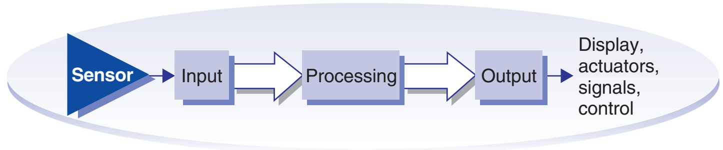

Sensors: The First Stage in the Measurement Chain

Part 2 in a series of tutorials in instrumentation and measurement

Kim R. Fowler and John L. Schmalzel

In Part 1 [1], we set up the context for the tutorial articles by addressing the question of why we measure. Hence we introduce many of the common sensor strategies that constitute the first stage in the measurement chain. While every element of that chain is important, the choice of an appropriate, robust sensor is one of the critical decisions that must be made.

Sensors are ubiquitous. Your automobile, if built within the past 20 years, has many sensors: manifold pressure, oxygen concentration of the exhaust gases, temperature, and airbag accelerometers, to name just a few. Formula One race cars now have over 150 sensors that communicate via wireless telemetry to the engineering team; these can be sampled up to 1,000 times each second, which can create as much as 2 Mb of data per lap of the race track [2].

This article, the second within the tutorial series, will continue to use examples from test stands for testing rocket engines, as was done in Part 1. Measurements of the weight of liquids, their temperatures, and their flow rates in these rocket engine test stands require sensors and the understanding of how to use them.

Sensors Versus Transducers

These two terms are regularly interchanged because they identify the same thing—almost. A transducer changes one form of energy to another, whereas a sensor produces an electrical output regardless of the energy input. That is, sensors are a subset of transducers. A voice coil speaker, for example, is a transducer because it converts electrical energy to mechanical displacement. (The voice coil is also an actuator, which is an output device; we will address these in a later issue in this series.) In comparison, the piezoelectric element found in one type of accelerometer is a sensor because applied mechanical force creates an electrical output. Sensors are the natural inputs to a measurement system, producing electrical signals that directly interface to the signal-conditioning element. (The topic of signal conditioning follows after we finish with sensors.)

First Steps—Understanding the Measurand

Every measurement has a target—a physical parameter of interest. Termed the *measurand*, this is what drives the entire measurement process. The measurand could be a certain property of a material or a condition of a process. In each case, a single

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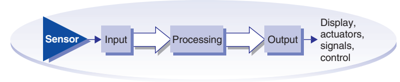


sensor or a collection of sensors is needed to selectively transduce the desired measurand. The electrical signals from the sensors are input to the instrumentation chain to ultimately produce the measurement of the measurand. Examples of possible outputs include a microstrain of 2.4, a temperature of 534 °C, or an acceleration of 0.6 m/s^{-2}. The majority of applications involve some common measurands; Table 1 summarizes many of these along with representative sensors for each.

Sensors as Black Boxes—For Now

Every sensor has a characteristic input (stimulus)-output relationship, which is the transfer function. The transfer function defines how the output electrical signal depends on the input stimulus. The definitions that follow help describe the transfer function of a sensor (Figure 1) [3].

No attempt will be made here to delve into the inner construction and working of each sensor type and its transfer function. In the next installment of the tutorial, some sensor models (transfer functions) will be included because they will be needed to understand some of the signal conditioning issues and approaches that must be employed.

There's Plenty More to Consider

Once you map a measurand to a set of possible sensors that appear able to do the job, you must address another layer of issues. Every application will have a unique set of requirements (these relate to the transfer function of the sensor) that need to be sorted through to arrive at the best choice of sensor. The following list contains some issues that are likely to prove important in your application. Before diving headlong into what may be a painstaking process, try asking first:

- Before going through a potentially complicated screening exercise, it's a good idea to check with the resident brain trust. You are likely to find that a certain sensor has been prequalified for your particular application. Even if there isn't anyone handy to ask, check out the sensors in similar areas. It doesn't make much sense to spend lots of time proposing a sensor for a routine application that may require a lengthy qualification process or find that you've rediscovered the existing sensor of choice.

