TERMINOLOGY USED IN INSTRUMENT ACCURACY

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The purpose of this paper is to offer a brief explanation and discussion of many key terms used in describing instrument accuracy. The terms included within this discussion are most commonly used for defining performance standards with primary sensing elements typically used in the measurement of flow, level pressure and temperature instruments. Many of the terms used may apply to controllers, recorders and final control elements. However, the focus provided herein is the primary element device. The specific devices include transmitters (differential pressure and temperature) and flow meters (*e.g.,* magnetic, vortex, turbine, variable area and positive displacement).

This paper is written for the benefit of the typical user of instrumentation products to include instrument engineers and technicians. A comprehensive discussion of precision measurement must address calibration and traceability issues. The scope of this paper will be limited to discussing the terms associated with the application of instruments rather than addressing the issues of maintaining accuracy. Calibration is a key issue in determining the continuous performance of an instrument and is worthy of discussion. However, it is complex enough to warrant a separate discussion.

A fundamental understanding of gas laws and the effects of compressibility are necessary for selecting and applying instruments used for gas measurement. This is obvious since the majority of the flow measurement devices used in industry are volumetric, and volume changes under actual conditions. We will begin our discussion with the assumption that this base understanding exists. There will be no debate regarding the merits of direct or indirect mass measurement devices nor a comparison the advantages of mass measurement over volumetric. The decision to use any specific technology for a solution must be weighed upon the need for mass measurement vs. volume, the accuracy requirements from the measurement, the overall installed cost of the solution while taking into consideration user and industry standards and the additional ownership costs affected by maintenance and life expectancy of the product.

Many of the concepts discussed herein will be painfully obvious to the experienced instrument user. The goal is to provide a logical discussion of most key terms and thereby offer a condensed reference guide for any user of instrumentation products. These terms cross the boundaries of ISA, ASME, AGA, ANSI, API and various manufacturers' terminology.

ACCURACY TERMS

Accuracy is a composite statement of performance that defines the quality of the instrument measurement. It is the difference between the reading of an instrument and the true value of what is actually being measured. Accuracy is normally expressed as plus or minus a percentage of either reading, calibrated span or the full scale of the instrument. Accuracy is one of the most critical factors to consider when applying an instrument for a given application. Accuracy is also a term that is most misunderstood by the typical user. The reason for this misunderstanding is due to the myriad of effects on instrument accuracy and the ability of manufacturers to offer varying interpretations for the expression of instrument accuracy. In the world of marketing this is commonly known as creative "specmanship."

ACCURACY STATEMENTS

- % Reading (% Rate)
- % Calibrated Span
- % Full Scale
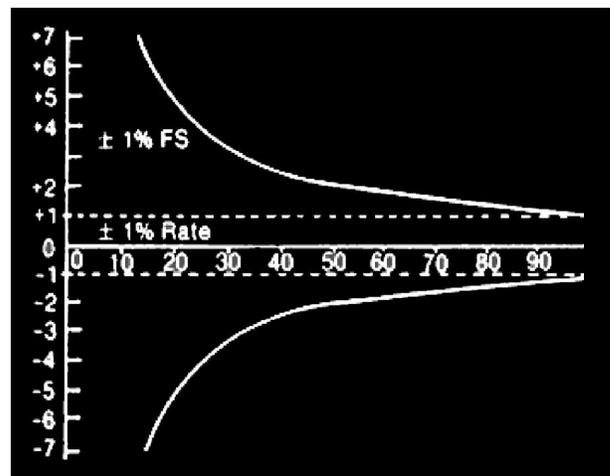
% Input

FIGURE 1.

As stated in the discussion on accuracy, the specification may be expressed in terms of a percentage of reading, calibrated span or full scale. As illustrated in Figure 1, the comparison is enlightening. An instrument accuracy stated as a percent of reading maintains a constant window of error throughout the measurement range. A device with an accuracy expressed as a percent of span or full scale possesses an ever-widening envelope as

the measurement reading moves farther downscale. This makes it imperative that the user operates the instrument as high as practical in the span in order to maintain accuracy.

Absolute accuracy is a term that defines how the performance of an instrument relates to a traceable standard.

Composite Accuracy includes the total effect of accuracy, linearity and repeatability on an instrument at reference conditions.

