Contributed Paper

Tech Talk: (8) Instrument Measurement Performance

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David Otterson
Institute of Measurement and Control, Billingham, UK
davidotterson@ntlworld.com

Tom S Nobes
CE&I, Capabilities Leader, Sellafield Ltd, Warrington UK

I. Introduction

This paper describes the definitions, the interpretation and the impact of process instrument measurement errors and their allowable tolerances. This includes familiar terms like 'accuracy', 'hysteresis', 'error' and so on, and less familiar terms like 'distribution' and encourages the application of a simple, uniform and coherent method of specifying process instrument measurement accuracy and switching tolerances.

It gives the reader

- An overview of terms and definitions used in process instrument measurement,
- Guidance on how instrument performance is determined and stated by a manufacturer.

II. Parameters Used in Process Instrument Settings

A. Overview

Every measurement is subject to error. Error is simply a deviation from the truth and may be characterised in a number of ways. A measurement statement is only complete if it is accompanied by a statement about its accuracy. Historically, the definition of process instrument accuracy has proven to be a 'minefield'. This has led to considerable confusion between Process Engineers, Control and Instrument Engineers, instrument manufacturers and Operations and Maintenance staff with regard to the realistic performance expectations of process instruments.

Performance figures (particularly accuracy) quoted by instrument manufacturers are often taken as fact, or at least taken on face-value, with no consideration of how they were derived nor any constraints required to achieve them.

Usually, process instruments are designed for realistic operating conditions (those likely to be encountered in factories and on process plants) and should be evaluated under these same conditions. Unfortunately, it is not practical to evaluate performance under every possible combination of operating conditions. For this reason, instrument manufacturers will undertake evaluations in laboratory (or 'Reference') conditions, and those results will be quoted in their sales brochure.

Process instruments are sold in a competitive market, and manufacturers are engaged in an 'arms race' for better performance. This competition occasionally leads to performance figures that are perhaps only achievable under specific and limited conditions. Experience has shown that when installed on plant, the actual instrument performance is often inferior to the 'Reference' conditions.

B. Why Controlling the Accuracy on Process Instruments Is Important

We may be interested in measurement accuracy for several reasons including the following:

- The measurement is used in financial or other inventory control;
- The measurement is used in product quality control or environmental discharge monitoring, where unknown accuracy may have legal implications;
- The measurement is used in a Safety Instrumented System (SIS), for example, for vessel overfill detection.

C. Where Do the Measurement Errors Come From?

It is impossible for any process instrument on plant to take a 'perfect' measurement because we have no perfect instruments operating in perfect conditions. Errors may arise from the following:

- Changes due to ageing, wear, poor readability, electro-magnetic compatibility (EMC), ambient temperature, vibration and so on.
- Process deviations from the flow sheet, flow-diagram (or more importantly the process instrument data sheet) defined it, for example, static pressure may be higher or lower, 'clean' liquids may actually contain suspended solids, 'pure' sample gas may contain impurities (like water vapour), liquid levels may have scum or foam on the surface and so on.
- The measurement is not straightforward, for example, ultrasonic flow meters send a signal through one metal pipe wall, into the liquid and out through the opposite pipe wall. Poor ultrasonic coupling with the pipe and deviations to the

expected pipe dimensions and material may influence the measurement. Almost all gas analysis and pH measurements (pH is a measure of the acidity or basicity of an aqueous solution) present notoriously difficult non-linear measurements.

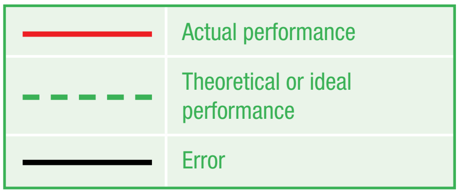
- Where analogue instruments are used, reading accuracy is affected by the limit of the human eye to determine the scale graduation under the pointer. Here, there are two aspects: (1) accuracy is often quoted as a percentage of full-scale deflection (FSD), so readings are more accurate when the deflection is near full scale; (2) the spacing between scale graduations means one might be only able to say the reading is on graduation n, n + d or half way between –n+d/2, so the reading can only be given to an accuracy of d/2. In addition, a parallax error may be introduced as a result of the relative positions of the reader's eye, the instrument pointer and the fixed dial. A simple everyday example of parallax can be seen in the dashboard of motor vehicles that use a needle-style speedometer gauge. When viewed from directly in front, the speed may show exactly 60; but when viewed from the passenger seat, the needle may appear to show a slightly different speed, due to the angle of viewing.
- Calibration test equipment, unless itself calibrated and maintained to a sufficiently greater accuracy than the instrument under test, may add significantly to the measurement uncertainty.

D. How Process Instrument Terms Are Defined

Popular definitions are compliant to international standards American National Standards Institute (ANSI)/ International Society for Automation (ISA) 51.1:1979.[1] It is important to know that documents published by different organisations or in different countries may use different definitions. For example, the word 'span' and 'range' are often transposed.

