AMPLIFIERS: MORE THAN JUST READOUT DEVICES

Electronic gaging amplifiers are one of those devices whose full potential is rarely appreciated by their owners -- sort of like Range Rovers that never leave the pavement. Gaging amplifiers are often used simply as replacements for dial indicators where a higher degree of resolution is required. This is to ignore numerous opportunities to make gaging more efficient and productive.

Some amplifiers, for example, incorporate dynamic measurement capabilities, including Minimum (Min.), Maximum (Max.), and Total Indicated Reading (TIR) functions. The amplifier "remembers" the highest and lowest points measured on a part, and displays either or both of them, or subtracts the Min. from the Max. to calculate TIR.

This is useful when gaging round parts in a V-block fixture, or measuring the height of a flat surface. The operator can quickly turn a shaft through a complete revolution, or move a flat part around under the gage head, without pausing to read the display. When manipulation of the workpiece is complete, the operator may select to display the maximum or minimum ID, OD, height, depth, or runout.

Other advanced functions can speed gaging setups. The "auto-zero" function is the electronic equivalent of the rotating bezel on mechanical dial indicators: the operator brings the gage head into rough contact with the master, and simply zeroes the amplifier, eliminating the need for ultra-careful positioning of the gage head. A "master deviation" function allows the addition of a fudge factor to the zero setting. Say your spec calls for a nominal dimension of 1.99980", but you've only got gage blocks handy for 2.00000". No problem. Simply set your zero at 2.00000", master the gage, program in a deviation of +.00020" to all measurements, and *voila*! Quick and easy mastering, without the hassle of post-measurement arithmetic.

A "preset value" allows switching between comparative and absolute measurements. In other words, instead of gaging deviation from nominal, the amplifier displays actual part dimensions. (In the above example, if a part is .00010 above nominal, the display will read 1.99990".)

Many amplifiers accept signals from two or more gages. This means that more than one part feature can be measured on a multi-gage fixture, by simply "toggling" between the inputs. Somewhat more sophisticated is the capability for differential measurements, in which the amplifier subtracts the reading of one gage head from the other: for example, you can derive straightness by calculating the difference in height of two co-linear points on a shaft.

Amplifiers also allow the user to establish tolerance limits, and some incorporate green, amber, and red lights to indicate "in tolerance," "approaching limits," and "out of tolerance" conditions. Alternately, the lights can indicate different part-size categories for match-gaging applications. Through digital output ports, the same electronics can be used to drive large accessory lights, enhancing parts sorting efficiency or bad-part identification in high-volume applications.

These digital output ports represent a great benefit of modern benchtop gaging amplifiers. Through them, gaging data can be used to control production machinery on an in-process basis, replacing expensive, dedicated closed-loop controllers at a fraction of the cost.

In one real, representative application, a gage head is positioned to measure a workpiece while it's still on a grinder. The user of this system assembled it using an off-the-shelf, hermetically sealed gage head, and a standard benchtop amplifier connected via the digital I/O ports to the grinder's computer-numeric controller. The grinder shifts to a shallower depth of cut when the gaged data approaches the specified dimension, and stops automatically when the spec is reached. As long as the system is calibrated adequately, no post-process gaging is required.

Besides these enhancements to the gaging process, the most important and widely used feature on modern amps is the RS-232 port for data collection. Now, through SPC, intelligent decisions can be made about the sample lot or the process. Amplifiers also provide analog output to drive strip chart recorders for continuous part measurement.

Not all gaging amplifiers incorporate all of the features listed here, although most modern amps incorporate some of them. When selecting a new amplifier, one can readily enough identify the product features needed to meet the requirements of the application. For those who are currently using amplifiers simply to take comparative measurements, it may be worthwhile to review the owner's manual, to look for built-in functions that can enhance your productivity.