Reference Accuracy is the baseline accuracy for many instruments. This specification does not include some of the effects that cause instrument error such as temperature and static pressure effects. Reference accuracy is the percentage of error associated with the instrument operating within designed constraints under reference conditions. This is the most liberal of accuracy statements and is commonly misinterpreted as a benchmark for evaluating one instrument against another. To further confuse the user, this accuracy statement may not take into consideration errors induced by the output mode, such as the error associated with digital to analog conversion necessary to obtain a current output.

Reproducibility is an ISA term that is the combination of linearity, repeatability, hysteresis and drift.

System Accuracy is a term used to define the overall accuracy of a process measurement involving more than one component used in series or parallel. This is an excellent means to determine the total error induced on a process variable that will be used for recording or controlling purposes. Individual instrument errors must be calculated as an error of reading (not a percentage error) for a given measurement point. The combination of errors then is averaged using a statistical approach such as taking the square root of the sum of the squared errors. For example, a flow instrument has an error of plus or minus one percent of calibrated full scale. The scale is 0-100 SCFH. The reading is 50 SCFH. The error is plus or minus 1 SCFH. The recording or controlling device has an error of plus or minus one half percent of range. The range is 0-100 SCFH. The reading is 50 SCFH. The error is plus or minus .5 SCFH. Using the formula: $(1^2 + .5^2)^{1/2}$ = a system accuracy of plus or minus 1.1 SCFH.

TERMS ASSOCIATED WITH ACCURACY

Damping does not affect instrument accuracy but does have an effect on the quality of the control loop. Damping is used to slow the response of the instrument to process changes. It is necessary to use damping when there is process noise and/or input fluctuations that are undesirable for control. Damping may be implemented by mechanical or electrical conditioning. Damping is a means to average the process variable over time in order to stabilize the output to the controller. For that reason

(particularly with electronic means) the adjustment is expressed in terms of "seconds" of damping. Damping may be applied to an instrument with poor installation technique or inappropriate application of the instrument for the process. For this reason, it is important to recognize when applying damping that the need is valid.

Deadband: All instruments exhibit a point where some change in process data cannot be measured. This error is commonly expressed as a percent of reading. Deadband is simply the ability of the instrument to react to small process variable input changes. Deadband may be associated with resolution because it does affect the ability of an instrument to measure continuous data. However, resolution addresses the ability to continuously measure the process variable. Deadband only addresses the ability to monitor minor changes from a given process variable reading. An instrument with a deadband of plus or minus one tenth of a percent and a span of 100 psi has the ability to not read small changes of plus or minus 1 psi at any reading point. If a resolution of plus or minus 1 psi is necessary, a tighter span or an alternate technology is advised. Deadband has an effect on instrument accuracy when very small changes are expected.

Filtering is sometimes confused with damping. Filtering is actually the ability of an instrument to accept or reject an input signal. There is more than one interpretation for filtering an instrument signal. Filtering is commonly used to ignore intermittent spike input signals to the instrument that may not be actual changes to the process input. For example, noise may be measured by vortex flow meters or magnetic flow meters from hard solids in a liquid flow application. The solids interfere with the continuous measurement of the flow signal by introducing an error normally interpreted as a flow spike. Damping of the signal may help to alleviate the problem. However, this type of signal spike is irrelevant to the measurement of the process. Therefore, the ability to ignore the spike is advantageous. Another common type of filtering is the use of capacitors on a DC power supply to minimize the effects of AC ripple voltage.

Hysteresis: A true and accurate measurement of a process variable shall yield a beginning measurement and an ending measurement cycle that is equal. That is, the upward curve from zero to one hundred percent and the downward curve from one hundred percent back to zero are identical. Any deviation from these two curves is defined as hysteresis. Hysteresis is also linked to deadband. Since deadband affects the ability of the instrument to react to small instrument input signals, this effect amplifies the hysteretic error.

Linearity is described in ISA Standard S51.1 as the deviation from the calibration curve of an instrument from a straight-line relationship between zero input and 100% input. Ideally this is a forty-five degree slope. Most instruments do not possess a linear output with respect to input under reference or actual conditions.