III. Individual Measurement Errors

There are many types of individual errors that are quoted in process instrument brochures. However, there are usually only five (excluding reading errors) that manifest themselves in industrial applications. In all figures, the following key applies:



The following text describes errors appearing under static (as against dynamic) conditions.

A. Zero Error

Zero error manifests itself as a constant deviation (either positive or negative) between the input and output (*Figure 1*). For example, if a pressure transmitter ranges from 0 to +2000 mmWG (millimetre Water Gauge (pressure)) but actually reads from +5 to +2005 mmWG, the error is constant at +5 mmWG. This is known as a 'zero offset' or 'bias'.

Zero error can often be identified without the use of calibration test equipment (e.g. the pump is switched off, but the flow meter shows a + or – reading). Often, it is associated with instruments having being damaged by process conditions beyond their rating.

B. Range Error

Range error as depicted in *Figure 2* is the difference between the actual upper range value (URV) and the required URV. Here, the reading error will increase in proportion to the transmitter input.

C. Hysteresis Error

Here, the error magnitude and direction are dependent upon which direction the input is moving (see *Figure 3*).

Figure 1. Zero error

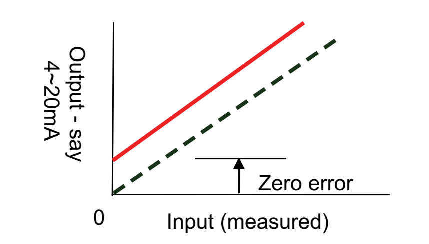
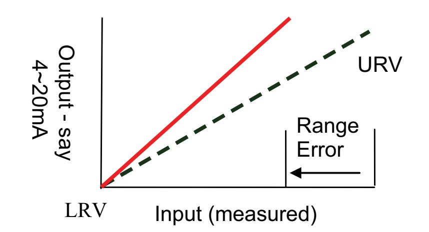
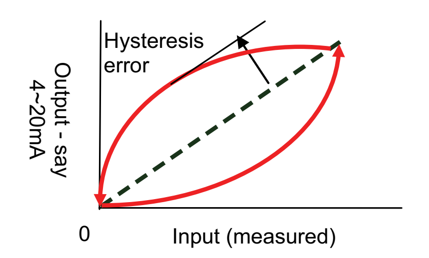


Figure 2. Range error. Range error is shown here as a positive error, but it can also be negative error. It is also wrongly called a 'Span error'



LRV: lower range value; URV: upper range value.

Figure 3. Hysteresis error (exaggerated)



At zero, the input and output align. As the input rises, the output lags behind the input (the lower curve), thus the output is always less than the input, all the way up to 100% input. On reduction of input, the output now lags behind the input (the upper curve), thus the output is always more than the input. Graphically represented hysteresis error often produces a trapezoid or ellipse shape, but can also produce other shapes.

Hysteresis error is often difficult to identify and quantify. It often affects the accurate operation of safety trips and the positioning of final control devices such as control valves.

Its main causes are

- Mechanical wear in linkages, hinges, bearings and so on;
- Age-hardening, work-hardening or damage to measurement diaphragms, bellows and so on;
- Friction in moving parts.

Mechanical instruments are very prone to hysteresis error, for example, control valve actuators, limit switches, pressure switches, thermostats and so on, because their mechanical moving parts wear and become slack.

Modern 'smart' microprocessor based instruments are less prone to hysteresis error as they have almost no moving parts. Surprisingly, hysteresis can often be a benefit to some instrument loops, particularly loops where it produces a slight delay or lag that avoids switch 'chatter' (i.e. repeated, nuisance switching on and off).

D. Linearity Error

Here, the error magnitude and direction can be complex.

In *Figure 4*, at zero, the input and output align as the input rises, and the error is negative and variable. At some point, the error becomes positive and still variable. By nature, linearity error has no fixed shape, but it often produces a 'snake' shape.

Linearity errors manifest themselves mostly in analysis instruments. This is often because the measurement itself is non-linear, pH and conductivity being good examples.

The signal processing capability of modern smart instruments allows manufacturers to greatly reduce linearity errors.

E. Drift Errors

Drift manifests itself as an error that changes magnitude or direction over time, for example, *Figure 5* shows a level gauge ranging from 0 to +2000 mm

Figure 4. Linearity error

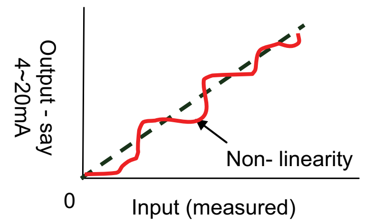
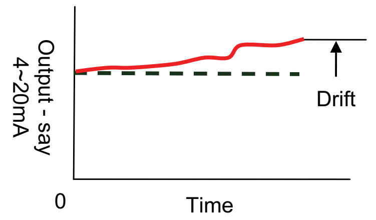


Figure 5. Drift error



reading 1050 mm. The level has not changed in a long time, but the reading on successive days does.

