# Intelligent Instrumentation

## Principles and Applications

Manabendra Bhuyan

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*God has blessed me with a wonderful family and a*

*wonderful teacher in Instrumentation*

*I dedicate this book to my wife Nanti, daughter Pahi, and son Pol, and*

*to*

*Prof. Manoj Kumar Ghosh, retired professor of IIT Kharagpur, India*

# Contents

# Preface

Classical sensors have been traditionally used in various measurement and process control applications for a variety of parameters. A signal-conditioning circuit when interfaced to a sensor enhances the performance of the sensors manyfold. Signal-conditioning operations are very common in instrumentation systems and have been used since long in the field of measurement and process control applications. With the advent of microprocessors and digital-processing technologies, such signal conditioning operations have been developed rapidly and the technologies have been found to have a good rapport with instrumentation systems. Many such sensors with microprocessor-based signal-conditioning devices have attracted a high volume of consumers.

The applications of instrumentation and process control have grown rapidly requiring medium-to-extremely complicated measurement systems. During the last decade, many new types of process parameters have evolved requiring new technologies of sensor or signal-conditioning systems. While classical sensors target general types of measurement systems, the newer sensor technologies focus on more specialized process parameter measurements. In many situations, such a sensor has not only to measure a process parameter, but has also to take additional decisions and perform many other nonconventional operations such as validation, compensation, and classification. This new category of sensors carries the tag *intelligent* and has expanded the scope of incorporating *intelligence* to instrumentation systems.

## Why Do We Need a Textbook on Intelligent Instrumentation?

Incorporation of intelligence to classical sensors has been done by researchers and sensor manufacturers in various ways. Based on the design approach of such sensors with added intelligent features, several varieties of intelligent sensors are modeled, implemented, and even marketed commercially. Due to the nonavailability of specific definitions, there is no straightforward indication in such innovations about the requisite features of an intelligent instrumentation system. Very often, a sensor integrated with a digital processor in a single chip is also termed an intelligent sensor, but it is not indicative of any intuitive ability of the sensor's functionality. There are many texts on intelligent sensors and instrumentation, but none of them define the technologies and services in a categorial manner. Moreover, many of the intelligent sensors developed so far are commercially viable due to the important services they offer, while many of them are not due to inappropriate design methodology.

Texts on intelligent instrumentation and intelligent sensors abound in various research articles and manufacturers' application notes; however, general texts on their design approaches are still far less than expected. *Intelligent Instrumentation: Principles and Applications* is designed as a textbook for a first course on intelligent instrumentation.

Why do we need a classroom course on intelligent instrumentation? Over the past decade or so, many universities have included topics on intelligent instrumentation in their courses on classical instrumentation. These topics mostly cover *integrated smart sensors* and the broad topics covering the entire family of intelligent instrumentation are found missing. Conventional instrumentation has rapidly shifted to intelligent instrumentation over the last decade. Researchers are continuously trying to add intelligence to sensors using state-of-the-art methodologies, but researching for a target service is different from understanding the underlying principles and design methodologies of intelligent instrumentation.

This author has taught conventional instrumentation with varying patterns of course structures for the last 30 years. Since five years or so, I have tried to cover some topics on 'intelligent instrumentation' in the classical instrumentation course. However, the students' confusion as to which book to follow motivated me to write a textbook on intelligent instrumentation covering the design methodologies and their relevant applications.

## Who Will Benefit Most from This Book?

This textbook is not self-contained and neither does it try to be not to go too much beyond its scope. It is intended as a classroom course for engineering graduates and covers the theories and applications of intelligent instrumentation or an elective course. The contents of this book can also be spread over two semesters. Apart from its usefulness in the classroom, this book will also be useful for practicing engineers and manufacturers. Besides theory on intelligent instrumentation, it includes many applications as case studies and, hence, can also be useful for researchers. The readers would also need to take a course on instrumentation as a prerequisite for this book, though Chapters 1 and 2 do cover the basics of sensors, transducers, and their performance characteristics.