Consider the following list of issues if you don't get the answers you need or if you are navigating uncharted waters for your organization:

- *Span or range:* What are the smallest and largest values of stimuli the sensor reasonably will encounter (Figure 1)? You need to determine the useful range of the sensor—does it encompass the anticipated span of the intended application? If the dynamic range of inputs is very large, then the units may be expressed logarithmically in decibels, which are ratios of power or force.
- *Full scale output:* What is the maximum excursion of the output electrical signal? That is, what is the difference between the minimum output for the smallest input stimulus and the maximum output for the largest input stimulus (Figure 1)?
- *Accuracy:* How much does the measured value—the output from the sensor—deviate from the true (NIST-traceable) value of the measurand? Does the selected sensor offer the accuracy required by the application? (Please note, accuracy is not the same as resolution! They are

Definitions

Transducer: changes one form of energy to another (e.g. a mercury thermometer transforms thermal energy into expansion of the liquid metal).
Sensor: produces an electrical output regardless of the energy input or stimulus (e.g. a baby thermometer uses a thermocouple and conditioning circuitry to convert thermal energy into an electrical signal that represents temperature).
Measurand: a physical parameter of interest, it is the stimulus (e.g., thermal, acoustic, radiofrequency, light, or mechanical energy such as pressure, acceleration, or temperature).
Transfer function: a characteristic input (stimulus)-output relationship, which defines how the output electrical signal depends on the input stimulus.
Span or range: the smallest and largest values of stimuli the sensor will encounter.
Full scale output: the maximum excursion of the output electrical signal.
Accuracy: the deviation of the measured value—the output from the sensor—from the true value of the measurand.
Resolution: the smallest increment of input stimulus that can be sensed (e.g., the change of a single bit within an analog-to-digital converter).
Linearity: the proportionality of the sensor output to the measurand input.
Threshold: the minimum and maximum input detection levels beyond which the sensor produces no usable output.
Hysteresis: the sensor response dependence on previous inputs, the sensor has a different transfer function for increasing input stimuli from decreasing input stimuli.
Noise: every value outside the realm of specificity (e.g., shot, Johnson, or 1/f noise within a device).
Precision: the repeatability of the measurements from the sensor.
Sensitivity: the conversion efficiency of the sensor; the sensor gain of output amplitude/input amplitude.
Specificity: selective conversion of the desired measurand and is relative immunity to other measurands (e.g., a pressure sensor's ability to reject temperature affects).
Stability: the long-term behavior of the sensor (e.g. temperature drift, or the change in a pressure sensor's output for changing temperature).