Depending upon the instrument, there are many variables that can affect linearity. For example, most differential pressure transmitters use a sensor technology that is inherently nonlinear under reference conditions. As process and ambient temperature and static pressure change during actual conditions, there are effects on linearity. Pressure transmitters vary by class. A baseline for a pressure measurement is the common pressure transducer. The transducer converts a pressure signal input into a voltage signal output. A pressure transmitter extends the pressure input range and typically provides for a current output in order to extend the transmitted distance. There is the added value of compensation for these transmitters to stabilize the output for the negative effect of temperature on the linearity of the output. This transmitter class is referred to as conventional. The pressure effect is compensated by zero adjustment while under static pressure conditions. The top of the transmitter class is referred to as "smart" due to the added capability of higher performance standards and the ability to offer intelligent communications from the transmitter for configuration and diagnostics information. Smart transmitters have multivariable sensors for temperature and pressure compensation. The sensors feed information to microprocessors that manipulate the output by comparing the input process variable, ambient temperature and static pressure (flow transmitters) with a characterization algorithm stored in an EPROM within the transmitter. The characterization feature of smart transmitters offers the ability to accurately produce an output with respect to input change as the actual environmental conditions change.

Piping effects (flow profile effects): The installation of the instrument has the potential for greatly affecting accuracy. Whether the application is liquid, gas or steam, the flow profile entering the instrument typically dictates the ultimate performance. Reynolds number constraints, turbulence, grounding, buildup on pipe walls, degradation of orifice plates, positioning of elbows, valves, reducers, cavitation, multiphase flow, internal pipe imperfections and other variables all play into the ability of a specific instrument technology to measure accurately. It is beyond the scope of this paper to address these effects. Many instruments are blamed for incompetent measurement when actually those instruments have suffered from incompetent installation guidelines. The guidelines for standard installation applications are difficult to keep up with. To complicate the issue, manufacturers vary on the recommended installation practices for a given technology. This adds to the confusion for users. The point is that it is reasonable to adhere to the manufacturer's recommended installation practices. This should be compared with industry standards such as those published by ISA and API.

Pressure effects on instrument accuracy typically apply to the static pressure effect on zero or span of a differential pressure transmitter. For conventional transmitters, this error may be partially resolved by adjusting the zero while the transmitter is under operating line pressure. If there are swings in operating pressure, then this error cannot be properly compensated for with conventional transmitters. New generation smart transmitters offer characterization with the ability to sense pressure changes and automatically correct for the error thereby minimizing the effect.

Rangeability is closely linked with turndown. Most instrument technologies offer the ability to adjust the measurement range. It is important to discuss rangeability because the use of instruments is limited to certain ranges in order to maintain accuracy. Instruments may be over-ranged and operate reliably within design limits. However this is often at the sacrifice of some accuracy. The degree by which an instrument may be over-ranged depends upon the technology and the manufacturer of that technology. Under-ranging an instrument often has negative effects on accuracy. Some accuracy statements qualify the degree of accuracy depending upon where the instrument is operated within the span capabilities. A case can be made that liberal use of range application can save the cost of ownership by reducing the number of spares. After all, a transmitter with a maximum range of 100 IWC and a minimum range of 5 IWC can be used for the 70 IWC and the 10 IWC applications. However, the combined possible errors as stated in typical specifications will yield lesser performance on the lower span. Prudent users will apply the appropriate range as they would use the proper tool for the job and carefully evaluate the desired results.

Repeatability is the ability of an instrument to precisely duplicate a measurement while operating under the same conditions while the input signal is made in the same direction. The input signal may be consecutive movements from zero to one hundred percent or vice versa. Many individuals believe that repeatability is as valuable as a high degree of accuracy. In actuality, good accuracy cannot be achieved without good repeatability. What causes poor repeatability? The instrument has a poor repeatability specification, the instrument has a defect, or there are one or more influences causing the problem with a good instrument. Some of these influences are piping installation problems, cavitation from valves and pumps, hammering from vapor pressure problems, temperature changes (ambient and process), noisy power or grounding and vibration.

Resolution is the ability of the instrument to continuously measure and transmit all process variable data. In digital systems the smallest interval that exists between two measurement samples defines resolution. Most current technologies offer microprocessors for the benefit of enhanced performance. The tradeoff from the use of microprocessors is speed and resolution. Digital measurement involves sampling of the process variable. While the process variable is being sampled, there may be small dead spots where process data is lost. On many smart instruments, there may be multivariable data sampled. Microprocessor instruments typically process

input information via analog to digital converters. The resolution of these types of instruments is dependent upon the resolution of the converters. For example, a twelve bit resolution A/D converter has the resolution to within $1/2$ of 4,096 counts or in electrical terms 1 mV for a 2.048 volt input. Converters include signal conditioning, sampling, multiplexing and conversion processes and there are accuracy and linearity specifications tied to converter. This is may or may not be incorporated into the accuracy specification of the instrument. In addition, there are roundoff errors to consider with converters. New technology is enhancing the ability to increase the resolution and accuracy of converters. The fact that this resolution error exists is not all bad. It must be considered however in the application of the instrument.