## How Is This Book Different from Others?

The basic feature of this book is that it explains the underlying design methodologies of intelligent instrumentation for researchers and manufacturers in a textbook-like language, translates these methodologies to numerical examples, and provides applications in case studies. There are at least 80 solved numerical examples and 14 case studies in this book. The major features of this book are as follows:

1. **Prerequisite chapters**: To understand the design methodologies of intelligent instrumentation, readers need to be familiar with the concepts of sensor devices and their performance characteristics, and signals and system dynamics. Chapters 1 through 3 cover these topics.
2. **Design emphasis**: The basic design principles of intelligent sensors are emphasized in Chapters 4 and 6 and their applications are shown using numerical examples and case studies. This approach helps the students to use the principles in real-world problems.
3. **Intelligent processing**: Intelligent sensors rely on signal processing operations such as calibration, linearization, and compensation. Chapter 5 deals exclusively with intelligent signal processing operations and provides a wide range of numerical examples.
4. **Artificial intelligence**: Artificial intelligence is one of the major components of intelligent sensors. Use of artificial neural networks (ANNs) in sensor signal processing is very useful nowadays and can solve many real-world problems. A chapter is included to explain such issues (Chapter 6).
5. **Integral use of MATLAB®**: MATLAB programs have been provided throughout the book to validate the design approaches. MATLAB can be used not only to prove the design methods, but is also an essential tool for many signal preprocessing and statistical measurements.

## Organization

Chapter 1 provides a brief introduction to the basic concepts of process, process parameters, sensors and transducers, and classification of transducers, with examples ranging from radio-isotopic sensors to biosensors. The aim of this chapter is to provide a review of classical sensors and transducers.

Although a basic course on instrumentation is a prerequisite for this book, this chapter will serve as a refresher course.

Chapter 2 deals with the performance characteristics of instrumentation and measurement systems that discuss the static and dynamic characteristics. Since the intelligent processing of sensors focuses on enhancing their performance, the topics covered in this chapter will be an essential component of the book.

Intelligent signal processing deals with various types of sensor signals and the readers must therefore understand the concepts of signal representations, various transforms, and their operations in both static and dynamic conditions. Chapter 3 intends to provide such an understanding and knowledge to the readers.

Intelligent sensors developed so far by various researchers use different technologies and provide different services. The nomenclature of intelligent sensors is a complex task since, in most cases, the technologies and services are overlapping. Chapter 4 provides a unified approach to classify the intelligent sensors with their underlying design principles. It describes smart sensors, cogent sensors, soft sensors, self-validating sensors, VLSI sensors, temperature-compensating sensors, microcontrollers and ANN-based sensors, and indirect measurement sensors.

While discussing intelligent sensors in Chapter 4, the basic signal conditioning techniques were not elaborately explained. Chapter 5 addresses the issues dealing with intelligent sensor signal conditioning such as calibration, linearization, and compensation. A wide variety of calibration and linearization techniques using circuits, analog-to-digital converters (ADCs), microcontrollers, ANNs, and software are discussed in this chapter. Compensation techniques such as offset compensation, error and drift compensation, and lead wire compensation are also discussed here.

Chapter 6 deals with intelligent sensors that rely on ANN techniques for pattern classification, recognition, prognostic diagnosis, fault detection, linearization, and calibration. The chapter begins with the basic concepts of artificial intelligence and then moves on to ANN applications.

Interfacing of intelligent sensors to the processor and the users is a major issue. In order to achieve higher efficiency, uniformity, and flexibility of intelligent sensors, various interfacing protocols have been developed either in wireless platforms or on the Internet. Chapter 7 discusses a few important interfacing protocols in the wireless networking platform.

At the end of every chapter, a reference list is included to aid the reader consult the original text wherever necessary. Questions and problems for practice are also provided in a separate chapter as Chapter 8.

## An Advice to Course Instructors

This book covers topics more than are required for a semester. Course instructors may organize the topics in the following manner:

***Option 1*** (when the students have not taken a course on instrumentation)

Semester 1: Course—Introduction to intelligent sensors (Chapters 1 and 2, Sections 4.1 through 4.7)

Semester 2: Course—Signal processing for intelligent sensors (Sections 4.8 and 4.9, Chapter 5)

***Option 2*** (when the students have already taken a course on instrumentation)

Semester 1: Course—Intelligent instrumentation (Chapter 4, Sections 6.1 through 6.2.2)

Semester 2: Course—Signal processing for intelligent sensors (Chapter 5, Section 6.2.3)

Chapter 7 is a supporting chapter; course instructors may therefore include one or two topics from this chapter depending on the requirement.