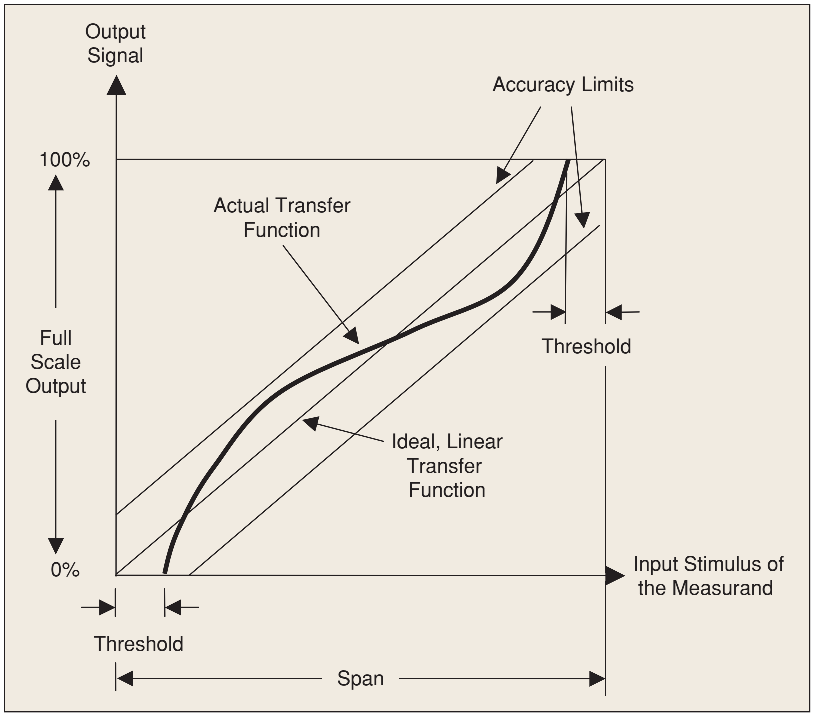


Fig. 1. Transfer function for a sensor and some of the characterizing parameters.

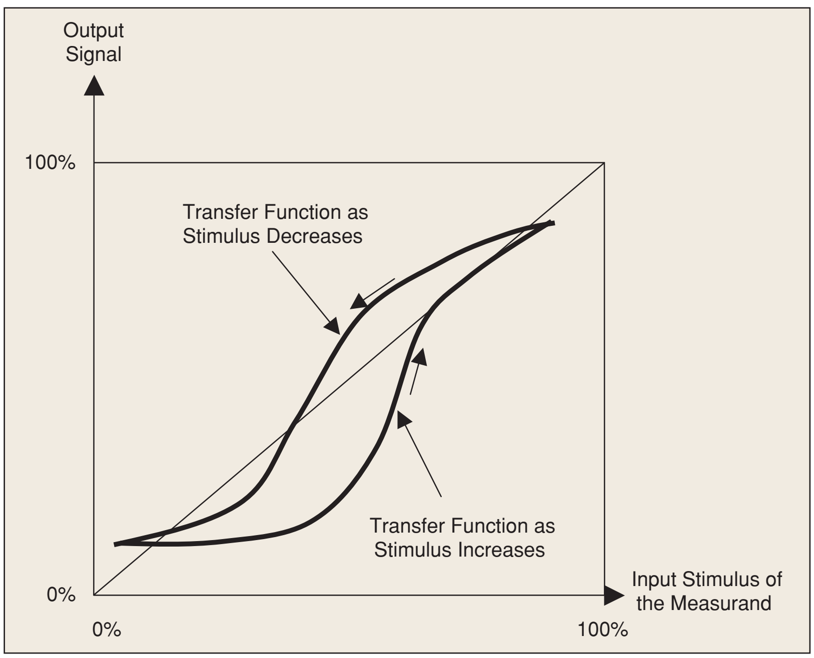


Fig. 2. An example of hysteresis and how it might affect the transfer function of a sensor.

related values but not synonymous.) (Figure 1)

- *Resolution:* What is the smallest increment of input stimulus that can be sensed? The smallest increment sensed is not necessarily the accuracy because the transfer function may be nonlinear (Figure 1).
- *Linearity:* What is the form of the transfer function relationship between measurand input and sensor output? A linear relationship means that it is very simple to convert sensor output to measurement result. However even for highly nonlinear sensors, this usually will not be a concern since there will be plenty of computing horsepower available for linearization somewhere along the measurement chain (Figure 1).
- *Threshold:* What are the minimum and maximum input detection levels beyond which the sensor produces no usable output? That is, if your measurand varies somewhat above or below estimated nominal values, will you still be able to measure it (Figure 1)?
- *Hysteresis:* Does the sensor response depend on previous inputs? For example, will a sensor provide the same result for a pressure of 1,000 kPa regardless of whether it was raised from 500 kPa to the target value or was reduced from 1,500 to that level (Figure 2)?
- *Noise:* Includes everything outside the realm of specificity. Does the sensor output have a high enough signal-to-noise ratio (SNR) for the regime of interest? For example, the noise floor (dark current) of a photodiode is usually not a concern if the application involves measurements well above that floor, because the SNR would be high. However, for measurement of very low light levels, acceptable SNR requires selection of a sensor with low dark-current.
- *Precision:* How repeatable are the measurements from the sensor? That is, for a measurement repeated with identical input conditions, how much will the results vary and how much can you tolerate? (Please note, precision is not accuracy. Accuracy describes how close the sensor is to a static ideal. Precision describes how results vary dynamically; i.e., for identical input, how close the output returns to the same value.)
- *Sensitivity:* What is the conversion efficiency of the sensor? Think of this as the sensor gain: output/input. This parameter will affect subsequent signal processing steps and contributes to overall SNR.
- *Specificity:* Does the sensor offer a highly selective conversion of the desired measurand, which is relatively immune to others? Temperature effects are ubiquitous. You may not want to measure temperature with your sensor, but it is likely to be influenced—sometimes strongly—by temperature. Many sensors include some form of temperature compensation to minimize such

