Fundamentals of Test Measurement Instrumentation

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Introduction to Test Measurement Instrumentation

"I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it, but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of Science, whatever the matter may be."

– Sir William Thompson, Lord Kelvin (1827–1907)

1.1 Introduction

The opening quotation, by Lord Kelvin, shows the importance of being able to measure parameters and record or display the resulting measurements in numbers. Measurements allow us to make specific conclusions about the physical conditions of a test object and about how the object responds to changes in its environment. These measurements allow us to verify that the object will perform correctly under the specified conditions and verify that future changes to the object do not affect its performance. The quotation also underscores the important role that measurements play in advancing scientific knowledge.

This book introduces students, technicians, technologists, and engineers to the specialized test instrumentation that is used in R&D laboratories, in testing organizations, and in industrial maintenance departments. The book will focus on the practical application of test instrumentation and emphasize the importance of creating a "mea-

surement system" that involves components, installation, wiring, and calibration. The design, application, and calibration of systems for measuring pressure, temperature, flow, force, displacement, and vibration will be discussed. A significant portion of the book will be devoted to the calibration of test instrumentation, including detailed information about calibration equipment, calibration methods, and calibration records.

You will learn to:

- design test measurement systems
- select appropriate equipment
- understand the characteristics of system components
- understand system and component calibration
- understand the operating principles of transducers
- determine overall accuracy of a system
- formulate basic test procedure designs

1.2 Why and Where Test Measurement Instrumentation Is Used

Test measurement instrumentation is used to obtain the values of the physical parameters that exist in an environment, process, or product. Examples of these physical parameters include temperature, pressure, flow, motion, force, and strain. We need to make these measurements in order to test theories and equipment, to verify that a product's specifications are met, to monitor the operation of equipment, or simply to tell us how hot it is outside. Test measurement instrumentation is used in research and development laboratories, in product development centers, in manufacturing plants, in maintenance facilities, and in commercial and household products.

Research and development (R&D) laboratories are prime users of measurement instrumentation. Pure research that expands knowledge and verifies the theoretical advances in science is carried out by government labs, university labs, and the labs of large companies. The development laboratories apply the theoretical knowledge and scientific advances to

improve the equipment, operation, and facilities used by society. Product development centers then design, test, and improve new consumer and industrial products based on the work of the R&D laboratories. Manufacturing plants produce the final products and use measurement instrumentation to verify that their products meet specifications. This measurement activity takes place during the production and maintenance phases of the plants' work. Measurement instrumentation is increasingly being built into commercial and household products. Automobiles are now full of sensors and displays, for example, and appliances have ever more sophisticated measurements and controls.

1.3 Components of a Test Measurement System

A test measurement system usually consists of several separate components for measuring some physical parameter that are joined by some means of transferring the measurement information about the parameter between the components until the information is finally presented in a form that the system operator can use. The components that are found in a typical system include the sensor, the signal conditioner, and the display. Most electrical and electronic-based systems use copper wiring as a means of transferring measurement information while other systems can use pneumatic, hydraulic, optical, or wireless transmission.

In its simplest form, such as a pressure gauge, the components of a test measurement system are all contained within the same device. The sensing element (bourdon tube, bellows, diaphragm, etc.) moves in a manner that is proportional to the applied pressure. This movement is transferred to the gauge pointer through a series of gears, levers, and cams, which translate the element motion into a proportional rotational movement that drives the gauge pointer. The pointer moves to a position that is equivalent to the applied pressure, and the resulting pressure is read by the user on a circular scale located under the pointer and attached to the face of the gauge. In the case of the pressure gauge, the bourdon tube, bellows, or diaphragm is the transducer or sensor. The gears, levers, and cams form the transmission system; the pointer and dial form the display or readout.

