PRESSURE-SENSOR FUNDAMENTALS: Interpreting Accuracy and Error

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Before you choose a pressure-measuring instrument, make sure that you fully understand the ins and outs of the manufacturer-provided data.

To choose the best pressure sensor for a particular application, it is important to understand some of the key terminology (and euphemisms) that most manufacturers use, as well as some of the limitations of sensors currently on the market.

A previous article ("Introduction to Pressure Measurement," *CEP,* March 2014, pp. 28–34) covered the basic principles of pressure measurement, showed visual representations of typical pressure sensors and their internals, and discussed how to navigate through the sea of choices ranging from a raw sensor element costing a few dollars to a smart transmitter costing thousands of dollars. The earlier article pointed out that a smart transmitter is not always a smart choice, and that it pays to spend the extra time to determine the right class of instrument for a particular job (instead of spending extra money for an unnecessary product).

Just as there is no overall best car, there is no overall best pressure sensor. A Lamborghini may seem like the perfect car to some — but if you want to get three kids to school and put a bike in the trunk, it is inadequate, no matter how superior it may be in other respects.

The same is true for pressure sensors — although you can pay top dollar for certain features and functions, virtually every feature commands a compromise in other areas. A display, useful and informative on the one hand, increases the instrument's size and power consumption, reduces its operating temperature range, and is susceptible to mechanical abuse, shock, and vibration. Additional software makes life easier and enhances functionality, but also drastically increases the probability of (user) errors, and it requires processors, memory chips, and many other components that reduce reliability and may shorten instrument life. Even seemingly simple features, such as linearization and active temperature compensation, not only have a price tag — they can also result in other behaviors that are not described in any datasheet and may have dramatic consequences that could render the device completely useless.

Gray areas in instrument performance

A gray area in characterizing the performance of any instrument is the definition and interpretation of datasheet values. Although it may seem simple and relatively straightforward to compare two numbers (*e.g.,* a linearity of 0.5% vs. 0.25%), it is not clear which of the two devices is actually the better choice, and here is why:

• Only if exactly the same standards and definitions are applied can two values be compared. This is not as easy as it may sound. (For example, we show later why a sensor with a nonlinearity of 0.5% can be equal to or even better than a device with a nonlinearity of 0.25% best-fit straight-line.)

• Both instruments may be totally wrong altogether, because linearity may actually be of little or no importance for the particular application.

Likewise, it is necessary to understand test results and definitions. Although it seems logical that a higher rating is better — for example, an ingress protection of IP67 vs. IP65 — it is also true that in certain environments, the numerically lower-rated (IP65) unit will survive much better than the seemingly higher-rated (IP67) device.

This article sheds light on some of the industry's jargon and provides guidance to help you read between the lines of manufacturer datasheets and answer the following questions:

• How much accuracy do I really need?
• What is not printed on the manufacturer's datasheets

that I need to know? (*e.g.,* how will an instrument actually function under vibration?)

• How do I translate performance data, test results, and definitions into real-world applications?

• How do I determine the reliability of a pressure sensor?

• What factors do I need to consider to make the best choice for the application?

Accuracy pitfalls

Engineers commonly use the term "accuracy" and intuitively make assumptions about it. In the instrumentation world, there is no exact definition or international standard defining the term accuracy — it is open to assumptions and interpretation.

An instrument's accuracy cannot be described by a single number (even if some people tell you that it can).

It is a linguistic trap that engineers tend to fall into: We say accuracy, but we are actually describing a series of values that define the inaccuracy — an expected or allowed deviation from an ideal state. But, because that ideal state has so many different dimensions and varies considerably from application to application, "accuracy" needs to be broken down into separate, well-defined parameters, as explained in the following sections.

Measuring error

In its simplest form, the term accuracy is often referred to as an expected or tolerable deviation of the characteristic curve of an instrument from an ideal state at a described set of conditions (Figure 1). Those reference conditions are typically room temperature, and normal barometric pressure
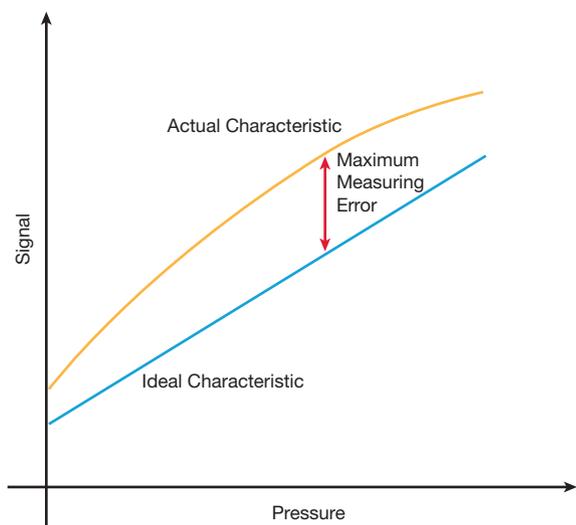
▲ **Figure 1.** Measuring error represents the maximum deviation of a sensor's measured value from the expected value. It is the difference between the actual-characteristic curve (yellow line) and an ideal-characteristic, or reference, line.

and humidity with no other external influences applied (*e.g.,* vibration, electromagnetic fields). A practical way to determine this is to test the device under laboratory conditions — taking multiple readings of increasing and decreasing pressure from zero to full scale — and compare the output of the device under test (DUT) with a known standard, *i.e.,* reference sensor. The maximum deviation of all measured values from the expected values could be called the measuring error of this individual device.