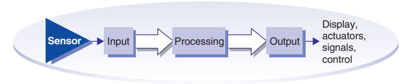


Table 1. A representative compilation of measurands and sensors.

Measurand	Sensor	Characteristics
Acceleration/force	Strain gauge	Low-level signal needs conditioning
	Semiconductor strain gauge	Simple circuit integration; temperature sensitive; good force sensitivity
	LVDT	Low acceleration range
	MEMS	Small structure; can be integrated with signal conditioning electronics
	Piezoelectric	High output impedance; needs charge amplifier conditioning
Displacement	Strain gauge	Low level
	LVDT	Use feedback to linearize
	Capacitive	High sensitivity to small displacements
	Potentiometer	Simple use; mechanical wear limitations
DNA	Gene chip with quartz crystal microbalance (QCM)	Coating of single-strand DNA available for sequence-specific binding QCM oscillation frequency proportional to amount of paired DNA
Flow	Turbine impeller	Mechanically invasive; simple conditioning
	Pitot tube	Uses pressure transducer
	Electromagnetic	Needs contact with conductive fluid
	Restrictor plate	Differential pressure across an orifice
	Doppler ultrasound	Senses particle, bubble motion
Gas	Electrochemical cell	Potential is function of gas concentration
	QCM with selective coating	QCM oscillation frequency based on amount adsorbed
Light	Phototransistor/photodiode	Sub microsecond response, simple circuit integration
	Photoresistive	Resistance proportional to light intensity
	Photomultiplier	Exquisite sensitivity; needs kilovolt supplies
	CCD camera	Video; very high data rates
Magnetic	Hall effect	Semiconductor based
	Magnetoresistor	Resistance proportional to magnetic field
Pressure	Switch	Simple design and use
	Strain gauge	Low-level signal needs conditioning
	Variable capacitance	Small; nonlinear
Sound	Microphone	Cheap; simple to use
Temperature	Thermocouples	Low-level signals; wide temperature ranges, poor linearity, cheap
	Thermistors	Low cost; modest temperature range, high sensitivity; nonlinear
	Resistance temperature detector	Accurate, repeatable, more linear than above
	Silicon semiconductor	Restricted temperature range, linear

(Adapted from [6, Table 7.8], used with permission.)

unintended measurand effects; alternatively, you may need to perform this yourself.

- *Stability:* Is the long-term behavior of the sensor adequate for the application? If the sensor is installed today, will it give acceptable performance next year—or at least until the next calibration cycle?
- *Survivability:* This is a statement of ruggedness, environmental suitability, etc. Can the fundamental sensor element in combination with its packaging and interconnect survive in the environment of the measurand?
- *Safety:* Does the sensor offer intrinsic safety compatible with the application environment?

Example Temperature Applications

Let's consider some typical applications to highlight some of the points that we've just made. Because temperature measurements are so common, we'll start there and discuss nominal applications as well as some specialized cases.