Process instruments can drift over prolonged periods, but it is equally true we often wrongly diagnose the causes of drift. It is important to remember that drift is not some kind of inherent feature of process instruments but usually occurs because something has happened to the instrument. Reasons include the following:

- Changes to ambient conditions (temperature, vibration, blockages, etc.);
- Wear, ageing and physical damage;
- Poor proof-test or poor routine calibration, that is, every time the process instrument is maintained, it gets 'adjusted'. At the next maintenance, it gets 'adjusted back'. This back and forth is reported as drift, when it is often just an unrealistic expectation by the plant operators or over-enthusiasm on the part of the instrument technician.

Hysteresis is also often wrongly diagnosed as drift (e.g. when the differential pressure (dp) switch did not switch at the precise point, it may be wrongly attributed to drift).

IV. Combining Process Instrument Errors

As if the five main errors were not bad enough, we remember that every instrument will suffer from most, if not all, of these five errors. Fortunately, the magnitude of each error is usually very small in modern process instruments. So how do we express these combined instrument errors? There are two ways:

1. Simply add the individual errors together to obtain the total error:

that is

Zero + Span + Linearity + Hysteresis + Drift

that is, (±0.1%) + (±0.2%) + (+0.5% to −0.9%) + (+0.1% to −2%) + (±0.5%) gives

Positive errors = +0.1 + 0.2 + 0.5 + 0.1 + 0.5 = +1.4%
Negative errors = −0.1 + −0.2 + −0.9 + −2 + −0.5 = −3.7%

Total worst case error is +1.4% to −3.7%.

It is very unlikely that any process instrument would be as bad as this (i.e. it is difficult to see how a single instrument could possibly have the extreme values of every individual error. As practical examples, the instrument ambient temperature cannot possibly be at say −20°C and +50°C at the same time, the range cannot be at both ends of the span at the same time and so on.

2. Combine the individual errors into a combined error. This method takes the root-mean-square values of the individual errors.

Using the same figures as above

$(Zero^2 + Span^2 + Linearity^2 + Hysteresis^2 + Drift^2)^{1/2}$
gives

Positive going errors = $(+0.1^2 + 0.2^2 + 0.5^2 + 0.1^2 + 0.5^2)^{1/2} = +0.75\%$
Negative going errors = $(-0.1^2 + -0.2^2 + -0.9^2 + -2^2 + -0.5^2)^{1/2} = -2.26\%$

Combined error is +0.75% to −2.26%.

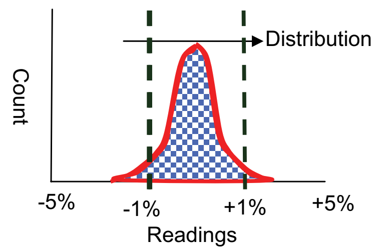
V. The Distribution of Errors

We enter the world of 'statistics' and it can be complex. However, we usually need to understand just one statistic, the 'error distribution'.

In the example in *Figure 6*, a manufacturer has developed a new mass-flow transmitter. His desired accuracy is ±1.0% of reading. In a series of tests, he cycles the transmitter between 0 and say 500 kg/h many times and notes the transmitter readings. Some are a little more than 500 kg/h, some a little less. He plots the readings on *Figure 6*; each blue dot is one of the many readings. The test is then complete.

He then calculates the average value of all the readings and marks this on the graph, then marks every individual reading for each test. In this case, a very few readings were beyond ±1.0%, some were within ±1.0% and most were effectively 'spot on'. This often results in a near normal or Gaussian distribution, allowing the manufacturer to describe the distribution by a mean value and a standard deviation.

Figure 6. A 'normal' distribution



From the diagram, the manufacturer determines the following:

- Of the many readings, 99.7% of them were within ±1.0%;
- Only a few were outside ±1.0%.

If 99.7% or more of readings are within the stated accuracy, this is a 3 sigma distribution, where sigma is the standard deviation.

The manufacturer can now claim that

- Accuracy = ±1.0% of mass-flow rate reading;
- Specification performance is to 3 sigma.

In other words, if you install and maintain the instrument to the manufacturers specifications, you can be 99.7% sure that every reading you take will be within ±1%.

In conclusion, uncertainty can be claimed as being

- 3 sigma, if 99.7% of the readings fall within the stated accuracy;
- 2 sigma, if 95.0% of the readings fall within the stated accuracy;
- 1 sigma, if 68.0% of the readings fall within the stated accuracy.

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Reference

1. ANSI/ISA 51.1:1979. Process instrument terminology (R1993).