The measuring error includes all relevant errors at a constant (reference) temperature, such as nonlinearity, hysteresis, nonrepeatability, zero offset, span error, etc. It can be determined directly from the actual-characteristic curve. If the pressure-measuring instrument is operated at this temperature, then the maximum measuring error is indeed the maximum error with which the pressure can be measured with this individual device.

Making sense of it all

Although measuring error may sound like a reasonable way to define and determine the accuracy of a pressure sensor, the usefulness of this single value is quite limited for several reasons. First, it is unclear how an instrumentation engineer should apply this single value to any given application. An actual-characteristic curve of a pressure sensor (Figure 1) shows that this maximum deviation only occurs at a certain point on the curve (as indicated by the red line).

For example, a 1,000-psi pressure sensor could have a total maximum deviation as high as 3% of full scale, or 30 psi. Based on the actual- and ideal-characteristic curves, it is reasonable to assume that an instrumentation engineer does not need to allow for a deviation of 30 psi at every pressure. If a pressure of 100 psi were applied, the output would almost certainly not read 70 psi or 130 psi; it would more likely fall in the range of 95–105 psi.

Most manufacturers have therefore adopted a much narrower definition of accuracy, which combines nonlinearity, hysteresis, and nonrepeatability in a single number. This number is typically an order of magnitude smaller than the measuring error, because it eliminates the (often) substantial zero and span errors. At first glance, it appears to be a more reasonable characterization: It fulfills the demand for a single number, and at the same time seems to be closer to what engineers actually experience in the field. However, as with measuring error, it isn't clear how the instrumentation engineer should apply this error under a particular set of conditions. Even worse, this type of accuracy definition wrongly suggests that two very substantial and important errors of pressure sensors — zero error and span error — are irrelevant to accuracy. As a result, they are often ignored by instrumentation engineers.

Looking for the simple answer

Figure 1 demonstrates clearly that unless all deviations are so small that they can be completely disregarded as negligible (*i.e.,* values in the range of 0.01% or below for typical industrial applications), accuracy simply cannot be expressed as a single number. A set of numbers is necessary to describe the deviation of a real instrument from an ideal instrument, for three reasons:

1. The actual characteristic of a real instrument is not constant and not linear; it changes with pressure, temperature, time, etc. So without reference to the exact conditions, two seemingly identical instruments may show two completely different behaviors.

2. A datasheet is intended to describe the characteristics of a total population of sensors. To address the inevitable variation among individual devices, a datasheet should include some statistical elements, such as typical, average, or maximum, as well as deviation ranges.

3. Not every deviation from ideal is relevant to every application. The simplest example of this is a bathroom scale that performs a reset to zero every time it is turned on — the zero error and zero shift due to temperature are irrelevant for this particular application.

The following sections look at the important parameters relevant for pressure measurement and present some practical examples.

Nonlinearity

This may seem to be the easiest-to-understand parameter for comparing the performance of different sensors, and it is often used as the primary parameter to differentiate "more-accurate" from "less-accurate" sensors. Unfortunately, this is probably one of the worst parameters to choose for the purpose of selection and classification of sensors, as its definition varies widely and some of the technology used to achieve lower numerical nonlinearity values actually causes performance degradation in some applications. Furthermore, in most cases, nonlinearity has little practical implication.

Nonlinearity is a way to express how far any particular reading of a sensor deviates from a straight reference line under identical conditions — *i.e.,* how "curvy" the sensor's characteristic curve is compared to a straight line. It is typically expressed as a percentage of full scale — for example, a nonlinearity of 0.25% in a 1,000-psi sensor means that anywhere between zero and full scale (0–1,000 psi), the sensor output can be as much as 2.5 psi off what it should be.

Nonlinearity is defined as the largest deviation (positive or negative) between the actual-characteristic curve and a reference straight line. There are several ways to determine the reference straight line. The two most common are the

terminal method and the best-fit straight-line (BFSL) method (Figure 2).

Terminal method. In this method, the zero error and span error are eliminated, and an ideal line connecting the zero and full-scale values on the actual-characteristic curve is drawn (green line in Figure 2). Nonlinearity describes how far the sensor's actual-characteristic curve deviates from this ideal line.