IT'S AN ANALOG WORLD

In spite of what some Internet addicts may think, the world is analog, not digital. A simple example that proves this statement is what happens when we try to cross a busy intersection on foot. If the world were digital, we'd be limited to working with simple "on/off" information, indicating "car present/not-present." If we took several readings over time, we would be able to extrapolate, *but not directly detect*, a car's direction, speed, and acceleration. By the time we had done all that, that car would be long gone and we'd have to start collecting the next data set. But because the world is analog, a brief glance is all we need to detect presence, distance, direction, speed and acceleration. This enables us to react safely, either by staying put or crossing, choosing our rate of acceleration somewhere along a continuous but finite scale of values.

Analog gaging devices also contain more information than digital ones. Just watching the sweep of the needle across the dial of an analog amplifier, from "a little on the plus side" to "a little more on the plus side" may provide a machinist with all the information he needs to make the right decision to maintain control over his process—even if he doesn't actually read any numbers from the dial. So in spite of the benefits of digital instruments (more on this below), analog systems still have an important role to play.

Analog amplifiers excel in "dynamic" applications, where the gage head moves relative to the part (or vice versa). For example, when "exploring" parts for flatness using surface plate methods, the user slides the gage stand around on the plate, and quickly observes the amount of variation in the part. If the user had a digital amplifier, he would position the stand, wait for a moment to read the value on the display, reposition the stand, read the display a second time...and so on, until a sufficient number of data points had been collected.

The same principle applies to measuring out-of-roundness, in which the part is turned on a V-block beneath a stationary gage head. Using an analog amplifier, the user can directly observe the amount of variation, compare part size to the mastered dimension, and see whether the variation is all on the plus or minus side, or balanced around zero.

Machine tool setup is another valuable application for analog amps. For example, to ensure good centering when preparing to final bore a hole, a lever-type gage head is mounted on the machine spindle, with the contact against the inside of the bore. By turning the spindle back and forth by hand, and making cross-slide adjustments while watching the movement of the amplifier needle, the user can readily center the bore directly under the spindle. The same principle applies to positioning a fixture on a machine table by means of a reference "button" on the fixture.

Some analog amplifiers accept inputs from level-sensing devices, in addition to dimensional transducers. Electronic levels are of value when installing a new machine or truing up an existing one: the analog display enables the user to watch the effects of leveling adjustments in real time. If the amplifier has dual inputs, two levels can be used in tandem for "differential" measurements, to check parallelism or squareness between surfaces.

When selecting an amplifier for dynamic applications, look for adequate response speed to display change as soon as it occurs. Also, consider the needle's tendency to overshoot the measurement during rapid changes: some amps control this better than others.

Other important features include: switchable "normal/reverse" settings to make setup and interpretation easier; a dial with selectable range/resolution settings to accommodate a variety of tolerance specifications; and an analog output port for collecting data on a strip chart recorder.

None of this is to imply that analog amplifiers are always the best choice. Digital systems are superior for the purposes of data processing and output, and the generation of feedback for the control of CNC machines. Some digital amps incorporate "dynamic" features that automatically capture minimum or maximum readings, or calculate the difference between the two (i.e., TIR). Although the digital amp user can't see the sweep of a needle, he can still obtain "variable" information fairly readily.

In a nutshell, digital devices are generally preferable where:

- The measurement is static—neither gage nor part are moving.
- Output for data collection or analysis is desired.
- High resolution over long range is required.
- Analog devices are preferred when: The measurement is "dynamic," involving a moving part or gage.

- You want to observe trends or rates of change, as in approach-to-size, leveling, positioning, flatness, and out-of-roundness measurements.
- High resolution over short range is required.

THREE HEADS ARE BETTER THAN ONE

Electronic gages are the instrument of choice for many demanding inspection applications. Digital electronic amplifiers offer high resolution, excellent stability, and the ability to output to data collectors, and can be integrated into feedback-controlled manufacturing systems. Furthermore, they can be programmed to capture minimum or maximum readings, to calculate TIR and average ("nominal") measurements, and to combine readings from more than one gage head, in addition to numerous other options and features that vary with make and model.