Thermocouple Type	Typical Application Temperature Range	Construction (+ : −)
B	0–1820°C	Pt(30%)Rh: Pt(6%)Rh
E	−270–1000°C	Chromel: Constantin
J	−210 to 1200°C	Fe: Constantan
K	−270–1372°C	Chromel: Alumel
R	−50–1768°C	Pt(13%)Rh: Pt
S	−50–1768°C	Pt(10%)Rh: Pt
T	−270–400°C	Cu: Constantan

Table 2. Some thermocouple choices (from [3] and [4]).

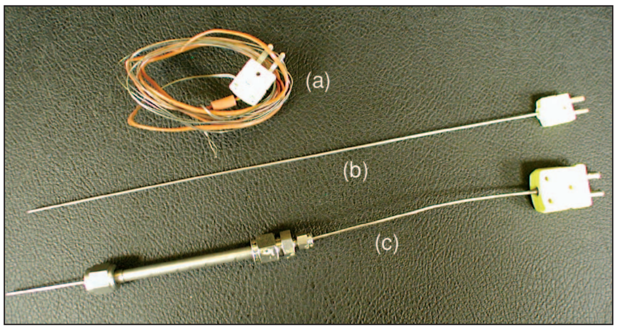


Fig. 3. Typical thermocouple configurations: (a) wire, (b) probe, and (c) probe with well suitable for mounting using standard threaded pipe fittings.

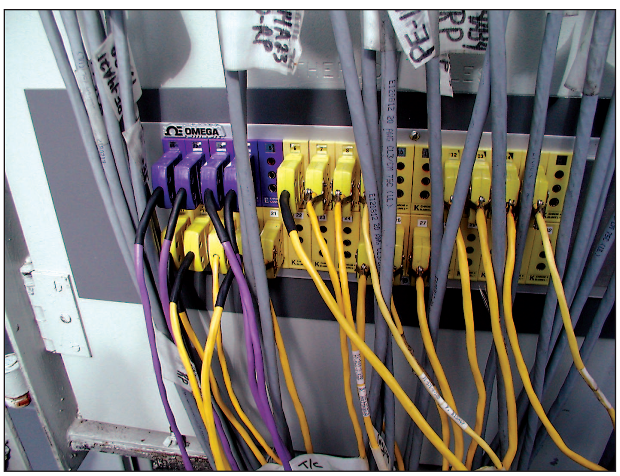


Fig. 4. Thermocouple patch panel.

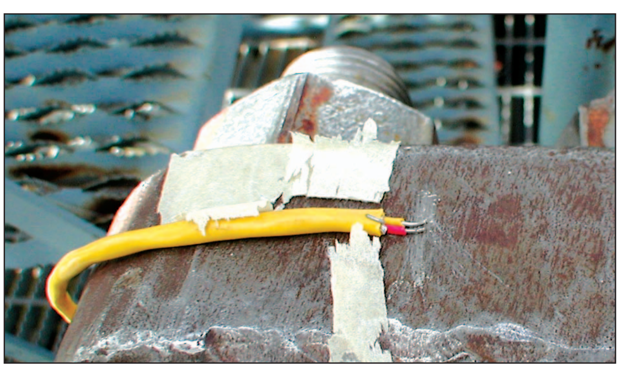


Fig. 5. Direct weldment of TC to component.

Application 1. Basic Temperature Measurement on Piping Systems Using Thermocouples

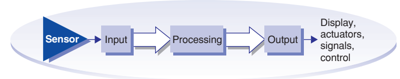
Tests of rocket engines in static test stands require a tremendous number of sensors and a huge data logging system with many types of instrumentation. Measuring the temperature of fluids and gases in pipelines is of frequent interest and a part of the data logging system. For example, at NASA-Stennis, the temperature of both gases and cryogenic liquids are of interest. Measurements must routinely span the range of -196 to +100 ºC; for temperatures associated with test articles, the upper limit can be much higher. Table 2 summarizes some popular thermocouple (TC) types and their associated temperature application ranges. Considering the temperature ranges, modest accuracy requirements (±2 ºC), the hundreds of measurement points, and long experience, TCs are the sensors of choice for routine temperature measurements. They provide acceptable accuracy for most measurements, and although highly nonlinear [4], linearization is a standard feature of the many types of signal conditioning equipment available.