Best-fit straight-line method. Judging sensors based on their nonlinearity was taken to an impractical level with the invention of the BFSL method. This definition can cut the numerical nonlinearity error in half — without actually changing sensor performance in any way (blue line in Figure 2). The best-fit straight line is purely fictitious and is deliberately drawn to minimize the numerical difference between it and the actual-characteristic curve (yellow line). The BFSL is positioned in relation to the measured-characteristic curve in such a way that the sum of squares of the deviations is minimal. There is no requirement for this line to be parallel or in any other way related to the ideal line of the terminal-based method — making it virtually impossible to judge when and where the sensor will actually deviate and by how much.

For the terminal method, the maximum deviation occurs somewhere between zero and full scale, typically right in the middle of the range. With the introduction of the BFSL method, determining the location of the maximum devia-
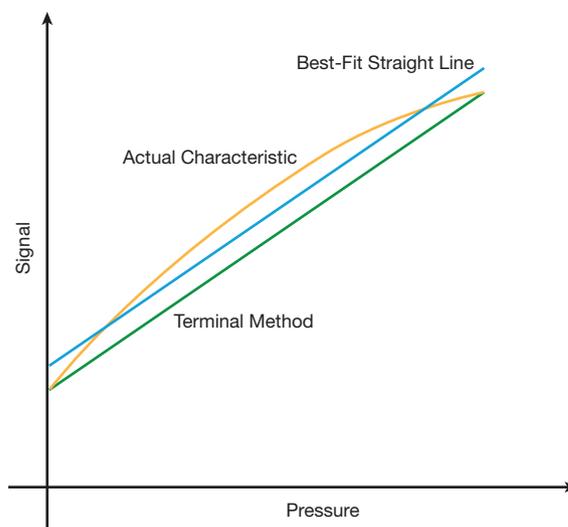
▲ **Figure 2.** Nonlinearity is a measure of the positive or negative deviation of the actual-characteristic curve from a reference straight line. The terminal method of determining this reference line (green line) usually results in a deviation twice as large as that of the best-fit straight-line method (blue line). The nonlinearity of electronic pressure-measuring instruments should be compared only if the reference lines were determined in the same way. However, the position of the BFSL is typically not disclosed and can vary from sensor to sensor.

tion becomes guesswork. A sensor could have nonlinearity of 0.1% using the BFSL method, but a nonlinearity of 0.2% using the terminal method.

Practical implications. Most sensors are not pressured to the full-scale value on their label. If, for example, a maximum system pressure of 600 psi is expected, a 1,000-psi sensor may be chosen based on available pressure ranges and other practical considerations.

Furthermore, the typical readings under normal operating conditions may be somewhere in the range of 300–500 psi or even lower. As a result, the nonlinearity for the typical working range would be much smaller (red line in Figure 3). When operating at the typical pressure of 500 psi, only half of the characteristic curve is being used, and the nonlinearity error can be reduced by up to one-fourth of the original value.

So, if a 1,000-psi well-designed (*i.e.,* the characteristic curve makes a steady and continuous arc beginning at zero and ending at full scale) pressure sensor has a 0.25% nonlinearity, in the middle of its range (at 500 psi), the sensor output will be off by 2.5 psi. The tangent of the actual-characteristic curve is parallel to the ideal line at this midpoint. Therefore, the differential nonlinearity between two close values is practically zero. As a result, any change in pressure (*e.g.,* from 500 psi to 505 psi) will cause a linear change in the sensor output. And, if the sensor is equipped with an analog amplifier with virtually infinite resolution in the signal path, the smallest changes in pressure can be measured with an extremely high precision. If the sensor is used to measure pressures only up to half of its total range, the expected nonlinearity of the partial actual-characteristic curve will be approximately one-fourth of the original error — a maximum deviation of about 0.625 psi over the range of 0–500 psi (typically occurring at 250 psi) can be expected.
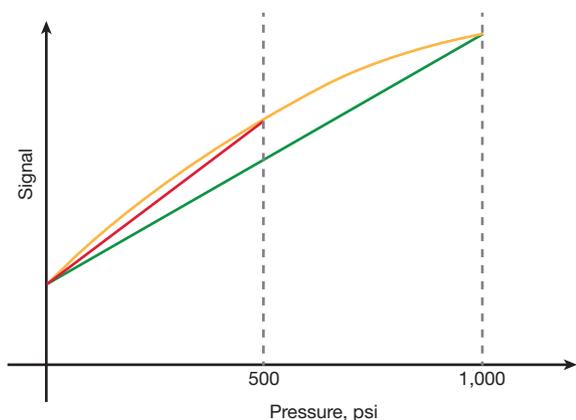
Even if the absolute deviation from the ideal line is zero at the upper and lower ends of the range, the differential nonlinearity is at its maximum. If the application requires very accurate tracking of the smallest change in pressure close to zero or close to full scale, the relative error is much higher at those two operating points.
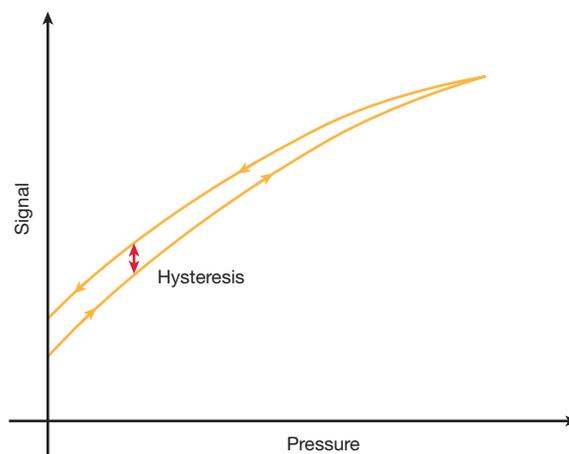
In real-world applications, this is very important — whenever tight control of a certain setpoint is required, use a sensor that has this setpoint at the center of its range.