An example of a slightly more complex test measurement system is a digital pressure gauge. In this case, the sensing element, such as a dia-

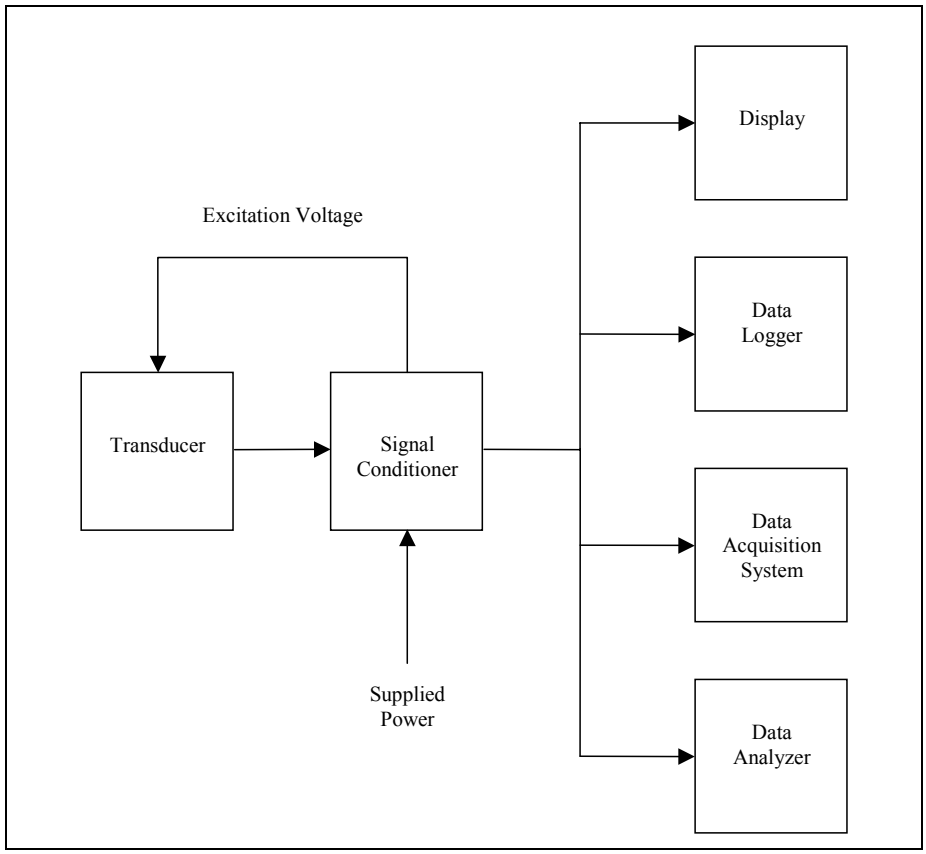


Figure 1-1. Typical Test Measurement System

phragm, has strain gauges attached that respond to the strain in the diaphragm material that occurs as a result of the applied pressure. Wiring connects the strain gauges to a power source and to an electronic circuit that converts the resistance change of the strain gauges into an analog voltage. Other electronics are used to linearize the voltage and provide adjustments that scale the voltage so it is proportional to the applied pressure. The analog voltage is then converted into an equivalent digital voltage, and this voltage is used to drive a digital display, which indicates the pressure in the desired units. The digital voltage can also be used to drive a liquid crystal display that mimics the traditional pressure gauge pointer and scale.

Additional electronics can provide a voltage or current output that can connect the gauge with wires to other equipment so the pressure reading can be used for remote displays, data recording, or the control of other equipment. A power source such as a battery or DC power sup-

ply must be included in the system in order to provide power for the electronics and displays. This electronics can include a microprocessor, which is used to accept the raw electronic signal and perform the data manipulation needed to provide display and output signals. In the case of a digital pressure gauge, the transducer or sensor is the diaphragm with its attached strain gauges. The sensor output and sensor power are transmitted through wires to the electronic signal conditioning circuits, and the user reads the pressure on the liquid crystal display on the gauge.

An example of a complex test measurement system is the measurement of the exterior surface temperature of a space vehicle. The temperature sensor must be mounted in such a way that it is protected during the launch, space, and re-entry environments (potentially subjecting it to vibration, vacuum, radiation, space debris) while ensuring that it is still close enough to the exterior surface to make an accurate temperature measurement. The sensor's wiring is led through the space vehicle's wall in such a way that the pressure containment between the vehicle's interior and the space environment is preserved. The wiring is connected to a signal conditioning unit that provides the excitation power for the sensor and electronic circuits so the sensor's signal from the sensor can be processed into a form of signal that the measurement system can use. This signal could be an analog voltage, a digital voltage, a current, or a digital signal to be connected to a computer bus.

