MEASURING MACHINE TOOLS WITH BALL BARS

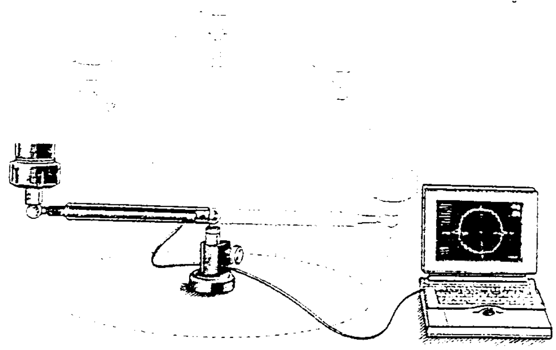
Every time we detect a part that is out of tolerance, the implication is that something went wrong in the machining process: either the operator made a mistake, or the machine tool did. A lot of the time, problems with the machine get blamed on the operator. Rather than expect the operator to compensate for every machine tool problem -- at the expense of increased setup time and scrap -- it makes more sense to quantitatively assess machine error through the process of characterization. Then the operator can either compensate more efficiently, or better yet, address the problem directly by adjusting the errors out of the machine. There's a big philosophical shift involved here: rather than gaging parts to detect problems, we gage the machine to prevent them. It's particularly important with CNC machines, where we expect the machine to do much of the work for us.

The telescoping ball bar is one of the most useful and economical devices to characterize CNC machine tools. A simple 10-minute check with a ball bar can often provide much of the information needed to verify a machine's performance. If the machine is out of spec, the same tool can provide the data to diagnose many errors. It's also particularly useful in acceptance testing of new machines.

As characterization tools go, a ball bar is a fairly simple device. It consists of a telescoping shaft with precision balls at both ends and a transducer in the middle to measure changes in shaft length. The balls fit into sockets (usually magnetic) placed on the machine itself: one is fastened to the table; the other in the spindle or tool holder. The transducer is wired to a gage readout or computer.

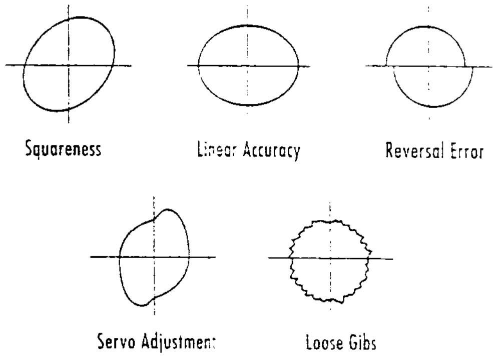
The machine is set up at a zero, or starting position, and then cycled in 180° and 360° motions, as shown in Figure 1. Normally, this is done in the middle of the machine's work area or wherever most of the machining is performed. The ball bar detects deviations from the programmed circular or semi-circular paths, and the computer generates a polar chart readout of the deviations.

Fig. 1



By checking accuracy in the XY, XZ, and YZ planes, the machine's overall contouring accuracy can be assessed, and the nature and sources of error can be determined based on characteristic patterns of the polar charts. (Additional tests can be run on machines with more than three axes of movement or on two-axis lathes.) As shown in Figure 2, linear and squareness errors appear as oval elongations of the trace. Reversal error -- often caused by worn ball screws -- shows up as a sharp displacement along the axes. Servo adjustment problems are indicated by smooth-shaped deviations near the 0°, 90°, 180°, and 270° positions, and loose gibs produce a saw-toothed pattern all around the trace. Naturally, several errors may be present simultaneously, which can make interpretation more difficult.

Fig. 2



Squareness Linear Accuracy Reversal Error

Servo Adjustment Loose Gibs

Note that the ball bar is primarily a test of contouring performance. Other tests can be run to check repeatability and Hysteresis. However, because of its short measurement range (about .080"), it is not an effective tool to check linear or volumetric accuracy over the machine's range of travel. For these jobs, a laser interferometer may be required.