Hysteresis

When the characteristic curve of a measuring instrument is recorded at steadily increasing pressure and then at steadily decreasing pressure, the output signals at any particular pressure generally do not exactly match. The maximum deviation between the increasing and decreasing characteristic curves is referred to as the hysteresis (Figure 4).

The hysteresis effect caused by the applied pressure is more precisely called pressure hysteresis, and it is not the only type of hysteresis that a sensor may experience. Another form of hysteresis is temperature hysteresis, which occurs when the temperature goes from hot to cold or from cold to hot. This should not be confused with temperature error, which is discussed later in the article.

Any sensor, under identical conditions, will provide a (slightly) different output depending on whether the applied pressure is increasing or decreasing. This can be observed by noting the zero-pressure output of an instrument, steadily increasing the pressure up to full scale, and then steadily decreasing the pressure back to zero. Due to the nature of hysteresis, the output readings during rising pressure are typically lower than the readings on the return path to zero;

▲ **Figure 3.** If only a portion of a sensor's pressure range is used, the device's nonlinearity will be lower. For a 1,000-psi sensor that typically operates at 500 psi, only half of the characteristic curve is relevant. The nonlinearity error over this smaller range (shown by the red line) is one-fourth of the original value.

▲ **Figure 4.** Hysteresis error is hard to distinguish from other errors, and it cannot be predicted for a specific moment, because it depends on whether the pressure was rising or falling before the measurement was taken.

in fact, the sensor will indicate a residual output (slightly above zero) even after the pressure is completely relieved. The largest deviation between the rising and the falling readings is defined as the hysteresis.

In layman's terms, hysteresis makes it look and feel like the sensor is "resisting," or is lagging behind. The extent of this apparent lag depends on the inherent properties of the sensor materials and the design principle of the sensing element. Stainless steel is especially prone to hysteresis effects due to the internal structure of the material. Soft sealing materials, glued/bonded strain gages, or other elements affected by the deflection due to the pressure, such as diaphragms, can also contribute to this phenomenon.

Unlike nonlinearity and other parameters (such as zero error and span error), hysteresis cannot be adjusted, electronically compensated, or counteracted in any other way — except by fundamental design and choice of material. It is an inherent indicator of the design and manufacturing quality of the sensor. The sensor error caused by hysteresis should always be well below the design limits of any application.

The effects and implications of hysteresis are often underestimated, because hysteresis error is very hard to isolate and distinguish from other errors. However, hysteresis error needs to be treated like a measurement uncertainty, since it cannot be predicted at any given moment in time. Hysteresis is a result of all pressure changes the sensor has ever experienced during its lifetime — each (new) change in pressure contributes to hysteresis. Small changes in pressure cause a very small amount of hysteresis, while any large change in pressure, up or down, contributes significantly to the phenomenon.

Practical implications. In a real-world application, if the pressure is expected to vary between very low and very high, the instrumentation engineer must consider hysteresis when choosing a sensor, especially if the application requires a high degree of repeatability.

Avoid hysteresis if possible. Don't choose instruments that have significant hysteresis error (*i.e.,* greater than negligible for a particular application), as it is a sign of a poorly designed instrument.

Nonrepeatability

Electronic pressure-measuring instruments are also subject to random influences. Therefore, the output signals for successive measurements of the same pressure values are not always exactly the same (Figure 5). One simple way to observe nonrepeatability of pressure sensors is to cycle the pressure continuously — *e.g.,* from 10% to 90% — and record the readings. The values typically scatter around a center value, and the width of the scatter represents nonrepeatability. Nonrepeatability error is defined as the largest deviation between the highest and lowest measurements of

the same pressure taken under identical conditions. High repeatability (*i.e.,* a small nonrepeatability error) is a basic requirement of every dependable sensor system.

Nonrepeatability (like hysteresis) is an important parameter on which to judge the design and manufacturing quality of the instrument, as it is a direct reflection of the sensor's inherent quality. Nonrepeatability should be as low as possible within the design limits of the application.