The temperature signal could be routed to displays for the crew, to computers for data storage, and to on-board alarm systems to warn crew of abnormal conditions. The signal could also be sent by radio transmission to satellites that would then retransmit the temperature data to one or more ground stations. This would enable ground personnel to monitor the vehicle's exterior temperature.

1.3.1 Transducers

Transducers or sensors are the front end of the measurement system. They are the devices that interface directly with the equipment or environment about which we want information. They transform the physical parameter of interest (pressure, temperature, vibration, etc.) into a

form that can be further used and processed by other devices until the user eventually has the information he or she desires.

Some transducers, such as thermocouples or piezoelectric accelerometers, have a self-generating output. In this case, the sensor element provides an electrical output through the action of the physical parameter on the sensor element. The thermocouple provides a small voltage output whenever the temperature at the junction of the two joined metal wires is different from that at the ends of the wires where the voltage is read with a voltmeter. The piezoelectric sensor element provides an electrical charge output whenever a change of force is made to the crystal sensor element.

Other transducers such as resistance temperature detectors (RTDs) and strain-gauge-based transducers need a power supply in order to produce an electrical signal. In the case of the RTD, a small electrical current is passed through the resistive element so the signal- conditioning circuit can determine the resistance of the RTD and thus the temperature associated with that resistance. In the strain gauge transducer, one or more resistive strain gauges are connected in a Wheatstone bridge circuit. This Wheatstone bridge circuit operates by the application of an excitation voltage to it, which enables the resistance change of the strain gauges to be translated into an equivalent voltage change.

There are thousands of transducers available commercially today, and hundreds more are introduced every year. Each transducer has a specific design that makes it more or less suitable for a given application. It is the job of the test measurement professional to select the most appropriate sensor for the application at hand. This means he or she must understand the basic operating principle of the transducer, the complete specifications of the transducer, the test environment and range of test conditions, the measurement requirements, the effect of external influences on the transducer, and the transducer's installation and calibration requirements. It is the goal of this book to give you information about a wide range of sensors so this selection process will be easier. With experience and knowledge, you will learn that certain transducer types are more suitable to certain measurement situations, simplifying the selection process.

1.3.2 Signal Conditioners

Signal conditioners lie at the center of the measurement system. They serve to receive the output from the transducer, carry out some basic processing of the signal, and pass the signal on to the display, storage, and analysis components. Signal conditioners may also supply an excitation voltage to power the transducer. Some transducers are self-contained units that have the signal conditioning circuit built into the body of the transducer. In strain gauge pressure transducers, the Wheatstone bridge completion resistors, temperature compensating circuits, regulated bridge power supply, and amplifier can all be contained in the transducer. The only external connections are an unregulated power supply and an output display. The advantages of this type of transducer include less electrical noise pickup on the output signal, less expensive cabling, and ease of use. The disadvantages include limitations on the environment in which the transducer can be used (temperature, pressure, radiation, etc.) and nonrepairable electronics, which means plants may have to discard this more expensive type of transducer when it is damaged.

The number and variety of signal conditioners is smaller than that of transducers. Certain types of signal conditioners can be used with a number of transducers that share a common operating principle. For example, a strain gauge signal conditioner can be used with a strain gauge pressure transducer, a strain gauge load cell, or with strain gauges used to determine stresses in materials. A charge amplifier can be used with piezoelectric accelerometers or piezoelectric pressure transducers. Each type of signal conditioner, however, is still designed to perform to certain specifications and to have certain features. The test measurement professional must still ensure that the signal conditioner is compatible with the selected transducer and that the signal conditioner's specifications meet the test measurement requirements.