One of the ball bar's strengths is its ease of use on all kinds of machine tools. This makes it an economical aid when seeking ISO 9000 certification, which requires companies to establish procedures to monitor and control their manufacturing processes. It is also part of a new standard, ANSI B5.54, which establishes methods for evaluating machining center performance. By measuring machines to a consistent standard, it is possible to establish an "error budget" for all of the processes that contribute to a certain part. And this allows companies to target quality improvement efforts more effectively.

'ROUND AND 'ROUND SHE GOES...

The calibration of machine tools is no longer an uncommon practice. By measuring the positioning and geometric contouring accuracy of a machine tool, it is possible to make effective adjustments, schedule preventive maintenance, and tighten machining tolerances. As a result, the use of calibration tools such as ball-bars, laser interferometers, and electronic levels is growing in popularity in machine shops.

In order to tweak out the last source of machine error, we have to look at the spindle itself. It is, however, difficult to take measurements on a spindle that's running at several hundred or several thousand rpm, unless you have the right tools. That's where spindle analysis equipment comes into play.

Spindle errors may be present, individually or in combination, in three different directions: radial, axial, and tilt. Radial error motion may appear either as synchronous or asynchronous errors. Synchronous error is a deviation that occurs fairly repeatably on every revolution of the spindle shaft, and it shows up on the workpiece as errors of form or geometry. Asynchronous error is nonrepeatable, and it shows up as problems of surface finish. Axial errors tend to generate surface finish or flatness problems, while thermally-induced tilt errors contribute to location problems in parts. The ability to measure errors can give the user a window on how the spindle contributes to geometry, position, and texture problems. By addressing spindle error, it is possible to reduce or eliminate these problems, which makes it easier to meet dimensional tolerance specifications.

It is critical to measure deviation under dynamic conditions, with the bearings warm and all normal sources of vibration present. Spindle error analyzers rely on capacitance gages to measure deviation while spindle is actually running, at speeds up to and over 100,000 rpm. "Cap gages" use the principle of electrical capacitance to measure the volume of air between the probe and the target — a precision steel test ball or mandrel fixed in the toolholder.

One or more probes may be held in a "nest" fixture fastened to the machine's table: with five probes in place, it is possible to measure radial, axial, and tilt errors with the same setup. (Assuming a vertical-spindle machine tool, the probe layout would be: two vertical pairs oriented at 90 degrees to each other, and one directly beneath the mandrel.) The procedure is described in the ANSI/ASME B5.54 standard, "Methods for performance evaluation of computer numerically controlled machining centers." In spite of its name, the methods are equally applicable to manually controlled machine tools. B5.54 also describes the use of a "wobble plate" — in which the steel test ball is intentionally offset from the spindle axis — as well as methods to test for short- and long-term thermal stability.

As part of the "toolbox" of calibration tests, spindle error analyzers play an important role in characterizing a machine tool's total potential accuracy and monitoring changes in accuracy over time: this is a valuable form of information for the efficient scheduling of jobs and machines. Spindle error analyzers are useful for checking out a spindle after a crash — often a much cheaper approach than to simply resume cutting metal and hoping that nothing's wrong. They can serve as troubleshooting tools, to help identify problems of form and texture, and even to track down specific components in the spindle that may be causing the problems. And spindle error analyzers can be used for acceptance testing of new and rebuilt spindles, helping buyers make informed purchasing decisions by providing a means to objectively compare the accuracy performance of different makes and models.

There are three ways to observe spindle errors. You can see them in part rejects. You can hear them as noisy, worn spindle bearings. Or you can observe them before they become a real problem with a spindle error analyzer.

IS YOUR MACHINE SQUARE?

We've looked at many important aspects of the performance of machine tools, including straightness of travel, pitch, yaw, and roll, and spindle accuracy (i.e., radial and axial deviation). Another critical aspect of machine geometry is that of squareness between axes. Any out of squareness will be directly reflected in the part being machined. And like pitch, yaw, and roll, the farther the machine moves from the intersection of its axes, the larger the influence of the squareness error.