Practical implications. The practical implications of nonrepeatability are the same as those for hysteresis, and, depending on the application, may need to be factored into the selection process. It is best to choose sensors with nonrepeatability that is well below the design specification limits of the application so it can be neglected.

Obvious nonrepeatability (that can actually be measured/observed and is greater than other errors) is a sign of an inadequate and unreliable pressure sensor. Do not select such an instrument.

Zero-point error

The zero-point error (red arrow in Figure 6) is sometimes hidden in the small print of a datasheet. Still, it is an error that may make a large contribution to the total error, especially if only part of the range is used. The zero-point error is typically expressed in the datasheet as a percentage of full scale, but its absolute value remains the same across the entire pressure range. Thus, the relative error is larger at lower pressure readings. For example, for a 1,000-psi sensor that has a specified 2% zero-point error (that may sound large, but it is not unusual), the absolute error that can be expected is ±20 psi. This means that at a working pressure of 100 psi, a zero-point error of ±20 psi translates into a 20% potential error.
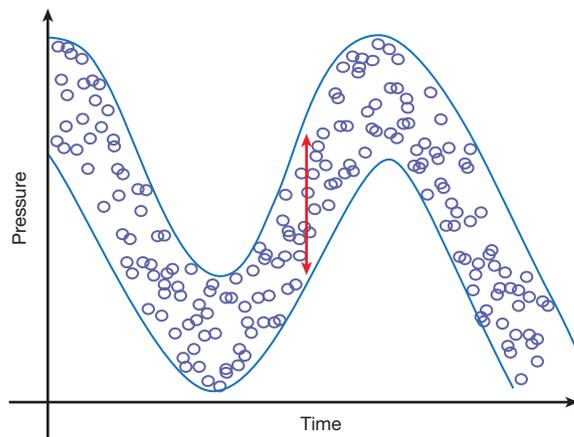
▲ **Figure 5.** Nonrepeatability characterizes the extent to which the output signals for successive measurements of the same pressure vary. The sensor represented here, which has an extremely high amount of nonrepeatability (as shown by the red arrow), measured pressure during numerous cycles between high and low pressure.

Article continues on next page

Practical implications. If it is possible to read the sensor output at a defined, nonpressurized state, a programmable logic controller (PLC) can be adjusted to interpret that output signal as zero, thereby eliminating the sensor's zero-point error. If the sensor later needs to be replaced and there is no opportunity to recalibrate the PLC to the (different) zero point of the new sensor, the zero-point error may account for a large part of the measuring error.

A high zero-point error is typically a sign of poor process control during the instrument's manufacturing. It is also an indication that the manufacturer did not test and adjust the device at zero pressure. High tolerances on the zero-point error are responsible for high reading errors when only a portion of the full pressure range is used.

Span error

No sensor has a perfectly adjusted output signal at full pressure — this is called span error (green arrow in Figure 6). The span error is typically smaller than the zero-point error (at least according to most datasheets). It also has a less drastic effect in most applications that use only a portion of a sensor's full pressure range, because it scales down in direct proportion to the applied pressure (from its maximum at full scale to zero at zero pressure). In practical terms, a span error of 1% in a 1,000-psi instrument translates into ±10 psi allowed deviation at 1,000 psi, but only ±5 psi at 500 psi and ±1 psi at 100 psi.

As with the zero-point error, a low span error indicates a high degree of process control during instrument production; it is typically achieved by the manufacturer adjusting each sensor individually in a controlled environment. In contrast
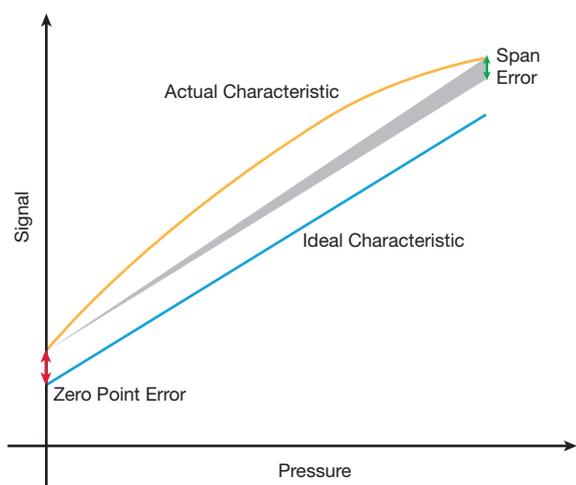
▲ **Figure 6.** The zero-point error represents an offset of the entire range of pressure values, and can often be adjusted for by the PLC. The span error ranges from zero at zero pressure to a maximum at the sensor's maximum rated pressure, and is directly proportional to the applied pressure at points in between.

to zero-point error, the span error cannot be adjusted in the application, as that would require the use of highly accurate pressure references and a tightly controlled environment, rather than a simple PLC calibration.