Mapping the available TC choices to the basic temperature measurement requirements suggests that Types E, J, K, and T would be appropriate choices. Type J TCs can be problematic for corrosion in exposed conditions. Experience over time has made Type K the most commonly employed; Type-T TCs are also used. Figure 3 shows some representative thermocouple configurations. Figure 4 shows a typical termination block that emphasizes the high number of thermocouple measurement points expected on one portion of a rocket engine teststand. Many of the applications involve safety-critical items, so in this environment it is important to use prequalified sensors and associated mounting hardware when appropriate.

Application 2. Robust Temperature Measurement on Piping Components

Again, rocket engine tests provide a good example for robust measurements of temperature. One requirement of the test environment at NASA-Stennis is to chill piping systems in preparation for a test. Operators on one test stand determined that a good indicator of proper conditions was the temperature on a particular pipe coupling. That is, the entire run line was ready when the periphery of a pipe coupling reached a certain temperature set point. In this case, the TC wires were spot-welded directly to the coupling. This interesting variation is shown in Figure 5.

Although not obvious from the photograph, the actual construction is shown in Figure 6. The normal welded junction that would be made between the two leads of the Type-K TC is now



made by separately welding each TC lead to the coupling component as shown in Figure 6(a). This results in the effective TC circuit of Figure 6(b). By the "law of intermediate metals" [5], as long as the section of iron shared by the two effective TCs (Chromel-Fe; Alumel-Fe) is at the same temperature, then the effect is the same as a single, Type-K Chromel-Alumel TC.

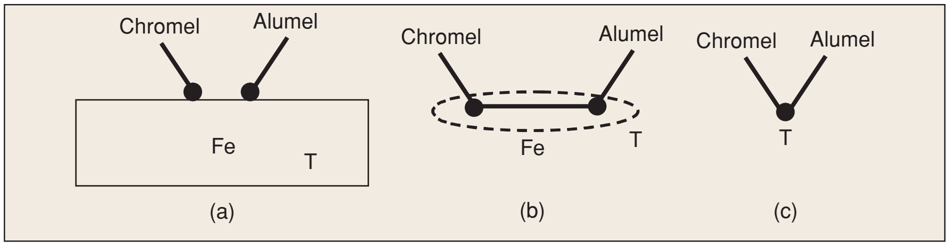


Fig 6. Schematic of pipe weldment TC application. (a) The standard leads of a Type-K TC are individually welded to the iron (Fe) pipe fitting. (b) The effective TC circuit consists of two TCs (Chromel:Fe and Fe:Alumel). (c) The effective TC reduces to a simple Type-K (Chromel:Alumel) when the shared metal, Fe, is at a constant temperature, T.

Application 3. Temperature Measurement on High-Pressure Piping Systems Using TCs.

A common requirement for temperature measurement in piping systems is to make an internal measurement so as to avoid the effects of pipe walls, which can be thick. A standard solution is to use some form of thermal well, which provides a sealed, physical intrusion into the pipe. Pressures and flow rates will dictate the construction requirements for the penetrations. Figure 7 and its inset shows a TC installation in a high-pressure, 58.6 MPa (8,500 psi) gaseous nitrogen (GN2) line.

Fig. 7. Intrusive TC measurement in a high-pressure GN2 line.

Other Measurands

Pressure and flow are other important and commonly encountered measurands, especially in any type of process control and manufacturing industry. Figure 8 shows two pressure transducers useful for modest pressure ranges.

