the part dimensions will be short by $\Delta\alpha \times \Delta T$ μin/in (μm/m) if the part is inspected at the accepted standard temperature of 68°F (20°C).

EXAMPLE: Assume that a piece of aluminum bar stock is being machined to a length of 10 inches (254 mm).

$\alpha_{machine}$ = 6 ppm/°F (10.8/°C)

$\alpha_{workpiece}$ = 13 ppm/°F (23 ppm/°C)

ΔT = +10°F (+5.56°C)

$L_{command}$ = 10 inches (254 mm)

$L_{machine}$ = 10 inches X (1 + 6μin/in/°F X 10°F)

= 10.0006 inches (254.015 mm)

$L_{workpiece}$ = 10 inches X (1 + 13 μin/in/°F X 10°F)

= 10.0013 inches (254.033 mm)

Therefore $\Delta T = L_{machine} - L_{workpiece}$

= 10.0006 inches - 10.0013 inches

= -0.0007 inches (-0.0178 mm)

The workpiece, when measured at 68°F (20°C) across this 10-inch (254 mm) dimension, will be short by 0.0007 inches (0.0178 mm).

This type of analysis should be combined with the machine tool positioning accuracy data to determine the expected workpiece accuracy.

It should be noted that the location of the various sensors on a machine tool is very important. The air temperature and humidity sensor should be mounted as close as possible to the actual measurement path so that they are monitoring the conditions that the laser beam is experiencing. Since air pressure changes slowly and is uniform over local areas, the air pressure sensor can be located wherever it is most convenient, such as inside the HP 5510A Automatic Compensator. The locations of the material temperature sensors, if any are used, are the most critical of all due to the multiplying effect of the coefficient of expansion, and they should be placed in positions that are representative of the temperature of the machine tool.

If a calibration of the feedback or position sensing device of the machine tool without regard to workpiece effects is desired, then the material temperature sensor should be placed so that it is monitoring the temperature of the positioning sensing device. This type of calibration procedure of the feedback device does not necessarily reflect errors which will affect workpiece accuracy due to Abbe' offsets, thermal differences, or other possible inaccuracies.

In either type of calibration, it is necessary to ensure that the temperature being monitored is representative of the entire length of the axis. This can be accomplished by using more than one material temperature sensor and averaging over the individual measurements. **However, if there is a large variation in temperature over the different sensor positions or with time, the magnitude of the variation should be investigated to ensure that the calibration accuracy can be met.** 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 the machine tool during the acceptance test **unless** the machine is specified to operate in that particular environment.

It cannot be emphasized too strongly that a thorough understanding of the thermal effects on machine tools is a necessary prerequisite to proper machine tool calibration.

Calculation of Exact Compensation Factor

A set of compensation factor charts is provided with the HP 5526A Laser Measurement System. However, the following formulas can be used to calculate the exact compensation factor to an accuracy of 0.1 ppm if desired:

T = Air Temperature R = Relative Humidity in %
P = Air Pressure C = Compensation thumbwheel setting, ppm (XXX.X)

$$C = \frac{10^{12}}{N + 10^{6}} - 999000$$

where N is given in English and Metric systems by:

English (T in degrees Fahrenheit, P in inches of mercury, R in %)

$$N = 9.74443P \times \frac{1 + 10^{-6} P (26.7 - 0.187T)}{0.934915 + 0.0020388T} - 1.089 \times 10^{-3} R \quad e^{0.032015}$$

Metric (T in degrees Celsius, P in millimeters of mercury, R in %)

$$N = 0.3836391P \times \frac{1 + 10^{-6} P (0.817 - 0.0133T)}{1 + 0.0036610T} - 3.033 \times 10^{-3} R \quad e^{0.057627}$$

in each case C is then corrected for material temperature with:

total C = C—(TF—68°F) X CEF.
or total C = C—(TC—20°C) X CEC.

where TF or TC = material temperature in °F or °C.
CEF or CEC = material coefficient of expansion in ppm/°F or ppm/°C.

B. Deadpath Error

"Deadpath" is another error associated with changes in the environmental conditions during a measurement. In simple terms it is an error due to an uncompensated length of laser light path and it will occur when the atmospheric conditions surrounding the laser beam change (causing a change in the laser wavelength) and when a temperature change in the material the optical interferometer and target reflector are mounted on occurs (causing a growth or shrinkage in the distance between the interferometer and target reflector).

In Figure 31(A) the "Deadpath" area of the laser measurement path is the distance between the optical interferometer and the reset (or Ø position) of the measurement (L_1). Assuming there is no motion between the optical interferometer and target reflector and the environmental conditions surrounding the laser beam path changes, then the wavelength will change over the entire path ($L_1 + L_2$). If the velocity of light compensation value changes to correct for the new environmental conditions, the 5526A Laser Measurement System will correct for the laser wavelength change over the distance L_2, but no correction will occur over the deadpath distance L_1. Thus, the HP 5526A Laser Measurement System will appear to have shifted the reset (Ø point) position.