Temperature impacts

An ideal pressure sensor would sense pressure and remain unaffected by other changes. Unfortunately, no sensor on the market today has achieved this ideal.

Every pressure sensor's output is somewhat affected by variations in temperature. Temperature changes cause the expansion and contraction of the sensor materials, fill fluids, and housings. Temperature changes also have an impact on the sensor's resistors, semiconductors, and electrical connections through the thermoelectric effect (*i.e.,* the conversion of a temperature difference into an electrical voltage).

A sensor's behavior in response to changes in temperature is typically characterized by two temperature coefficients: temperature effect on zero (TC zero) and temperature effect on span (TC span). Both are simple linear approximations of how much the output signal is altered by changes in temperature.

Temperature effect on zero. Like the zero-point error discussed earlier, TC zero is expressed as a percentage of full scale, but the absolute value of this shift in the output signal is constant over the entire pressure range. It, therefore, has the biggest impact on low-pressure readings.

A typical value of TC zero is 0.1% of full scale per 10 K temperature change. For a 1,000-psi sensor, this translates to an output signal shift (up or down) of up to 1 psi for every 10 K change in temperature. At 100 psi, for example, a 40 K temperature change, *e.g.,* from 20°C to 60°C, could produce a ±4 psi change in output — a 4% error. At 1,000 psi, the same 40 K temperature change would translate into an error of 0.4%, which would probably be quite acceptable.

Temperature effect on span. While the temperature effect on zero represents a parallel shift of the output signal up or down, the temperature effect on span represents a turn of the output curve — *i.e.,* the slope of the curve changes. TC span depends on the current temperature, and, like TC zero, is expressed as a percentage of full scale per change in temperature. Unlike TC zero, TC span has its maximum effect at the full-scale pressure, and it scales down linearly at lower pressures. A TC span of 0.1% per 10 K may result in an error of 1 psi for every 10 K of temperature change at full scale. However, at an operating pressure of 100 psi, the same TC span would create an expected maximum error of only 0.1 psi per 10 K temperature change. If the temperature changes from 20°C to 60°C, the resulting additional error at 100 psi would be only ±0.4 psi, but at 1,000 psi, it would be ±4 psi.

Temperature error and cost. Temperature-related errors not only contribute to the overall accuracy of a pressure sen-

sor in a particular application, but they also factor into the economics of designing and manufacturing pressure sensors — in particular the complexity and cost of production lines.

Although zero-point error and span error can easily be addressed during production by simply applying pressure and checking the output, temperature compensation is a complex, time-consuming, and expensive process that requires a significantly larger investment in production equipment and a deeper understanding of the influencing parameters. Instrument manufacturers with a high degree of vertical integration are better able to deliver high-performance temperature behavior at moderate cost. For example, they can apply principles such as compensation-at-source, whereby temperature compensation is performed on sensors or subassemblies during their initial production steps rather than on fully assembled systems at the end of the manufacturing line. In this way, data collected from various parts of the manufacturing process are combined in a beneficial way to enhance total performance and reliability instead of stacking up tolerances of all components and process steps combined.

Simplify your life? As pressure sensors become more and more of a commodity, users as well as manufacturers are looking for simple ways to grade or classify products. One such attempt that has gained some popularity is the total error band (TEB) method, which was developed as a simplified way to capture multiple (temperature) errors and provide a simple comparison of devices (Figure 7).

The TEB method provides an error envelope that the sensor is expected to stay within (gray box in Figure 7), while the TC method (yellow line in Figure 7) specifies a zero-point temperature error at reference conditions (*i.e.,* 20°C) and an increasing error as temperature increases or decreases. Because the TC method of determining temperature error involves calculating the temperature coefficients and resulting potential errors at every specific temperature, it gives a more-detailed description of the sensor's behavior than the TEB method, which adds a significant error at reference conditions.

As discussed earlier, the understanding — and also the correct specification — of each individual error allows the instrumentation engineer to decide which errors are relevant for his or her particular application and therefore optimize the match between sensor and application at the lowest cost. Because TEB is a generalization, it does not allow for this, which somewhat defies the object of the exercise.

Drift, shift, and long-term stability

Drift and shift are colloquial terms describing change that need to be clearly distinguished.

Shift is a change in output signal that has already occurred and has come to a halt, and the sensor now shows a new, changed (shifted), but stable, output. It can be caused by a change in temperature, by overload, or by aging of components.

Drift refers to a shift that is in progress — a slowly changing output signal over time. Typical reasons for drift include moisture in the sensor's circuitry, hydrogen absorption and diffusion by the sensor, and sensor overload that causes the sensor's material of construction to experience creep.

Sensor shift is usually related to an external influence and the output eventually stabilizes as the external influence stops changing. Drift, on the other hand, indicates a problem with the sensor itself — and that it can no longer be trusted as a reliable source of data. If drift is observed, the sensor needs to be taken out of service, because its output is changing (unpredictably) over time.