Users of electronic amplifiers can choose from a number of gage head types to generate the measurement signal. Cartridge, pantograph, and lever-type gage heads are the three most common, differing from each other mainly in the orientation of their sensitive contacts, and the mechanisms by which contact movement actuates the transducer. Other types of dimensional sensing devices that can be integrated into electronic amplifier-based systems include capacitance gages and laser devices, and these can be useful in applications that require non-contact sensing. But by far the greatest number of metalworking applications are satisfied with the three common "mechanical," or contact-type gage heads. Each of these has particular advantages for different applications.

The cartridge probe, or pencil-type gage head, is a compact cylindrical package, usually 3/8" or 8mm in diameter. Not coincidentally, these are the same diameters as dial indicator stems, and the cartridge probe was designed for direct replacement of indicators. Like dial indicators, the probe's spindle, or sensitive contact, has an axial motion. Readily incorporated into fixture gages and in-process gages, several cartridge probes can be positioned within close proximity, to measure closely spaced part features. For even tighter spacing requirements, some manufacturers offer special miniature probes, with diameters as small as 6mm and lengths below 20mm.

Numerous other options and variants are available to increase flexibility of application. Measurement ranges vary from as short as ±0.010" (±0.250mm) to as long as ±0.100" (±2.5mm), with linearity ranging from ±0.05% to ±0.5%. Longer ranges are available, but they are usually not applied for tight-tolerance measurements. (Linearity is typically a trade-off against longer range.) The standard plain bushings that support the spindle tend to be quite durable, but in applications that subject the spindle to significant side-loading, ball-bearing bushings can provide longer life cycles. The signal output cable is normally supplied straight and plastic-jacketed, but coiled cable is available for use on hand-held gages, and armored cable is available for harsh environments. Cable may exit the probe from the back of the cartridge (axially), or at a right angle—a small detail that occasionally makes mounting the probe much more convenient.

Most cartridge heads are splash-proof, with a protective rubber boot surrounding the probe's stem. Hermetically sealed versions are also available, for use in extremely harsh environments: for example, for in-process gaging during a grinding operation.

Cartridge heads tend to have relatively heavy gaging pressure—about 3.5 oz. (99 g)—but here too, optional specifications are available from some manufacturers. Another handy option is a pneumatic retraction accessory, to minimize side-loading on the spindle when inserting a workpiece into a gage fixture.

Pantograph, or reed-spring gage heads, are most often used in benchtop height comparators where both ruggedness and extremely high accuracy are required. The gage's contact is suspended by a pair of reed springs, which provide virtually force-free and friction-free measurement. (External springs or deadweights can be added if a specific gaging pressure is required.) Pantograph gage heads offer a measurement range of ±0.010" (±0.250mm) with repeatability of <0.5 microinches (<0.01µm). They are more accepting of side-loading than cartridge-type gage heads, and can be repaired more easily and economically if side-loading damage does occur.

Where the cartridge gage head replicates the action of the dial indicator, lever-type gage heads are functional replacements for test indicators. Electronic lever-type gage heads are typically used in connection with a height stand, often for surface-plate work. When mounted on a tiltable, extendable cross-bar, they can be positioned with a great deal of latitude relative to the workpiece. A clutch on the swivel further assists in positioning convenience, allowing the contact to be repositioned by as much as 20° without moving the body of the gage head. Their ability to measure in both directions further enhances versatility. In contrast, cartridge and pantograph gage heads are uni-directional, and must be positioned perfectly in-line with the dimension being measured.

The extended, pivoting contact of the lever-type gage head provides good access to working surfaces that may be hard to reach with other contact styles. Contacts with special shapes, and diameters as small as 0.010" (0.250mm) can be specified for use on really inaccessible workpiece surfaces. Repeatability can be as good as <4µ" (<0.1µm), and gaging pressure, at <0.14 oz. (<4 g), is light, making these heads well suited for high-resolution measurements on delicate surfaces or compressible materials.

All three types of electronic gage heads can be combined in a single fixture gage or application, and many amplifiers will accept all three interchangeably. All three can also be readily integrated with either digital or analog amplifiers. These features help make electronic gaging a very flexible approach to high-accuracy inspection.

ELECTRONIC GAGING BASICS

Mechanical gages are familiar and economical. Air gages offer non-contact measurement and ease of use. But for the highest levels of accuracy and performance, it's hard to beat electronic gaging. No other method combines all this: extremely high resolution; relatively long range; adjustable magnification; programmability; digital output; and flexibility to move from job to job.