Figure 9 illustrates a large, turbine flowmeter. Motion of the gas or liquid turns a turbine blade, whose motion is sensed with a magnetic element that has no mechanical contact and is communicated across a barrier to the outside of the sensor.

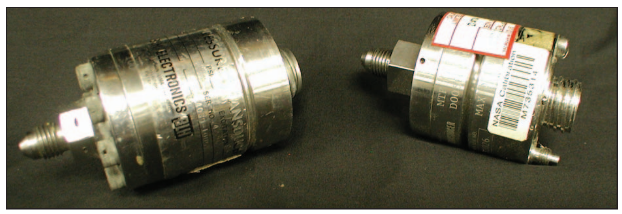


Fig. 8. Typical pressure transducers.

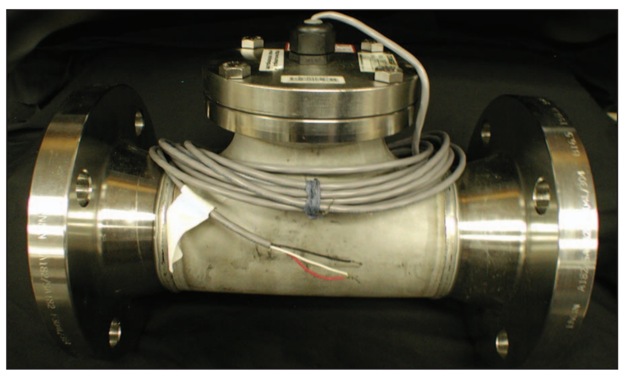


Fig. 9. Large turbine flowmeter.

Application 4. Flow Measurement on High-Pressure, High-Flow Pipe

An interesting technique for measuring flow in high-pressure, high flow rate applications employs a differential pressure measurement on either side of a restrictor plate to measure flow indirectly. Figure 10 illustrates such an application on a pipe used to convey high-pressure, high delivery rates of liquid oxygen. The inset shows the differential pressure transducer used to measure the drop across the orifice.

Before We Go

There are many, many more things that could and should be discussed. Some we will return to in later installments of the tutorial—for example, we'll look back inside several typical sensors when we treat the signal conditioning challenge. Others, such as an exhaustive treatment of all the various sensors available—is simply beyond the scope of this introductory series. When practical, we'll point out places you can go to get more information and in-depth treatment. And always, we welcome your comments and insights so that we can make improvements.

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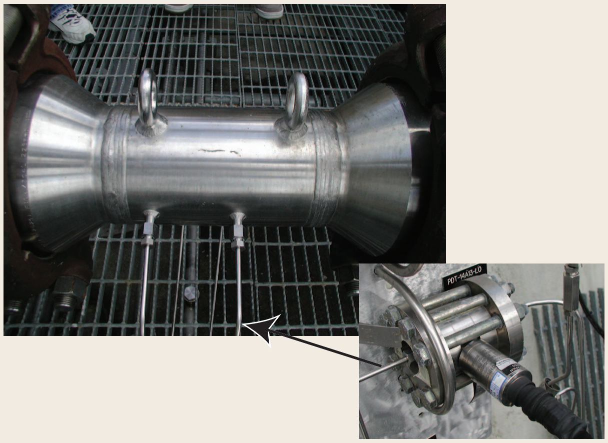

Fig. 10. Flow measurement using differential pressure across an orifice. The inset shows the pressure transducer, which communicates with the orifice section via two pressure lines.

For Further Reading

A.D. Khazan, *Transducers and Their Elements*. Englewood Cliffs, NJ: Prentice-Hall, 1994. Gives an exhaustive treatment of sensors.

J.G. Webster, *Medical Instrumentation: Application and Design, 3rd Editioin.* New York, NY: Wiley Textbooks , 1997.

Check out manufacturer's Web sites for access to a wealth of information about choosing and applying sensors, for example, http://www.omega.com, http://www.bksv.com/, and http://www.ni.com.

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