Other sources of resolution errors involve the specific technology used. DC Pulsed magnetic flowmeters sample a portion of a process variable at a fixed frequency typically between 7.5 Hz to 30 Hz. The lower the frequency equals lower resolution and therefore inadequate response time for noisy slurry applications or fast acting positive displacement pumps. Vortex flowmeters interpret vortex swirls commonly using piezo-electric sensors that appear to the electronics as a square-wave pulse input. The frequency is directly proportional with the velocity of the fluid. As line size increase each pulse represents larger volumes of flow thereby reducing resolution. Fieldbus networks offer an advantage of transmitting multivariable data as well as diagnostics from instruments. The data obtained from fieldbus instruments is valuable but because the data is intermixed with multivariable and diagnostic data. Since this data is shared with data from other instruments over the same wires, Fieldbus strategies must be weighed with the need for resolution and response time. Smart instruments with built-in PID algorithms help to address this issue by truly distributing the control to the field where the primary and final elements are co-located.

Many current technologies involve a means of sampling data in order to provide an output that implies real process conditions. Near instantaneous measurement is possible with some analog instruments but is not possible with instruments with digital electronics. Oddly enough, there is an explosion of accuracy statements that imply enhanced performance from smart (by default digital) instruments. The accuracy statements are correct but the response time and resolution of the instrument must be taken into consideration to qualify performance. The ability of an instrument to respond to and transmit process data quickly is important for some critical flow or pressure applications associated with fast-acting positive displacement pumps, compressor control and safety systems.

Response Time is the ability of an instrument to react to process variable changes. This is closely related to the terms resolution and damping. Most electronic instruments have a delay from the moment the process variable changes and the moment the change is indicated by the output signal. This delay will depend upon the type of instrument, the circuitry design (analog vs. digital), the deadband for the measurement reading, and the setting of damping adjustment that may exist on the instrument. The time delay in producing an output signal is typically expressed in terms of milliseconds. A very fast response time will be less than ten milliseconds. This type of device is appropriate for fast acting pressure measurement such as compressor applications. Microprocessor instruments may have a response time expressed in hundreds of milliseconds. These instruments may be very accurate and appropriate for many flow, level and pressure applications. A common sense approach is to compare the measuring instrument with the controller. Comparing the response time of the instrument with the desired sampling and execution rate of the controller provides data that is helpful in making a qualified decision about the use of that instrument for an application. A controller with sampling and execution rates in excess of 500 milliseconds does not necessarily need an input device with a response time of ten milliseconds.

Reynolds Number Effects: Reynolds number (Re) is defined by formula as the velocity of the flow times density times pipe diameter divided by viscosity. This specification is important for flow meter applications. A great deal of time may be used to discuss Re. To keep it simple there are fundamentals that help to keep this concept into perspective. First, there is the difference between laminar and turbulent flow. Re numbers below 2,000 are laminar. Between 2,000-4,000 the Re is transitional. Above 4,000 the Re is turbulent. Most flow meters need a Re in the turbulent region to operate accurately. The Re calculation is relatively straightforward. If this calculation is strictly applied and other installation requirements are adhered to, then the instrument should be expected to perform within specified tolerances.

Span Shift may have a negative effect on the accuracy of an instrument. If an instrument span is changed, there needs to be a calibration verification of the change. The instrument should be expected to perform within published specifications providing that a calibration device is used to confirm the zero and span of the instrument. Again, on pressure transmitters, temperature and pressure effects may cause span shift. Also, adjustment of zero alone may affect the span.

Temperature effects must be broken into two categories: process temperature effects and ambient temperature effects. Process temperature affects instrument performance in two ways. For liquid processes temperature variation has an affect on viscosity. For those flow instruments that are viscosity sensitive, the variation in viscosity must be understood and compensated for or there will be an error associated with the viscosity shift. Secondly, many sensors are typically located in close proximity to the process, there is the potential for an effect on the sensor with process temperature

variation. In addition, for gases there is an effect on the mass calculation with respect to temperature changes.