Long-term stability combines the effects of drift and shift. It is a very, very slow drift that results, ultimately, in a shifted output signal after a long period of time. It is typically defined as a percentage of full scale over a period of time (*e.g.,* 0.05% per year). This is the only sensor drift that you should accept.

Long-term stability describes the maximum shift in a sensor's output signal if, for example, you measure a known pressure, set the sensor aside, then a year later use it to measure the same known pressure again. This type of long-term drift is a result of the sensor components and the electronic circuitry aging over time, and it should typically go in only one direction (it could be either up or down, but the direction of the change should remain constant).

Long-term stability is not reversible. It is the only acceptable change in output signal between annual calibrations. If, in the interval between calibrations, a larger change in output is observed that cannot be attributed to other factors (*e.g.,* different environmental conditions like temperature, or the use of a different calibration standard), the sensor should be
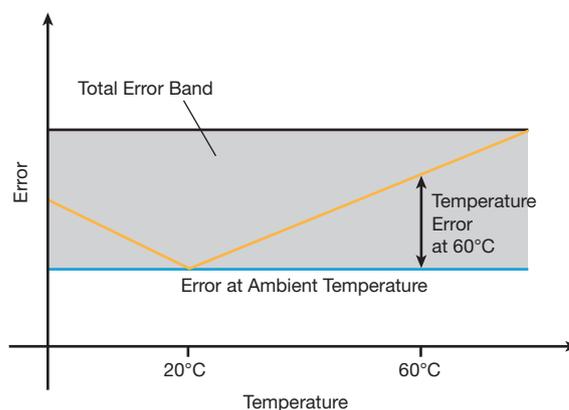
▲ **Figure 7.** The total error band (TEB) method specifies a maximum error over a certain temperature band. It, therefore, leads to higher error margin in certain areas than the temperature coefficients method (yellow line).

carefully inspected, and may need to be taken out of service. Never adjust the output signal of the PLC's input card or the output of the sensor to compensate for a larger shift and move on. Unless it can be clearly identified and attributed to other (controlled) circumstances or the application, any large shift in output is a clear sign of unintended, unpredictable behavior.

If this happens regularly, don't just change the individual sensor — change your sensor supplier!

Reliability and dependability

Another factor that goes into specifying and selecting the right sensor for the application is reliability. This has several aspects:

• Is the sensor under consideration worth the money, or will it fail prematurely and incur costs for a replacement (including equipment downtime and installation of the new device)?

• What happens to the process if the sensor fails?

• How can a failed or failing sensor be identified?

• What preventive maintenance regime should be implemented?

There are no simple answers to these questions. Inevitably, all devices fail at some point in time. An instrument that is very complex and is subjected to high stress levels (*e.g.,* high temperatures and pressures, or corrosive environments) will have a higher failure rate than less-complex devices in low-stress environments.

A standard way to characterize and compare reliability is the mean time to failure (MTTF), a statistical parameter that captures the probability of failure and is expressed as a time in years. Typical values for pressure sensors range from 100 to 1,000 years. This does not mean that a device is expected to work for 1,000 years. Rather, it means that if you have 1,000 of those sensors in the field, you can expect one of them to fail within any given year of service.

MTTF does not cover early drop-outs, such as instruments that fail immediately after installation and commissioning (those early failures should have been caught by the manufacturer and not shipped), and it does not cover failure after the end of a useful life (*e.g.,* after more than 10 years of operation).

Standard MTTF values are a direct reflection of the design quality with regard to component stress levels, as well as the complexity of the device — namely, the number of components in the system. Those two factors are the biggest contributors to MTTF values and are directly related to product functionality: the more functions that are densely packaged in a field housing, the lower the device's MTTF will be.

For example, MTTF values for smart transmitters may be in the low hundreds based on a 40°C maximum operating temperature, while standard industrial transmitters can easily have MTTF values in the 600-yr to 800-yr range, even at elevated temperature levels.

MTTF calculations often assume mild operating conditions (*i.e.,* temperatures not exceeding 40°C) in a controlled environment (*i.e.,* no vibration or rapid temperature changes). If your operating conditions are expected to be harsh, especially if instruments are operated at elevated temperatures, you should expect higher failure rates.

MTTF values are not intended to predict field survival rates, but rather to help equipment designers and users compare different designs. The cost of the downtime necessary to replace a failed instrument should be considered and be an important part in your overall instrumentation strategy.

Some remarks on test data

When evaluating an instrument manufacturer's test results, find out what standard test methods were used to perform the testing. And, before comparing two different instruments based on test data, make sure that the data were collected at the same conditions; otherwise, any attempted comparisons will not be valid.

Also find out about the functioning of the instrument during the test. There is a big difference between a sensor surviving some vibration without falling apart and a sensor operating under vibration and delivering accurate results. For example, if a sensor mounted on a machine with vibration present picks up the vibration and converts it into steadily changing output signals, that sensor will be of no use in an application that involves vibration.