In addition to the zero position shift due to a change in the environmental conditions around the laser beam in the deadpath (L_1) area a similar problem occurs when the table of the machine tool experiences a temperature change. If the table increases in temperature then the interferometer will physically move in relationship to the target reflector. Again, if the correct material temperature compensation value is inputted into the HP 5526A Laser Measurement System then the growth across the L_2 measurement path will be corrected for. However, the growth across L_1 will not be corrected for and a reset (Ø position) shift will again be seen on the display unit.

Thus, significant errors can occur when the distance from the Interferometer to the reset (Ø point) L_1, is large.

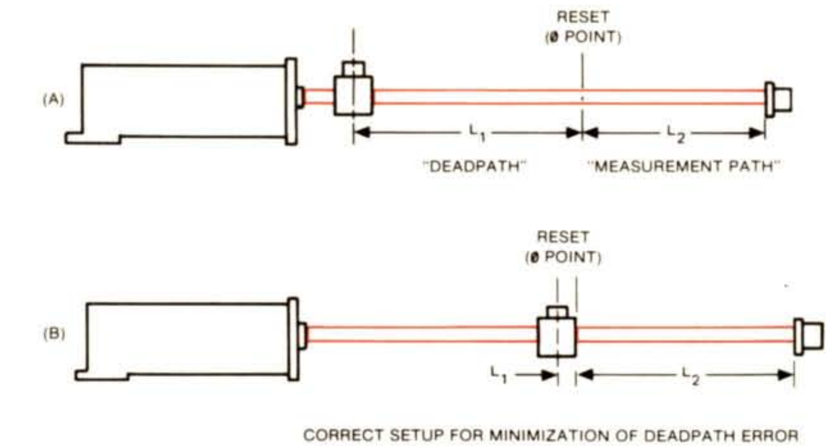


Figure 31 Deadpath Error

Deadpath Error Example

Velocity of Light Change

Assume that in Figure 31A the temperature around the Laser beam path changes by +10°F (5.5°C) causing an approximate laser wavelength change of 5 ppm and the following variables are:

$\lambda/4 = 6.23 \times 10^{-6}$ inches ($.158 \times 10^{-6}$ meters)

$\Delta\lambda/4 = 3.12 \times 10^{-12}$ inches ($.079 \times 10^{-12}$ meters)

$L_1 = 10{,}000{,}000$ quarter-wavelengths before environmental change.

= 62.3 inches (1,582 mm)

"Deadpath" error $= L_1 \times \Delta\lambda/4 = 10{,}000{,}000 \times 3.12 \times 10^{-12}$

= .000031 inches (.0008 mm)

Therefore, the reset (Ø position) on the 5526A Laser Measurement System will appear to have shifted by .000031 inches toward the target reflector.

Material Temperature Change

Assume that the temperature of the machine table changes by +5°F (2.8°C).

$\lambda/4 = 6.23 \times 10^{-6}$ inches ($.158 \times 10^{-6}$ meters)

$T = +5°F$ (2.8°C)

$L_1 = 10{,}000{,}000$ quarter-wavelengths before material temperature change.

= 62.3 inches (1582 mm)

α = Material Temperature Coefficient of Expansion of Machine Tool.

= 6.0 ppm/°F (10.8 ppm/°C)

Thermal expansion error in "Deadpath" region

$= L_1 \times \alpha \times \Delta T$

$= 10{,}000{,}000 \times 6.23 \times 10^{-6} \times 6.0 \times 10^{-6}\ /°F \times 5°F$

= .001869 inches (.0475 mm)

The reset (Ø position) appears to the 5526A Laser Measurement System to have shifted .001869 inches away from the target reflector.

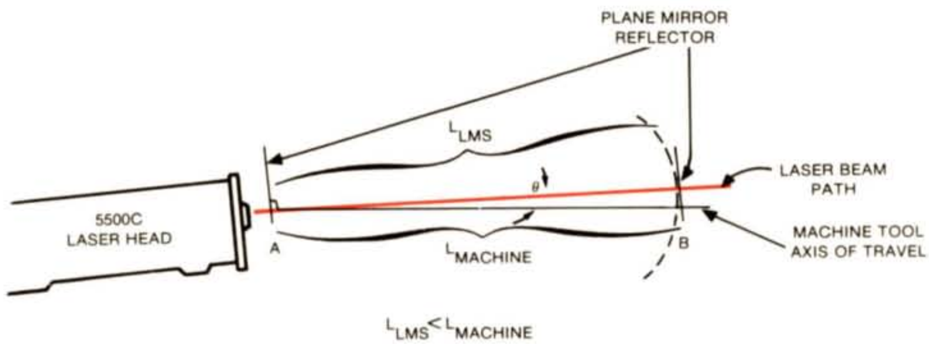
Total Ø position shift = Thermal expansion + Velocity of Light change = .001869 inches - .000031 inches = .001838 inches. (.0467 mm) away from the target reflector.