1.3.3 Displays

Displays are the simplest form of system output device used to measure the output from the signal conditioning circuit. They indicate to the user the value of the parameter being applied to the transducer. Displays can be analog or digital meters that indicate the raw voltage from the signal conditioner, or they can be meters that scale the raw voltage so as to provide an output in units of measurement (°C or

psig). Other displays include bar graphs and alarm indicators or a combination of both. These displays can be panel mounted or bench mounted, or they can be portable hand-held units. Most of these displays rely on the user to read and note the value being measured, although some displays have some limited ability to store and retrieve data. Most displays are designed to measure static or very slowly changing data since these are the only types of signals that users can process visually. An oscilloscope, on the other hand, is an example of a display that is designed for time varying or dynamic data.

1.3.4 Data Loggers

Data loggers are standalone display systems that are used to store data from a large number of sensors. Data loggers are usually used to record data that is changing fairly slowly. A snapshot of all the data channels is taken at approximately the same time, and the data is stored along with the time at which it was taken. The scan is repeated periodically, from a few times a second to a few times an hour. The data is later retrieved from the logger's memory device and presented to the user in tabular or graphic form. Tabular outputs present the data in a table, in which the data from all or selected channels is included along with its time of acquisition. Graphical displays provide the measurement information in the form of an X-Y graph, where the x-axis shows the acquisition time and the y-axis shows the multiple data points from one or more channels. The distinction between data loggers and computer-based data acquisition systems is somewhat blurry, and today the latter have largely replaced the standalone data logger.

1.3.5 Data Acquisition Systems

A data acquisition system is a refinement of the data logger but with the additional flexibility that a computer-based system with software provides. The software lets the user customize the way the system acquires, stores, and displays the test data. Multiple sensors are connected to the input of the data acquisition system. The outputs of the sensors are sequentially scanned by a multiplexer, which switches each signal to a common processing circuit. This common circuit can consist of filters, analog-to-digital converters, or even a common signal conditioning circuit. Once the data is in a digital format, it can be stored, manipulated, and displayed in any number of ways. Data

acquisition systems are capable of accessing hundreds of signals at speeds of over a million samples per second. They are ideally suited to measuring parameters that are changing very quickly.

Data acquisition systems range in size from portable, hand-held devices that access only a few points to personal computer–based systems and even to systems controlled by mainframe computers.

1.3.6 Data Analyzers

Data analyzers are a specialized version of data acquisition systems that have additional software that processes and analyzes the sensor data. Analyzers can be designed for a specific type of measurement such as vibration analysis, or they can be general-purpose analyzers capable of manipulating data in a variety of formats. Analyzers that use the Fourier analysis technique to deal with data in the frequency and time domains are an example of the general-purpose analyzer. These analyzers can be portable and capable of accessing only a few channels, or they can be computer-based systems that access a large number of channels. The portable systems as shown in Figure 1-2 have an oscilloscope-type display for real-time display of the raw and analyzed data. Computer-based systems have monitors for the data display. A typical computer-based system is shown in Figure 1-3.



Figure 1-2. Portable Data Analyzer
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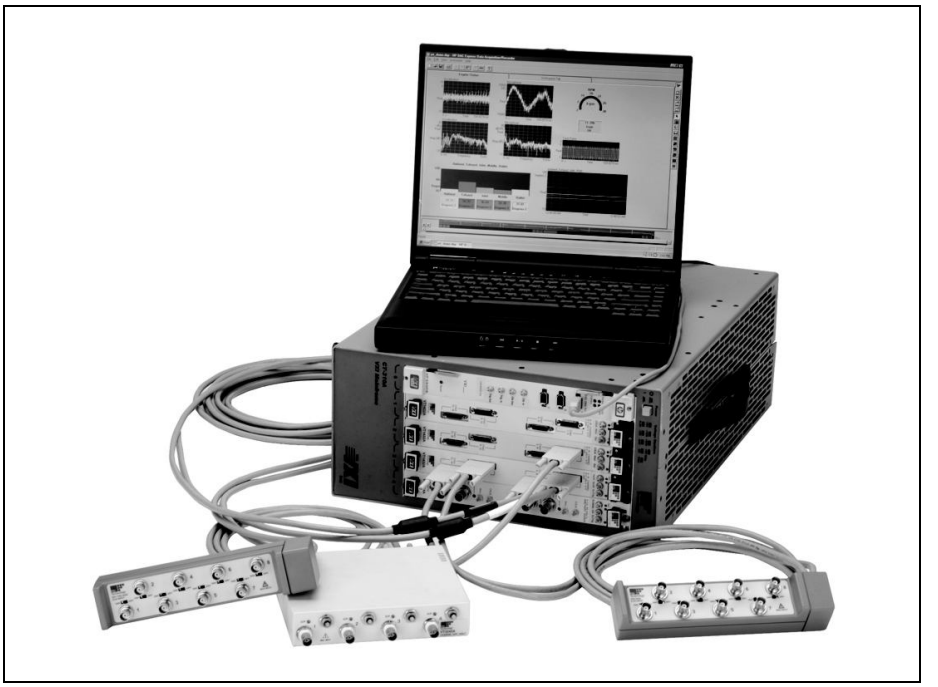