According to BS EN 61326 (an international standard for testing the electromagnetic compatibility [EMC] of measurement, control, and laboratory equipment), the behavior of any device under test (DUT) can be characterized as one of four different states:

• State A — During the test, the device exhibited normal operating behavior within the specified limits (*i.e.,* it complies with the datasheet specification even if subjected to the test conditions).

• State B — During the test, functionality was temporarily reduced, and the function or performance loss self-corrected (*i.e.,* the datasheet specification was impaired during test conditions, but the DUT recovered fully after conditions returned to normal).

• State C — During the test, functionality was temporarily reduced, and recovery required operator intervention or system reset (*i.e.,* the DUT lost functionality and did not recover automatically after conditions returned to normal).

• State D — Functionality degradation could not be recovered, and damage to the equipment, components, software, and/or data was permanent (*i.e.,* the DUT suffered irreversible damage).

Although BS EN 61326 deals with EMC testing, this approach of defining a DUT's state can be broadened for other types of testing (*e.g.,* vibration, shock, etc.).

So, a sensor under test with a functional State A can be expected to perform fully as described in the datasheet, even under the level of disturbance present during the test. If the datasheet does not specify a functional state, do not assume it is A; it may well be B or C — the instrument may survive that level of disturbance, but it will not perform within the specified limits.

Ask, don't assume

Numerical values in a datasheet or specification should be questioned not only with regard to definition and standards, but also with regard to applicability to the entire population of sensors. Unless specified, those values may be maximums — *i.e.,* no product ever exceeds that value — or typical values — only some (*e.g.,* 68%) of the products exhibit this type of behavior. The instrumentation engineer may assume that all datasheet values are maximums, while the manufacturer (conveniently) states typical values that are representative of the majority of products (Figure 8). Unless there is a huge safety margin on this parameter, this could lead to hazardous situations.

The final frontier

Keep in mind that a product may not deliver the same results and longevity if subjected to a variety of environmental conditions at the same time. For example, if a manufacturer states 10 million load cycles as a design limit, does that apply at all temperatures, if vibration and electromagnetic fields are also present and the unit is subjected to corrosive substances, humidity, and mechanical shock? The instrumentation engineer may assume that the load limit still applies, but the manufacturer may have chosen to subject
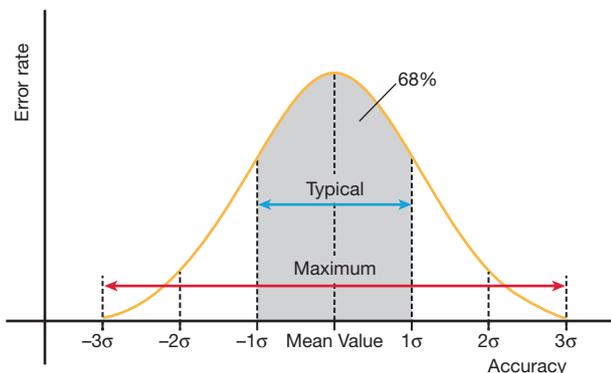
units only to one environmental condition at a time during design verification and qualification testing.

What may be a reasonable assumption for the instrumentation engineer can very well be seen as an unrealistic expectation from a manufacturer's point of view. Typically, large disclaimers in the product literature are an indication of this disconnect.

Many manufacturers use the term "compensated temperature range," and buyers may want to believe that in this temperature range all the errors are compensated for and that no errors apply. Unfortunately, that is not the case. The term compensated temperature range means that all of the stated temperature errors *fully apply* in that temperature range; outside of that range, the error is not defined — it could be any number. So, although the term "compensated" sounds like it means "taken care of" (or not present), in reality, it means that the error does apply.

Closing thoughts

Once you have all the facts, you are equipped for the final, and probably the most difficult, task — to apply those facts to your specific application. That is sometimes easier said than done, and involves a dilemma: Should you play it safe, over-specify, and pay the additional price? Or can you make a smart choice by striking the right balance between what is really needed and what is added as a "comfort factor"? The difference can easily be worth a thousand dollars or more on a single instrument. With the sheer endless selection of products, and very little standardization in place, this task can become quite a challenge.

Fortunately, any reputable manufacturer or supplier should have skilled salespeople and technical support groups that will help you to make the right choices for your particular application. Selecting the best pressure sensor requires a deep understanding of the functional principles and an investigative mind when it comes to reading and understanding manufacturers' data and specifications. Does it pay off? It certainly does in most cases. This is especially true if you are selecting instruments for a performance-critical application. A rigorous selection process should be mandatory if the application is critical to safety. **CEP**

▲ **Figure 8.** Values in datasheets are often assumed to provide a complete picture of the characteristics of an entire population of products (*i.e.,* a maximum value, represented by the red line). However, they may actually be typical values (blue line) representative of only a portion of the sensors.

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