The use of the Hewlett-Packard 10565B Remote Interferometer allows the optical elements to be positioned as close as possible to the required zero point of the measurement to minimize deadpath error (see Figure 31B). Also, since the optical components are small enough to be mounted in a spindle or on a moving element it is quite acceptable to mount the Reflector on a fixed part of the machine and move the Remote Interferometer in situations where this would be preferable to minimize deadpath.

C. Cosine Error

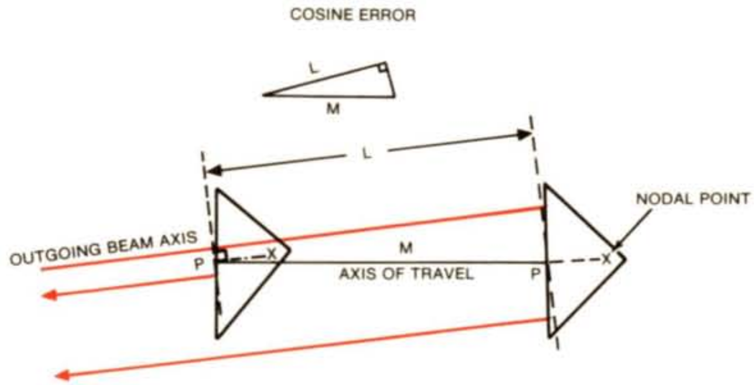
Misalignment of the Laser beam path to the axis of motion of the machine tool will result in an error between the measured distance versus the actual distance traveled. This misalignment error is usually referred to as cosine error because the magnitude of the error is proportional to the cosine of the angle of misalignment.

When the 5526A Laser Measurement System is misaligned to the axis of travel of the machine tool, cosine error will cause the measured distance on the Laser System to be *shorter* than the actual distance. This is best observed through the drawing below:



If a plane mirror is used as a reflector then the laser beam path must be perpendicular to the plane mirror to maintain beam alignment. As the machine tool moves from position A to B the laser beam will remain perpendicular to the plane mirror but it will translate across the surface of the mirror. The distance measured by the HP 5526A Laser Measurement System is L_{LMS} while the true distance traveled by the machine tool is $L_{Machine}$. By drawing an arc of radius L_{LMS} and centered at position A then one can easily see that $L_{LMS} < L_{Machine}$. The same relationship holds true when a cube corner reflector is used in place of the plane mirror (see Figure 32).

The best technique for elimination of cosine error in a linear measurement is to take care during the setup phase and use one of the alignment techniques recommended in the manual.



The laser beam reflects from the cube-corner after apparently "pivoting" about the nodal point. Since the optical path within the glass cube-corner is the same, regardless of point of entry, then the laser interferometer will measure motion of point P in the direction of the laser beam. Therefore, cosine error results in the laser measurement, L, being less than the true motion, M.

Since $\cos\theta = L/M$

$$\text{Error} = \frac{M - L}{M} = 1 - \cos\theta = \frac{\theta^2}{2} (\theta \text{ in radians})$$

θ		COSINE ERROR
(deg)	(rad)	
.001	1.7×10^{-5}	1.52×10^{-10}
.01	1.7×10^{-4}	1.52×10^{-8}
.08	1.4×10^{-3}	1.00×10^{-6}
.1	1.7×10^{-3}	1.52×10^{-6}
1	1.7×10^{-2}	1.52×10^{-4}

Figure 32

D. Abbe' Offset Errors

As a machine tool moves along its axis, the slideways have two distinct functions which they must perform. The first is that the motion is to be in a straight line and the second is that the motion should be free from angular deviations. The need for straight line motion is obvious since this is essential to be able to turn perfect cylinders or to mill straight slots. The errors induced by angular motion are more subtle and are related to the Abbe' principle as follows:

> If a displacement measurement is taken at a location which is offset from the displacement to be measured, then the slideways which provide the displacement must be free from angular motion.

A rule of thumb which is helpful for approximating the error attributable to an angular motion is:

> For each arc-second of angular motion the error introduced is approximately 5 microinches/inch of offset (5 microns/meter).

For a 10-inch (254 mm) Abbe' offset and a 2-arcsecond angular motion, the error in the displacement measurement would be: 10 inch x 5 μin/inch/arcsecond x 2 arcsecond = .0001 inch (3 microns).