The "basic" electronic gage consists of three elements: a gage head; an amplifier; and a fixture or a stand to position the gage head relative to the workpiece. We'll touch on each separately.

The most common gage head type is the LVDT (linear variable differential transducer), an electromechanical device consisting of a primary coil, flanked by two secondary coils connected in series, all surrounding a movable magnetic core (the spindle) which provides a path for magnetic flux linking the coils. When the primary coil is energized by a sinusoidal signal from the amplifier, voltage of opposite polarity is induced in the secondary coils. The device's net output is the difference between the voltages of the two secondary coils, so when the core is centered, net output is zero.

The null or zero position is very stable, making LVDTs ideal for high repeatability comparative measurements. And because the LVDT works on an inductive principle, its resolution is, in theory, virtually infinite. In practice, it is limited by the amplifier's ability to amplify and display the results. Ranges vary from ±0.010" to ±0.100" (±0.250mm to ±2.500mm), with linearity from 0.5% to 0.05% over the nominal range.

Even standard-duty LVDTs are very rugged, and heavy-duty versions are capable of extended use in the harshest environments. Less than 3" (75mm) long and about the diameter of a pencil, they can be laid out with great flexibility in fixture gages.

Gaging amplifiers are made in analog and digital versions. Analog amps are preferred where highest resolution is required (at short range); where multiple-range capability is desirable in a single task; where measurement involves watching trends (such as approach-to-size); or where part motion or exploration is required (e.g., measuring flatness over a large area). Digital amps are preferable where high resolution and relatively long range are required; where the measurement is static (no motion between part and gage); and where digital output is required for data collection or machine control. In general, analog amps tend to be used in machine setup and surface plate measurements, while digital amps are used in high-volume inspection applications.

Many amps have two input channels, and the ability to combine signals from two transducers into one measurement is another benefit of electronic gaging. In "differential" mode, the amplifier is programmed to add or (more commonly) subtract one signal from the other. This gives the gage the flexibility to measure parts when mechanical references are difficult or impossible to establish, or when two variables may exist simultaneously: for example, on nominally round parts that are subject to dimensional variation and out-of-roundness. Depending on gage setup, the amplifier can be programmed to display either or both variables.

A typical digital amplifier might offer a choice of three measurement range/resolution combinations: ±0.100"/0.0001"; ±0.010"/10 microinches; and ±0.001"/1 microinch (±2mm/0.001mm; ±0.200mm/0.0001mm; and ±0.020mm/0.00002mm). It is important to remember that microinch/sub-micron resolution on the display does not necessarily mean that level of accuracy in practice. The accuracy of the fixture and the master, the geometric consistency of the workpiece, the stability of the gaging environment, and other conditions will influence gaging results. In practice, accuracy below 10 microinches (0.000025mm) generally requires a laboratory environment.

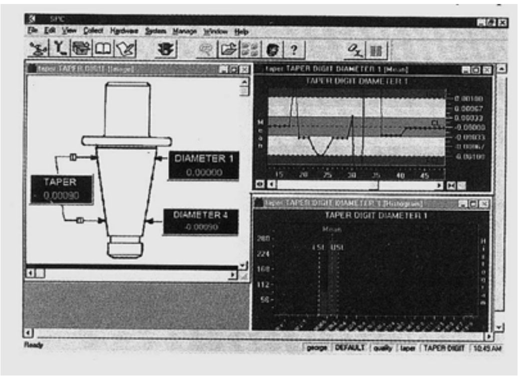
In order to achieve the best accuracy under shop-floor conditions, it is essential that the gage head stand be as sturdy and stable as possible. Platen, post, arm, and mounting bracket must all be totally rigid when locked. For high-precision height gaging, the arm assembly is often equipped with a lead screw mechanism, because the extra-sturdy arm is too heavy to be conveniently raised or lowered manually.