Figure 1-3. Computer-based Multi-channel Data Analyzer
(Courtesy, VXI Technology)

1.4 Characteristics of an Ideal Test Measurement System

Although the characteristics of an ideal test measurement system can depend on the total system, including sensor, cabling, signal conditioning, and displays, most of the characteristics of an ideal test measurement system involve the sensor or transducer. This is because it is the sensor that is located in the test environment or mounted to the test specimen. The rest of the system can be located remotely from the environment and specimen in a more benign area. This remoteness also ensures that the equipment does not have any effect on the test environment or on the test specimen. Such effects could mask or alter the behavior of the specimen in a way that impacts the test results to the point that erroneous conclusions are made.

The ideal sensor should have the following characteristics:

- *Be physically small and have a low mass.* Small size is important since the sensor often has to be attached to an existing piece of equipment which poses its space and accessibility limitations.

Tests are usually carried out on real or prototype equipment that was not designed to have sensors attached once the tests are completed. Small size is also important in ensuring that the sensor does not significantly change the test environment. The sensor's size can affect the flow distribution of the fluid surrounding the test specimen, for example. This changing flow pattern could influence the vibration behavior of the test specimen or affect the heat transfer between specimen and fluid.

Low mass is essential to ensure that the mass of the specimen with the sensor attached is almost the same as the mass without the sensor. The added mass will affect the vibration characteristics of the specimen and could also affect the heat transfer between specimen and surrounding atmosphere. If we wanted to know the acceleration of a specimen when exposed to a specific force exerted by the system that is connected to the specimen, we would mount an accelerometer on the specimen and measure the acceleration. The acceleration is equal to the force divided by the mass of the specimen plus the attached accelerometer. If the accelerometer mass is 1% of the mass of the specimen then the measured acceleration will be 1% lower than it would have been if the accelerometer was not present.

- *Not be influenced by extremes in the environmental conditions, such as temperature, pressure, radiation, and water or chemicals, to which it is exposed during the test.* The sensor should be immune to changes in these conditions as well as to the absolute level of these conditions. In reality, every sensor has environmental limitations, and the test measurement professional must select a sensor that can withstand the environmental test conditions. He or she must also understand and evaluate the impact that the magnitude and change in these conditions can have on the measurement system's output.
- *Be capable of measuring a wide range of variation in the value of the measured parameter, be highly accurate, and be highly linear.* Wide rangeability enables one sensor to cover the entire range of test conditions imposed on the specimen. This reduces the cost of having to install multiple sensors, reduces the space required

by multiple sensors, and reduces the number of tests that have to be run when sensors that fail under test conditions have to be replaced. High sensor accuracy reduces the measurement uncertainty and increases the confidence that the effect of the measured parameter on the specimen can be determined and reported. High sensor linearity improves both rangeability and accuracy. It also simplifies data analysis since a simple linear equation can be used in the data reduction process.

- *Be capable of a wide frequency response.* The sensor should be able to respond equally well to static or quickly changing conditions in the measurement parameter. The transducer's installation method, the wiring, and the frequency response capabilities of the rest of the measurement system also contribute to the system's overall frequency response. The operating principle of some types of sensors prevents them from being used under static or very slowly changing measurement parameter conditions. Piezoelectric sensors, for example, only provide an output when the measurement parameter is changing faster than a given threshold level. At the other extreme, all sensors have some limit to the upper frequency they can respond to. This is determined by factors such as sensor mass, physical construction, material limits, electronics, resonant frequencies, and so on.