The best technique for minimizing the effect of Abbe' offset errors is to think about what the measurement problem is before proceeding to set up the equipment. This is best illustrated through the following example:

> Assume that the machine tool being calibrated uses a leadscrew and resolver for the position feedback system. If the measurement problem confronting the inspector is "how accurate is the leadscrew/resolver system?" and the inspector sets up the HP 5526A Laser Measurement System with the optical interferometer located where the workpiece on the machine tool would reside and the target reflector at the location of the tool point then the laser measurement path is offset from the leadscrew/resolver scale. **To properly measure the accuracy of the leadscrew/resolver scale the inspector needs to mount the optical measurement equipment** (the remote interferom eter and target reflector) **as close to the leadscrew/resolver scale as possible.**
>
> If the inspector is confronted with the question of "how accurately will this machine tool cut a part?" and he proceeds to set up the laser measurement path as close to the leadscrew/resolver scale as possible his measurement results will not show the true accuracy of the machine tool. Typically, this measurement setup will show that the machine tool positions more accurately than it really does because he has removed the geometric angular errors of the machine's structure through his setup. **To properly measure the accuracy of the machine tool's positioning ability the inspector needs to mount one optical measurement device** (either the remote interferometer or the target reflector) **where the part would reside and the other optical device where the tool is placed.** Since it is difficult to determine where in a machine tool's coordinate system the part and tool would be located, the inspector should go one step further and measure the pitch and yaw angular errors as well as the linear positioning error in each axis to better describe the machine tool's overall accuracy.

Thus, in both examples above the inspector should first ask himself what it is that he is trying to measure and then set up the HP 5526A Laser Measurement System to minimize the offset.

ABBÉ OFFSET ERROR

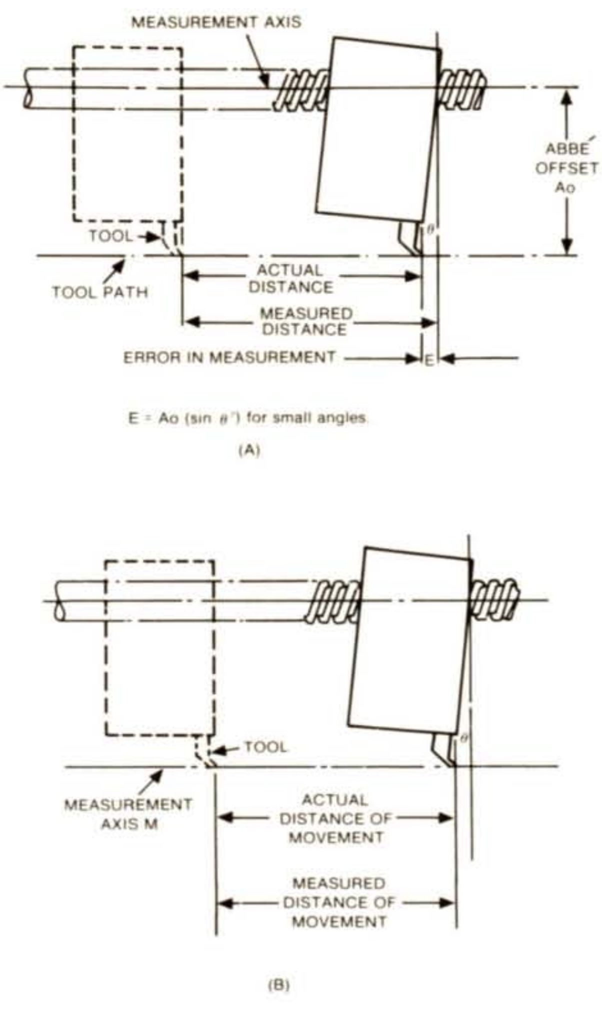


Figure 33 In Figure (A) the measurement axis is coincident with the leadscrew centerline and is measuring a displacement of the carriage at the leadscrew. This figure illustrates the displacement error E which is generated at the tool tip due to an angular motion θ of the carriage. Figure (B) shows the same carriage motion as Figure (A) but with the measurement axis coincident with the tool path. In this case the measurement system measures the actual displacement and there is no Abbe' offset error.

IV. Conclusion

The HP 5526A Laser Measurement System has proven to be a tremendous aid in the calibration of machine tools. By providing the capability of measuring linear, angular, straightness, squareness, and parallelism the HP 5526A Laser Measurement System can replace a large number of devices such as gage blocks, end standards, straightedges, dial indicators, cylinder squares, autocollimators and precision levels which were previously required to make the same measurements. Combining this versatility with the ability to make faster and more accurate measurements than were previously possible, the downtime of machine tools can be greatly reduced. This alone provides a considerable cost savings to the user.

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02-5952-7422

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