Another great benefit of electronic gaging is the ease with which components can be swapped around for different jobs. An amplifier that is used with two LVDTs for differential measurements in a fixture gage today may be hooked up to a single lever-type gage head in a comparator stand for height gaging tomorrow. Likewise, a gage head may be used with analog amplifier one day, and with a digital amp the next. No matter what your dimensional gaging problem, an electronic gage can probably be configured to handle it without too much fuss.

GAGING BY COMPUTER

In spite of the proliferation of personal computers in almost every other industry area, PCs are still somewhat of a rarity in gaging applications. Computers are rarely necessities for standard dimensional measurements, although almost any application can be enhanced through the use of PC-based gaging software. And while the use of "gaging computers" cannot serve as a substitute for sound gaging practice, the potential benefits they offer are greater, and the barriers to entry lower than ever.

At about $5,000 for a complete hardware and software package, a gaging computer is often cost-justified strictly on the basis of its ability to display multiple dimensions simultaneously, compared to the cost of multiple amplifiers or column gages to provide the same display capabilities. The break-even usually occurs at just four or five simultaneous measurements; as the number of measurements increases, the PC becomes ever-more economical.



For simultaneous measurements, multiple "light bars" can be arranged on the monitor, each bar growing or shrinking in height in response to the part dimension. The display can be programmed for "stoplight gaging," in which the bar changes color as the measurement shifts between in-tolerance (green), approaching limits (yellow), or out-of-tolerance (red). While measurements appear simultaneously in a numerical format beside each bar, a quick glance to verify that all the bars are green usually suffices to confirm the stability of a process.

Alternately, the monitor may display the part print, with measurements appearing callout-fashion beside each feature. This view may help the operator understand more readily where process adjustments are required. If he wishes, he may "toggle" between the different displays.

By mathematically combining signals from multiple gage transducers, PCs can be used for complex measurements such as flatness, parallelism, squareness, taper, and distance between centers, or to perform simultaneous diameter and out-of-roundness checks on a single feature. PCs typically have 16 or 32 input/output ports (usually expandable), and support essentially all mathematical operations, allowing flexibility in the number and arrangement of checks. They also offer all the capabilities of digital gaging amplifiers, including auto-zeroing, adjustable resolution, reversible polarity (i.e., plus/minus direction), and dynamic functions like "min," "max," and

TIR. Most amplifiers, however, permit only two simultaneous inputs, and their range of mathematical functions is typically limited to +, -, *, and /.

PC programming and display options are highly customizable, with multiple options accessible through passwords. Operation can be made as simple or sophisticated as the application requires. For less-skilled users, the program may boot directly to the required application, automatically capture measurements from the gage, and require no ongoing operator intervention other than loading the part on the gage.

At a higher level, software can lead the operator step by step through complex setup and measurement procedures, presenting instructions through a combination of text, graphics, and animation. Logic functions and event/action programming can help operators make decisions. For instance if the inspection task involves three hole diameters, the software may be programmed to give different instructions if one, two, or three of those holes are out of tolerance (e.g., "rework," "scrap," and "call manager," respectively). The same programming can be used to trigger automatic parts-sorting devices, or feed back to production machinery for closed-loop process control. In this type of application, the PC may replace multiple PLCs.

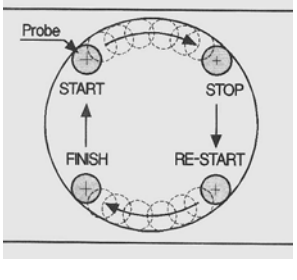
While there are numerous free-standing statistical process control packages, gaging computer software usually bundles these functions as well, easing the process of transferring data for the generation of X-bar and R charts, histograms, and all the other elements of SPC. Measurements can be automatically tagged with production data (such as machine number, operator, date and time, and events such as broken tools and coolant changes), and sorted and analyzed accordingly. SPC results can be displayed simultaneously with the results of an individual gaging trial, for a micro- and macro-view of the process at any moment. Finally, the ability to network PCs can eliminate the need for roving technicians with portable data loggers, and gives managers the ability to monitor all shop-floor processes from a central location.