Squareness can be measured with several different sets of tools, including: mechanical squares; telescoping ballbars; electronic levels; straightedges with indexing tables; and lasers with optical squares and straightness interferometers. The method one chooses depends upon the size of the machine, the accuracy required, the skills of the technician, and of course, cost (or what's available in the tool crib). The general guide to the measurement of machine tool squareness is to be found in the ANSI/ASME B5.54-1992 standard. By any method, measuring squareness comes down to comparing two nominally straight axes for a 90_ relationship. We'll look at a few of them here.

Precision mechanical squares are a very economical way of checking a small machine -- up to roughly 24" per axis. Beyond that length, the accuracy of artifacts tends to be inadequate for the purposes of machine evaluation, and/or their price becomes so steep that other methods become more economical. Mechanical squares come in a variety of configurations and materials, and they are supplied with a certificate of calibration, stating the maximum errors of straightness and squareness.

To measure the squareness of a vertical axis to a horizontal axis, the square is placed upright on the machine, and an indicating device (i.e., a test indicator or electronic gage head) is attached by means of a bracket or tool holder to the moving component of the vertical axis. The indicator is traversed across the vertical reference surface of the square, and measurements are recorded at convenient intervals. The data is plotted, and a best-fit line is calculated, the slope of which represents the squareness error (after allowing for the calibrated accuracy of the square itself). Like straightedges, squares are self-checking devices. To eliminate the effects of error in the square, rotate it 180° around its own vertical reference surface and re-run the test. Subtract one set of readings from the other to arrive at the machine's squareness error.

To measure the relationship of two horizontal axes, place the square on its side. Roughly align one leg of the square with one axis by taking measurements at the extreme ends of that leg, and adjusting the square's position until both readings are at zero. Then traverse and measure along each axis in turn at appropriate intervals, calculate best-fit lines for both axes, and add or subtract one slope from the other, as appropriate.

The process is similar when using a mechanical straightedge mounted rigidly on an indexing table, which is itself mounted to the machine table. One axis is measured along the surface of the straightedge, then the indexing table is rotated 90_ to measure the other axis. An optical straightedge may be substituted for the mechanical one on the indexing table, with a measurement laser and a plane mirror interferometer used instead of the gage head as the traversing "contact." As the interferometer traverses the optical straightedge, it measures the air gap between them. The 90_ reference in this case is still the indexing table, not the optics. Either way, calibrated error in the indexing table should be figured into the squareness calculation.

For machines with more than three feet of travel, a laser interferometer used in combination with an optical square and a straightness reflector is the most accurate method -- and probably the only practical one. This method relies upon no mechanical artifact for a reference: the straightness reflector (not the optical square) serves as the reference, while other elements of the optical system must be reoriented between the two straightness measurements. We'll go into more detail on laser measurements in the future.

No matter which method is selected, squareness between axes is a condition that must be examined during machine building and rebuilding, during installation, after a crash (always!), and as part of a periodic evaluation program designed to ensure the geometric accuracy of machine tools.

EVALUATING MACHINE TOOLS WITH LASERS

We've looked at several of the measuring tools used for machine tool evaluation, including telescoping ball bars, electronic levels, and mechanical "artifacts" such as precision straightedges and squares. While all of these play important roles in assessing a machine tool's positioning or orientation accuracy, the laser interferometer is the premier evaluation tool. It's not the simplest to use, nor is it inexpensive, but laser measurement systems provide greater accuracy, over a longer range, for a greater variety of measurements, than any other evaluation tool.

Lasers produce coherent light—that is, all the photons move in the same direction in measurable waves—and this is the key to their use as measuring devices. Using relatively simple optics, a laser beam can be split into two halves, each having half the amplitude of the original beam. If these two beams are aimed at the same point, and they travel the same distance, they arrive in phase, recombining as a single beam with the same amplitude as the original beam. On the other hand, if one of the beams takes a slightly longer path, the beams will be out of phase when they arrive, and the amplitude of the recombined beam will be lower, because of "interference." If one path is longer by exactly 1/2 the wavelength of the light, the two cancel each other out, and the resulting amplitude is zero. Changes in amplitude can be measured with a photodetector, such as a photodiode.