Other characteristics of the ideal sensor that need no further explanation are low cost, high output signal, ruggedness, ease of operation, and ease of attachment.

Since the ideal sensor does not exist, some compromise must be made when selecting which sensor to use in a given situation. The important thing for the test measurement professional is to identify and understand the limitations of the selected sensor. He or she should also account for the effects of these limitations on the uncertainty of the measurement. The magnitude of each of the limitations is provided by reputable sensor manufacturers and is spelled out in the sensor specification sheet. The user must determine the effects of any conditions not covered by the specification sheet. This may require the user to carry out tests on the sensor before using it in the planned test.

1.4.1 Process Influence on Transducer

The transducer's operating characteristics will be affected by the process to which it is attached and by the environment surrounding it. Conditions such as ambient temperature, pressure, and radiation will affect the transducer's specifications. The environmental operation limits to which the transducer has been designed will be documented in the specification sheet. The magnitude of the effect that each environmental condition has on certain specifications within the environmental limits may also be documented in the specifications. For example, the upper temperature limit for a pressure transducer may be specified as 250°F. The manufacturer has designed this transducer to operate up to this temperature. Use above this limit could damage the transducer to the point that it would no longer operate. The effect on the transducer's accuracy caused by using it at a temperature above room temperature may be ±0.01% per °F. At a room temperature of 70°F, the transducer's accuracy may be ±1%. If the transducer is operated at a temperature of 170°F, the accuracy would be changed by (170 – 70) × 0.01% = 1%, for a total accuracy of 1% + 1% = 2%.

The process to which the transducer is attached can also affect the transducer and its specifications. Unless a transducer is designed for underwater use, it should not be submerged, for example. If the transducer is to be connected to a fluid that is corrosive then the materials of construction must be compatible with the fluid.

1.4.2 Transducer Influence on Process

As described in section 1.4, sensor or transducer characteristics such as size and mass can affect the environment we are trying to measure or affect the performance of the equipment we are testing. One example of this influence includes using long steel-sheathed thermocouples that protrude from the test environment and conduct heat from the test fluid into the surrounding atmosphere (this is called stem conduction). Another is using resistance temperature detectors in a poorly conductive fluid or gas. The heat generated by the current passing through the resistance element of the RTD (this is called self-heating) is added to the heat produced by the fluid or gas. This can cause the temperature measurement to be slightly higher than if the self-heating was removed by a highly conductive fluid or gas. Selecting a transducer that minimizes the influence on the process is part of the job of the test

measurement professional. He or she must also understand and determine the degree to which measurements are affected by using a certain transducer.

1.4.3 Invasive versus Noninvasive Systems

A measurement system that has a large impact on the process or equipment being tested is described as an invasive system. Using a linear variable differential transformer (LVDT) to measure the dynamic displacement of a piece of equipment could be invasive, for example. The fact that the LVDT core must contact or be connected to the equipment changes the vibration characteristics of the equipment. The physical size of the core could change the flow patterns of the fluid around the equipment.

A noninvasive measurement system is one that has a very small or nonexistent effect on the equipment being measured. Using a laser displacement transducer would eliminate the problems just mentioned since there is no physical contact between the equipment and the transducer, and the laser beam would not affect the flow distribution.

Some compromise must be made when deciding which transducer to use since the cost of a laser displacement system may be much greater than that of an LVDT-based system. The deciding factor is whether the uncertainty in the validity of the measurement caused by using an invasive system is too large. The degree of uncertainty is something that must be decided before selecting the transducer system. The test measurement professional must determine how much uncertainty can be tolerated while still meeting the requirements of the test.

1.5 Differences between Test Measurement Instrumentation and Process Instrumentation

Test measurement instrumentation includes the transducers, signal conditioners, and displays used in laboratory, manufacturing, and maintenance organizations to measure physical parameters. These components are required during research and development testing, product development, production evaluation, and maintenance and repair operations. Figure 1-4 illustrates a typical test measurement pressure transducer. This pressure transducer is approximately three eighths of an inch long and weighs 0.2 grams.