Just a few years ago (when the world was still MS-DOS), PCs were intimidating to many users, and required substantial training to generate benefits in the hands of shop-floor users. That has changed, partly because the "average" machinist now does on-the-fly CNC programming, and partly because of the proliferation of Windows®. With their numerous cost-benefits and the elimination of the "fear factor," gaging computers should soon become a common productivity-enhancer in machine shops.

ELECTRONIC HEIGHT GAGES

In past columns we've looked at "basic" comparative height gages, which are used for layout tasks and other surface plate measurements. These consist of a comparator stand, plus a test indicator or an electronic gage head and amplifier. Related to these are instruments known as Electronic Height Gages. These offer a high degree of flexibility and functionality, so that, in addition to lab-based work, they are useful as production gages. In quality departments, they are used for first part and incoming inspections, and layout work, while on the shop floor, machinists use them for checking features on one-off parts.

The key features of the electronic height gage are: a probe that senses when the part is touched; a glass or capacitance scale that tracks the probe's height; and a readout/control unit. Many also incorporate a motor drive to position the probe. There is a base and a body, to maintain the components in a stable, rigid relationship, and to accurately position the scale perpendicular to the surface plate on which the gage rests. And often, there is an internal pump that generates a thin cushion of air beneath the base, allowing the gage to be moved around easily on the surface plate.



Glass and capacitance scales have gotten so good that these gages are reliable enough for shop-floor use, and so accurate over a long range as to blur the lines between comparative and absolute gaging. Most height gages can measure in both modes, and even toggle between them on a single measurement. Resolution of .0001"/.001mm, with accuracy of .0005"/.013mm over a range of 24"/615mm is common, while high-end instruments offer resolution down to 10µ"/.5µm and accuracy of .00012"/.0025mm.

Two sensing technologies predominate: touch triggers and active probes. Both types can be set to trigger from both downward and upward touches. Once these points are collected, it's easy to calculate the difference between them, for either inside measurements (such as slot lengths and widths, and inside diameters) or outside measurements (such as ODs or thicknesses). One can also average the two readings to find hole centers or center lines. From there, it's an easy step to calculate distances between centers.

The more common touch triggers send a signal to the scale only once per touch. Active probes, found on higher-end systems, constantly update their position, and record the position once they reach a stable reading on the part. In addition to single-point measurements, gages with active probes can be used for "dynamic" measurements, to explore a feature for straightness, flatness, MIN, MAX, or TIR.

Active probes have the potential to generate more accurate diameter measurements, because the user can tram the gage perpendicularly to the feature's axis, to capture the highest and lowest points on the top and bottom surfaces. (See figure.) To correctly measure a diameter with a touch trigger, a special contact is used, which is designed to seek the low or high point of the diameter.

Even the relatively simple control units associated with touch triggers tend to be highly capable. These are usually programmable for multiple measurement routines, can accept presets, and calculate widths, thicknesses, and distances between centers.

More powerful controllers, which usually accompany active probes, are required for dynamic measurements. These data processors are capable of generating SPC reports, and turning the single-axis height gage into a virtual two-dimension measuring machine. One can measure bolt-hole patterns and similar 2D relationships, by measuring the height of the holes, then reorienting the part 90° and remeasuring the hole heights again. The controller includes a one-button "90° flip" function to calculate results as X-Y coordinates (e.g., a hole center is 6.000" in from one edge, and 2.000" from an adjacent edge) or as polar coordinates (e.g., a hole center is 16.342° from a reference point, on a hypotenuse of 4.500").

The gage must be zeroed before measuring parts. This is usually done by touching the probe to the reference surface—usually a surface plate. Gages can also be referenced against a gageblock, or against a datum on the workpiece itself.

Before measuring inside or outside dimensions, the diameter of the ball end of the probe must be compensated for. This involves touching the probe to the top and bottom of a special reference artifact. The controller calculates the diameter as the difference between the measured reading and the known distance between the two reference surfaces.

While general-purpose measurement devices like electronic height gages can't compete with some types of comparative gaging for measurements requiring very high resolutions or throughput, they are ideal for most surface plate layout work, and for inspection of parts produced in small quantities.