In a typical setup to measure the linear positioning accuracy of a stationary-spindle, moving-table machine tool, the laser is mounted on a tripod beside the machine, aligned with one of the linear axes of motion. An optical beam splitter is mounted on the machine's spindle, and a reflector is mounted on the machine's table, at the end furthest from the laser. The laser is directed into the beam splitter, and one of the two resulting beams is directed by an attached reflector back through the beam splitter to the laser sensor. This becomes the fixed, or reference leg of the measurement path.

Meanwhile, the other beam—the measuring leg—passes through the beam splitter, proceeds to the second reflector at the far end of the table, and is returned through the splitter and recombined with the reference leg. This is where the "laser interferometry" begins: often, the beam splitter/reflector combination is referred to as an interferometer.

As the machine's table is repositioned, changes in the distance between the reflector and the interferometer will change the amplitude of the recombined laser signal. These changes in amplitude are converted to "counts," which represent the amount of displacement seen between the two sets of optics. This very accurate measurement is compared against what the machine's controller says is the table position, for an assessment of the linear positioning accuracy.

Several tests are normally run in both directions, to assess repeatability, and backlash or reversal error. Modified setups and different optics can be used to evaluate other machine characteristics, including: straightness of travel, squareness, flatness, pitch, and yaw.

Since the system is measuring changes on the scale of the wavelength of light, positional changes can be measured to 0.001 µm (or 0.1 microinch). This is far higher resolution than can be obtained with any other evaluation method. (Of course, environmental factors must be carefully considered and corrected to achieve accuracies at these levels.) Furthermore, lasers can be used to measure machine axes over 120 ft.—again, something no other instrument is capable of doing.

Any shop hoping to consistently meet specifications for tight machining tolerances should seriously consider laser-based machine evaluation. For those who wish to avoid the expense and training involved, there are service companies that can bring the equipment to you, perform the tests, and present you with the results—often with recommendations for corrective actions to improve machine accuracy.

LET'S LEVEL

The electronic level is a tool whose value is often unappreciated. It's is as easy as using a spirit level. You just have to make sure the surface you are measuring is clean. The issue is not how to use them--it is where.

The electronic level, has two general applications. The first is to show deviations from the horizontal by measuring the angular relationship between a surface and the earth's gravity. This function is used to level a machine and to check components for straightness. The second application is to compare the orientation of surfaces. Both applications can be extremely valuable in the machine shop.

The advantage of an electronic level over a spirit level is a matter of resolution. E-levels can resolve to 0.5 microinches. Auto-collimators and laser calibration systems can perform the same tasks, but E-levels are much faster, less expensive and do not have line-of-sight requirements.

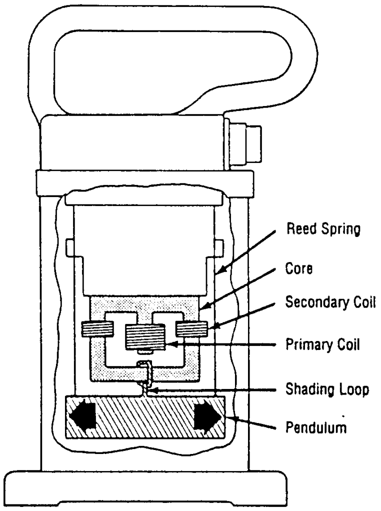
You can use the level to check any surface that is critical to machine function. Such level checks are especially useful when setting up a new machine.

Straightness checks are valuable in acceptance testing of new machines or surface plates. You can also use them to optimize the accuracy of an existing machine by avoiding sectors of the ways that are not straight. You may be able to obtain better performance than the manufacturer guaranteed by operating in the "sweet spots" on the ways.

Two sensing heads can be connected to a single amplifier and set for opposite responses to a common motion--in other words. A tilt to one side will measure a positive unit on one sensor and a negative unit on the other, canceling each other out. This setup can be used to sense differences in levelness between two surfaces, or between areas on a single surface. Because only differentials are sensed, the object being measured does not have to be level.