Ambient temperature has an effect on many sensors and electrical components. Those instruments with an analog current output typically have a higher error associated with ambient temperature changes than the instruments that use either a pulse output or a digital communications output. An instrument specification must be scrutinized to determine if the accuracy statement is qualified to include the temperature effect for the type of output intended. Depending upon the technology, ambient temperature may have an effect that is equal to or greater than the reference accuracy of the instrument. Ambient temperature may affect both zero and span of an instrument.

Turndown may be expressed in more than one way depending upon the instrument technology It may be expressed as either the ratio of the maximum measurement capability to the minimum measurement capability while maintaining accuracy, or as the ratio of the maximum span capability to the minimum span capability while maintaining accuracy. The latter definition normally applies to pressure transmitters and must be carefully evaluated for a given application. Instruments universally have a point on the low end of the scale where accuracy degrades. Specifications must be qualified to determine where accuracy falls off and to what degree the degradation occurs. Turndown is a term where much creativity is used with "specmanship."

Uncertainty and accuracy are closely related. However, uncertainty is more definitive when used in the context of instrument and system errors. This is due to the strict guidelines and equations associated with flow instrument standards. Uncertainty must take into consideration the actual operating conditions. Formulas used to calculate are common in flow measurement. An example of a standard formula can be obtained from ANSI/ASME MFC-2M-1983 titled "Measurement Uncertainty for Fluid Flow in Closed Conduits." The uncertainty revealed in these types of calculations are important in that they take away the focus on individual instrument errors by assigning a relative importance for each variable that impacts the flow calculation. These formulas introduce two very interesting concepts. First is the concept of two types of errors: Bias vs. Precision. Bias error may be obtained from the manufacturer specifications. Precision error is calculated using independent comparison tests. This concept is worthy of discussion for two reasons. First, bias error is commonly referred to as reference accuracy. Since instruments are not used under reference conditions, this accuracy statement is not valid. The errors associated with having an effect on reference accuracy should be taken into consideration. Second, not all manufacturers use the same standard to publish specifications. Some are more conservative than others in order to mass produce instruments. For a given product, there may be variance in absolute accuracy from one instrument to the next, although all the instruments in a particular class would meet the published

specification. This is obviously done with the intent to reduce manufacturing costs. Precision error calculation may allow for evaluation of a population of like-products in order to determine worst case and average accuracy. Taking into consideration the effects of temperature and pressure on accuracy requires some sophisticated test equipment that is normally associated with independent laboratories. Of course independent evaluation may reveal the conservative nature of some manufacturers to understate product specifications.

The second important concept revealed from the use of standard flow calculations is the use of "square root of the sum of the squares" for all errors after a weight has been applied to the individual errors. Because of the fact that errors are expressed in terms of plus or minus, it can fairly be argued that no instrument is likely to indicate a worst-case scenario whereby all of the combined errors will sum to a total error in one direction or the other. The use of the square root of the sum of the squares offers a fair averaging of these errors. A simple example of this analysis is given under "system accuracy."

Zero Shift is caused by numerous factors. What causes this error? The answer should be evident within the published product specifications. Zero shift that is measured outside the specifications might be caused by such variables as power or ground induced noise or a defect within the product. Process and ambient temperature effects and process pressure changes on some devices might inhibit the instrument to reproduce a zero input. Some technologies offer a feature to perform auto-zeroing to minimize zero shift. Smart transmitters offer real-time temperature and pressure compensation to help minimize the effect. The knowledge that zero shift can affect your measurement will help to define a calibration program to correct for this problem.

Other sources of error include mounting position effect of the instrument, RFI interference, power supply influenced error and gross calculation errors in the controller. The terminology used to describe instrument accuracy is broad with some overlap. There is casual misuse of some of these terms by users and sales people whereby confusion is created in the marketplace. Care must be exercised to learn the terminology and apply it appropriately.

The ability of an instrument to perform accurately is dependent upon many variables. It is the human factor in the equation that ultimately determines how well a technology performs. Process knowledge must be coupled with the knowledge of instrument technology and proper installation techniques to ensure success. Process operations and support personnel are living in a world of ever tightening constraints with higher performance expectations. The tools available to help guide the way are imbedded in the knowledge base of those who have been there before. A wealth of data is available in the form of text books and technical papers and bulletins. This author is grateful for the availability of

these tools and acknowledges authors of those sources by offering a list of valuable references.

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