As a final word, the applications described in the case studies may be referred to by researchers for designing their sensors for a particular application.

Suggestions, feedback, and comments from course instructors, students, and other readers are welcome for the improvement of this book.

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# 1

# *Background of Instrumentation*

## 1.1 Introduction

Due to necessity and curiosity, man tries to learn and understand the surroundings where he lives. The necessity comes from the urge to make man's life comfortable, whereas the curiosity leads to exploring unknown facts. In the scientific and technological world, learning and understanding of various phenomena of nature, universe, space, or man-made objects necessitates understanding the state, amount, or value of various factors that affect their phenomenon. Acquiring the knowledge of the state, amount, or value of various factors is termed as *measurement*. The factors cannot be explored fully unless the need or requirement can be quantified.

Similarly, a sense of relief cannot be obtained by a curious mind unless the facts can be explored. Exploration needs quantification of the information. However, accurate, quick, and intelligent quantification is always appreciated and, therefore, man always strives to do so.

The concept of measurement of physical factors is not new. The sundial used to measure time in Egypt dates back to the fifteenth century. In the medieval age, man learned to measure length by hand, palm, or finger. Some of the older concepts are translated into newer forms to present higher accuracy and efficiency, and many newer technologies have evolved with the advancement of science and technology with older concepts too. On the other hand, necessity and curiosity continue to flourish and have resulted in thousands of newer measurement parameters and, thereby, newer measuring instruments.

Human endeavor to quantify or measure a physical quantity has resulted in an added development to science and technology. As technology advances, measurement technology is also bound to expand. From a fire alarm to an electronic nose, from the laboratory pH meter to a counter to measure the number of sharks passing under the sea—in every sphere of our life, measurement systems are becoming increasingly common. However, measurement systems continue to develop by associating computing devices, which present them with a new feature—*intelligence*. This book will present step-by-step concepts that will help the reader to understand what those intelligent instruments are, how they work, and how such instruments can be developed for application.

## 1.2 Process

A process is a unit where a series of continuous or regularly occurring action takes place in a predefined or planned manner. However, we often encounter many systems where the process operation is random and cannot be modeled. Nonetheless, a system is regular or random, it experiences various forms of physical, chemical, or biological changes. The causes of such changes are the variations of some parameters that get reflected in some other parameters. These parameters are called process parameters or process variables. It is evident that the process dynamics mainly depends on the process variables. The process variables that indicate the state of the process action is called process outputs, whereas those that change the process action are called process inputs. An example of the process input and output parameters is explained with the help of a tea drier, as shown in Figure 1.1 [1].

The process of manufacturing black tea, which takes place inside the tea drier, is both a physical and a biochemical change of state of the fermented tea. The biochemical change in the tea is a complex process and difficult to model. Considering only the process of the physical changes of drying of the tea in the drier, the quality of product can be defined by the process output variables such as the moisture content and color of the black tea, whereas the moisture content of the input fermented tea, the feed rate, and the temperature of the drier can be defined as the input parameters. There are some other input variables, which are less responsible or not at all responsible for

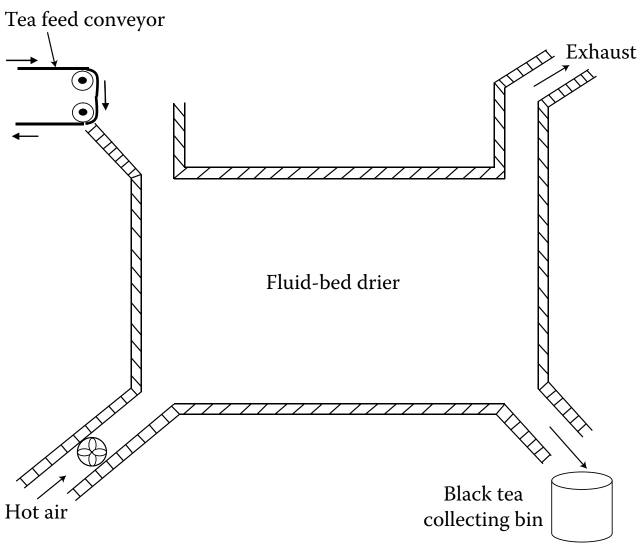


**FIGURE 1.1**
A tea drier.

the process action such as the density of the fermented tea. Similarly, some process output variables do not indicate any quality of the process, namely, the flow rate of the black tea in the drier. Hence, a process in a system constitutes manipulated input variables and controlled output variables. The manipulated input variables control the process dynamics, whereas controlled output variables carry the signature of the process operation.