You can check the flatness of a surface plate or machine bed by keeping one sensor stationary and moving the other to produce a series of straightness plots. The plots can help you isolate the best sections of the surface, or indicate whether or not resurfacing of the plate is required.

The electronic level is so useful, and so easy to use, it is a crime that it is not more popular.



Components of an electronic level's sensing head, which delivers a signal displayed on an amplifier in seconds of arc. The system offers greater resolution than spirit levels and is faster, less expensive and easier to use than auto-collimators or laser calibration systems.

USING DIFFERENTIAL LEVELS

A differential level consists of two electronic level sensors connected to a single gaging amplifier or readout. In differential mode, the levels are set up so that one outputs a positive signal, and the other outputs a negative signal. Tilting both levels at the same angle causes the signals to cancel each other and the readout to show zero. This is useful for avoiding the effects of local vibration when calibrating a machine tool. In use, one level, which is defined as the reference, is set at zero and remains stationary throughout a gaging trial. Measurements are taken from the second, active, level at various locations. The readout indicates measurements in units of arc-sec., plus or minus, relative to the first level.

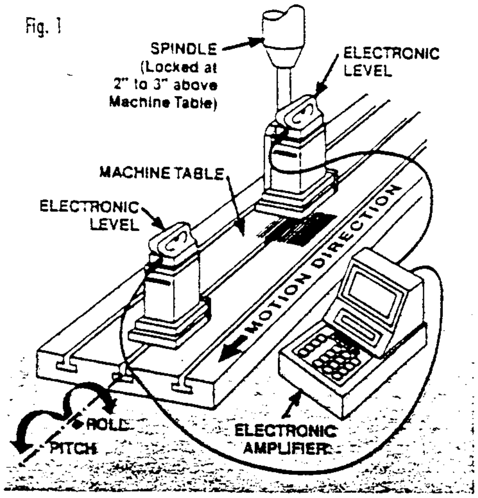
Absolute levelness -- i.e., levelness relative to gravity -- can be measured with a single electronic level. This is useful when setting up a machine tool for the first time, but it is not critical to machine performance. As the ANSI/ASME B5.54-1992 standard on machine calibration states, "Those who doubt this should note that machine tools work perfectly well aboard a ship." It is the levelness of various components on a machine tool relative to each other -- in other words, parallelism and squareness -- that affects tool point accuracy.

Deviations from parallelism and squareness can generate significant machining errors. Consider: an angular deviation of just 1 arc-sec. produces linear displacement of 5 microinches for every inch of travel. On a machine axis with 60" of travel, that adds up to .0003" of error. Then consider that 1 arc-sec. is just about ideal. Most unqualified machine tools exhibit 10-15 arc-sec. of error at various points along their travel.

Angular error can't be entirely eliminated, so it is important to measure it, in order to compensate for it. That's where differential levels shine: in measuring pitch and roll along horizontal axes, and pitch and yaw in vertical axes. (Horizontal-axis yaw and vertical-axis roll involve no deviations in levelness and must be measured by other means.) According to B5.54, angular deviations can also be measured with a laser interferometer or an autocollimator, but level systems are much cheaper, easier to set up and use, and capable of resolution and repeat accuracy as high as 0.1 arc-sec.

To measure roll along a horizontal axis (assuming a vertical-spindle machine), the active level is placed on the worktable, square to the axis being measured, while the reference level is held by the spindle, using a simple fixture called a spindle block, as shown in the figure. The table is traversed along the axis, with measurements taken at appropriate intervals: for 60" of travel, ten or twelve evenly-spaced data points should suffice. To measure pitch on the same axis, the levels are simply turned 90_ and the process repeated. To measure pitch and yaw in the vertical axis, the level on the table would be defined as the reference, and the vertical axis traversed.