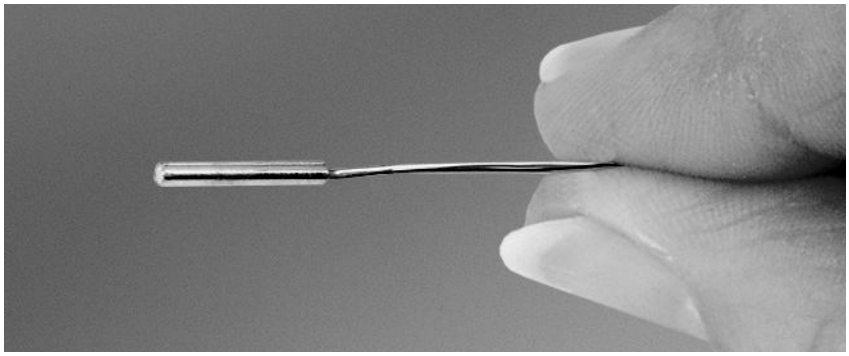


Figure 1-4. Test Measurement Pressure Transducer
(Courtesy, Kulite Semiconductor Products, Inc.)

Process instrumentation is the class of measurement equipment used in industrial process industries such as refineries, power plants, and chemical producers. It is used to measure, control, and provide alarm and shutdown signals. There is some overlap in these descriptions since process industries may also use test instrumentation, and test organizations can use process instrumentation if it suits the application. Table 1-1 provides the major differences between test measurement instrumentation and process instrumentation.

Table 1-1. Differences Between Test and Process Instrumentation

Test Measurement Instrumentation	Process Instrumentation
Used in laboratories, product development	Used in process industries
Designed for a specific application	Designed for a wide range of applications
Small and lightweight	Large and heavy
High frequency response	Static to low frequency response
Less stable	More stable
Less rugged	More rugged
Usually more accurate	Usually less accurate
Expensive due to smaller quantities used	Less expensive
Usually has a voltage output	4–20 mA DC output
Wider environmental range	More limited in environmental range
Typically uses separate signal conditioning	Self-contained signal conditioning
Sensors referred to as transducers	Sensors referred to as transmitters

The process instrument transmitter shown in Figure 1-5 is approximately nine inches high and weighs approximately twelve pounds.

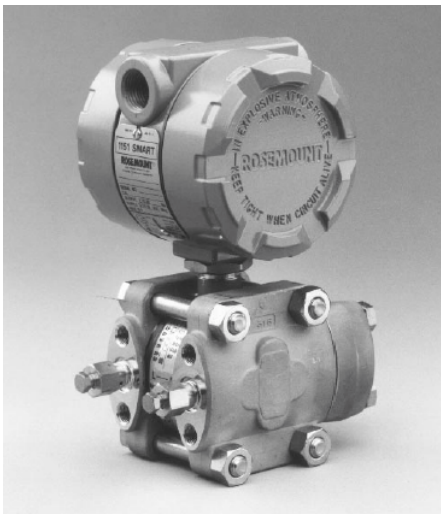


Figure 1-5. Process Instrumentation Pressure Transmitter
(Courtesy, Emerson Process Management, Rosemount, Inc.)

1.6 Smart Transducers

An Institute of Electrical and Electronics Engineers (IEEE) standard has been developed so analog output sensors can be easily interfaced with compatible signal conditioning and data acquisition hardware. IEEE 1451.4, Mixed Mode Interface for Smart Transducers, defines a method for providing a digital serial interface that downloads a digital file known as a Transducer Electronic Data Sheet (TEDS). This file contains information about the transducer that is read by the interfacing hardware, which then configures itself to the correct setup. This setup was previously set manually through hardware or software to provide the proper configuration. This effectively produces a plug-and-play type of system that relieves the user of much of the work associated with the system setup.

The TEDS file contains information about the manufacturer, model number, serial number, measurement range, sensitivity, and calibration data. This file can reside in an Electrically Erasable Programmable Read Only Memory (EEPROM) chip within the sensor body or in a file within the data acquisition hardware, the data acquisition computer,