## 1.3 Process Parameters

A process to be handled by measurement and instrumentation may vary widely. It may range from a simple and common type like an oven to a complex one like the fermentation of tea. Hence the parameter to be measured and controlled may also vary from the simplest like the temperature of the oven to a complex one like the flavor of tea during fermentation.

Moreover, the parameters may have to be measured under different stringent conditions—high pressure, high temperature, vibration, shocks, etc. There may be a good number of cross sub-conditions of these situations such as temperature measurement of high-pressure fluid, pressure measurement of hot gas, flavor measurement under humid condition, etc. The most important point in instrumentation under such condition is to select the right kind of sensor or to develop a special one to meet the requirement. This will need some sort of intelligence of the sensor to nullify the interfering effect inherently or by using special circuitry or computation.

A wide range of physical parameters in various systems—industrial, laboratory, biological, medical, etc.—are required to be measured. The most common physical parameters in industrial systems are time, temperature, pressure, flow, level, etc. Other less common parameters available in almost all systems are position, displacement, velocity, acceleration, weight, force, density, viscosity, etc. Some parameters are far less common and rarely need measurement or control, such as color, flavor, turbidity, sugar content, etc. The continued effort of human beings makes it possible to explore new facts and therefore newer parameters. The instrumentation will always strive to develop sophisticated techniques to address such parameters.

## 1.4 Classical Sensors and Transducers

Transducers and sensors are the basic devices needed to sense and convert the physical parameters to a convenient form. The convenient form of the signal is, most commonly, an electrical signal, which has many advantages compared to other forms such as mechanical, optical, fluidic, etc.

Physical parameters that need measurement in industrial, laboratory, medical, space, household, etc., are large in number. Transducers required for the most common physical parameters (almost 90%) include temperature, pressure, flow, and level.

Although it is not always specifically mentioned, a transducer may comprise two or more stages. The primary stage converts the physical parameters into other more easily measurable physical parameters, while the subsequent stages convert it to an electrical form. The first stage is called a sensor and the second stage is the transducer. A good example for a two-stage transducer is the load cell. A mechanical elastic member converts the load to a displacement or strain signal, while a resistive strain gauge converts the strain to electrical voltage on the application of a voltage. Mechanical devices like bourdon tube, bellows, diaphragm, spring, rings, levers, etc., are examples of primary sensors that convert the mechanical load or force to displacement signal.

A sensor is unique while a transducer is composite. A sensor structure gets more physically attached to the environment under operation than the transducer. Citing the same example of the load cell, the mechanical elastic member experiences the physical deformations and displacements in its molecular structure due to the application of load or force, whereas the displacement is converted to electrical signal using an electrical strain gauge. Here, the resistive gauge element does not directly react with the deformation, so it is a transducer.

### 1.4.1 Classification

Transducers are classified on the basis of various factors such as the type of electrical signal that a transducer develops. Hence, it can be classified as an analog or a digital transducer. Although most transducers are analog in nature, digital transducers are becoming popular due to their added features and advantages.

As explained earlier, a transducer may consist of a single unit, i.e., only the primary sensor or a combination of two stages. Thus, a transducer can be classified as a primary transducer or a secondary transducer. Transducers are designed based on different working principles; however, this author prefers to group the working principles into two classes—variable parameters type or self-modulating type, and the self-generating type. These types are interchangeably termed as active and passive transducers also. In the first type, the physical parameter causes the transducer to change an electrical parameter like resistance, capacitance, inductance, etc. These variable electrical quantities are converted to electrical voltage, current, or frequency with the help of an appropriate circuit powered by an external voltage source. Therefore, they are called as active transducers. In the other type, due to some inherent quality of the transducer, an electrical voltage is generated when the transducer interacts with the physical parameter and therefore separate power supply is not used in the transducer. This is why the transducer is termed as passive transducer. Many authors define passive and active transducers interchangeably; however, other processing circuits such as amplifiers, filters, etc., may have some active devices.

Although we commonly understand that a transducer transforms a non-electrical quantity into an electrical quantity, there is one counterpart of this, which is used for the conversion of electrical energy to mechanical or other form of energy. Taking the electrical instrumentation and measurement system as a reference, the first type of transducer is called an input transducer, while the other type of transducer is called an output transducer. The output transducers are also called *actuators*.