Fig. 1



For final qualification, B5.54 calls for a high degree of repetition. Tests are run with the table traversed in both directions, after which the levels are turned 180_ and the table is again traversed in both directions. Because of the ease of using electronic levels, this redundant testing can be accomplished quite quickly.

Based on the results, the machine is adjusted, and the tests rerun. The remaining angular deviation can be converted into linear error for any point within the work cube, using the formula: 1 arc-sec. = 5 microinches/inch. From this data, a tool point error chart for each axis can be created on a computer. The operator enters the appropriate figure under "work surface to tool point distance" for the cut, and the computer generates a new chart showing the correction required for any location along the axis.

USE A STRAIGHTEDGE TO ASSESS MACHINE TOOL ACCURACY

Machine tool evaluation can be used to detect problems such as lack of straightness in the travel of a machine's carriage. This can be extremely helpful in explaining why the groove you are trying to mill won't come out straight and square, and it can even suggest corrective actions to solve these problems.

But while it is growing in popularity in the most quality-conscious shops, machine evaluation is not exactly common practice. At its highest levels, evaluation can be a time consuming procedure, with a steep learning curve and a high-dollar barrier to entry.

But don't despair of obtaining the benefits of evaluation if you are short on time or cash. Many useful tests can be performed with simpler, less expensive equipment--some of which you may already own. It is possible, for example, to measure the straightness of a machine tool's horizontal axes of motion using just a straightedge and an electronic gage head and amplifier--or even a mechanical test indicator.

In this context, a straightedge is certified "artifact" that is traceable to known standard and accurate to a high degree. A typical glass or steel straightedge with a straightness specification of 10 microinches over 24 inches can cost over $3,000. A granite straightedge costs just $500 or so, but its accuracy is also less: about 50 microinches. Glass straightedges cost less than steel, but because of their fragility, they are usually confined to lab environments.

Although refinements are possible, the basic principle of straightedge-based machine evaluation is straightforward. The straightedge is placed on the carriage, parallel to the axis that is being tested, while a gage is mounted on a stationary part of the machine tool, with the sensitive contact positioned against the artifact. Assuming that we are traversing the table along the X axis, we can measure straightness in the Y or the Z direction, depending upon the orientation of the gage head and the straightedge itself.

Using an electronic gage head, amplifier, and chart recorder or computer, one can produce a continuous trace of straightness. If one is using a mechanical, lever-type test indicator, discrete readings can be taken at intervals of 1 inch or 2 inches.

When testing the Z (vertical) straightness of a horizontal axis, the straightedge should not be placed directly on the machine's carriage, because a lack of flatness in the carriage could telegraph itself right through the artifact. It is, therefore, important that the straightedge be supported properly by two precision blocks or parallels. The proper placement of these supports at the “points of least deflection” (length x .554) is critical to achieving maximum accuracy.

Regardless of a straightedge’s certified level of accuracy, it can be improved upon using a “reversal” technique, which lets the user measure straightness errors in the artifact itself to microinch accuracy. The procedure is similar to that described above, except that, after the first run, the straightedge is flipped 180 degrees around its long axis, and the gage head is also repositioned on the opposite side of the machine, so that it contacts the same edge of the artifact. The gage head’s direction of motion is reversed, so that a “bump” on the straightedge should read as a positive numeral on both trials. The test is re-run, and the results of one trace are subtracted from the other. Because the gage head was reversed, carriage errors cancel each other out, so any remaining deviation from zero reflects error in the straightedge. (This assumes that carriage errors are repeatable.) The results can be used as correction factors for all future uses of the straightedge.

Whether to use a straightedge or some other method depends on the level of accuracy required, the equipment and financial resources available, and the machine tool. A two-foot straightedge won’t work very well on a machine with ten feet of travel. On the other hand, it’s hard to fit all the necessary laser optics on a machine with a work envelope of one cubic foot.

A word of caution: In the interests of space, the above descriptions have been somewhat over-simplified, but the general idea remains valid: simple tools, such as straightedges, can serve a valuable function in optimizing machine tool accuracy. Check out their capabilities as a first step on the road to a more complete program of evaluation.