Most importantly, in the light of intelligent system, transducers are continuously being improved and featured with several added advantages, one of which is *intelligence*. In view of this, transducers can also be classified based on their intelligence as *dumb* transducers and *intelligent* transducers. Dumb transducers are mainly classical or conventional without any added intelligence. Intelligent transducers are further categorized into several subgroups based on their role of intelligence.

Transducers or sensors are sometimes named after the signal they handle, say, mechanical, thermal, optical, magnetic, pneumatic, radiation, biological, etc. In one sense, these sensors convert the corresponding physical signal into another form of signal; however, sometimes a transducer uses the corresponding physical energy as an intermediate signal and so such transducers are also termed by the same name. For example, an optical encoder for angular position measurement uses the optical signal, a radioactive sensor can be used to measure the level of liquid where radiation is the mediator only-calling them optical and radioactive transducer, respectively. Therefore, such nomenclature is always confusing and it is difficult to exhaustively classify the vast family of transducers. Various texts follow various methods of classifying the transducers, but this author finds the following classification as logical and optimal:

1. Self-generating type
2. Variable parameter type
3. Pulse- or frequency-generating type
4. Digital type

### 1.4.2 Self-Generating Transducers

Some materials have an inherent property due to which when the material is exposed to external stimulation, a voltage is developed. Transducers made of such materials are classified as self-generating transducers. Some examples of self-generating transducers are piezoelectric crystal, thermocouple, pH electrode, radioactive sensors, photocells, electrodynamic, electromagnetic, and eddy current type. Since a transducer does not have an external power supply, the voltage developed by almost all the self-generating transducers is of very low strength and cannot be directly used for displaying or actuating a control device. Therefore, voltage or current amplification is necessary before applying it to an indicator, a recorder, or a control device. Since corruption of the signal by noise is a very common problem in case of transducers generating weak signals, filtering of the signal to remove noise also becomes necessary. A self-generating transducer does not require an extra source of power supply, which is an advantage.

### 1.4.3 Variable Parameter Transducers

A major part of the transducers fall under this category of transducers. Unlike self-generating transducers, a variable parameter–type transducer cannot develop a voltage of its own; however, an electrical parameter of the device changes in proportion to the physical variable applied. The change in electrical parameter can be in

1. Resistance or conductance
2. Capacitance
3. Magnetic properties

#### *1.4.3.1 Resistance or Conductance Variation*

The resistance variation of a material is exploited for making these transducers. The geometrical or molecular configuration of the material is made to change causing its resistance vary, proportionately when a physical variable is applied. The variation of resistance is changed to a variation of voltage using a resistive circuit. The circuit uses a separate voltage source for the generation of the signal. Examples of resistive transducers and the physical variables that can be measured are [1]

Potentiometer—displacement, load, force, etc.

Strain gauge—strain, pressure, load, torque, etc.

Resistive thermometer—temperature, flow, etc.

Thermistor—temperature

Hygroscopic sensor—moisture content, etc.

E-nose sensor—flavor, humidity, etc.

#### *1.4.3.2 Capacitance Variation*

In capacitive transducers, the change in capacitance may be realized either by changing the dimensions of the capacitor or by changing the dielectric property of the material of the capacitor. When such variations confirm proportionality, the capacitive transducers can measure various kinds of physical parameters. The variation of the capacitance is utilized in a capacitive measuring circuit, namely, a capacitance ac bridge, an oscillator, an integrator circuit, etc. Examples of capacitive transducers are [1]

Variable area capacitor—angular displacement

Charging/discharging capacitor—rotational speed

Variable dielectric capacitor—moisture content, humidity, density, and liquid level

#### 1.4.3.3 Magnetic Properties Variation

The working principle of a magnetic transducer relies on the fact that one or more of the following magnetic properties change in accordance with the many physical variables. These magnetic properties are self-inductance, mutual inductance, reluctance, etc. In such magnetic transducers, the inductance of a magnetic coil is allowed to change by varying either the magnetic properties of the core material or the air gap in the magnetic core. In both cases, the inductance of the transducer changes due to change in the permeability of the magnetic core.

Variable inductance transducers are mainly used for dynamic measurements of physical variables such as pressure, displacement, acceleration, force, angular position, etc. A proportional voltage signal is developed with the help of an excitation voltage applied to a circuit, which comprises the transducer. Examples of magnetic transducers are single-core reluctance pressure sensor, linear variable differential transformer, rotational variable displacement transformer, electrodynamic rotary motion transducer, synchro angle transmitter, noncontact proximity sensors, and magnetostrictive force transducer.

#### 1.4.3.4 Pulse or Frequency-Generating Type

When self-generating types of transducers produce a train of pulses, frequency of which is proportional to the input physical variable, however, with constant amplitude, the transducer is called a pulse-generating transducer. The output pulses of such a transducer are applied to a digital counter, which determines the number of pulses during a specific time period, which is finally calibrated in terms of the input physical signal. Some examples of pulse- or frequency-generating transducers are optical disc type of rotational transducer, turbine flowmeter, radioactive flowmeter, shaft speed meter, pressure-sensing oscillator, shaft position transducer, and capacitive controlled humidity-sensing oscillator [1].

Digital transducers can generate a digital signal proportional to the physical variable, which can be conveniently interfaced to microprocessors or computers. Digital transducers have four distinct forms:

1. Direct digital encoding
2. Pulse, frequency, and time encoding
3. Analog-to-digital encoding
4. Analog-to-digital conversion

### 1.4.4 Radioactive Transducer

The absorption pattern or depth of penetration of radioactive rays liberated in a medium by radioisotopes such as $^{60}Co$, $^{137}Cs$, $^{192}Ir$, etc., is utilized in radioactive transducers. The radioactive rays liberated by a radioisotope are α, β, γ, and neutron radiations. The basic characteristics of radioactive rays that are important for instrumentation are

1. Penetrating power
2. Half-life
3. Half-distance

#### *1.4.4.1 Penetrating Power*

The penetrating power of α radiation (about 11 cm in air and 0.1 mm in fabric) is the lowest of all types of radioactive radiations. Moreover, it is easily absorbed by a sheet of writing paper and an aluminum foil of 0.006 cm thickness. Penetrating power of β radiation is higher than α radiation due to its smaller mass (10 m in air and 10–12 mm in fabric) and it can be stopped by an aluminum layer of 5–6 mm and a lead sheet of 1 mm thickness. The γ radiation has similar characteristics as that of x-rays and has the highest penetrating power (several inches of lead). When a radiation travels through a medium, its radioactive strength in the medium can be expressed by

$$I = I_0 e^{-\mu_L d} \tag{1.1}$$

where
$I$ is the strength of radiation after absorption
$I_0$ is the strength of radiation before absorption
$\mu_L$ is the linear absorption coefficient of the medium
$d$ is the distance traveled in the medium

$$= \rho\mu_m$$

where
$\rho$ is the density of the medium
$\mu_m$ is the mass absorption coefficient of the medium

The unit of radioactivity or strength of radiation is Curie (C).

The absorption coefficient varies as some of the parameters of the medium such as density, compactness, moisture content, impurities present, etc. vary. These parameters or some of their dependent variables can be measured based on this absorption principle of the radioactive rays. Two important properties of radioactive materials for instrumentation are *half-life* and *half-distance*.

#### 1.4.4.2 Half-Life

The continuous disintegration of the radioisotope reduces its strength. The time taken by the radioisotope to fall to half of its strength is known as half-life. The half-life of a radio isotope is given by

$$t_{half} = \frac{0.693}{\lambda} \tag{1.2}$$

where $\lambda$ = decay constant.

The half-life of radioactive sources varies from days to months to years. For the use of instrumentation, the half-life of a source should be high so that frequent recalibration of the detector is not required. In all radioactive sources, the date of activation and half-life is written on them by the manufacturer.

#### 1.4.4.3 Half-Distance

Half-distance of sources depends on the source energy level as well as the material of the medium. Half-distance is the thickness of the medium, which will allow only half the value of the source' intensity entering the medium. This is important for selecting a source depending on the thickness of the medium.

A basic radioactive instrumentation scheme for detecting physical parameters requires the following components:

1. Radioactive source
2. Radioactive detector
3. Electronic processing unit
4. Indicator or recorder

Some of the radiation detectors are

1. Geiger–Muller counter
2. Scintillation counter
3. Ionization chamber
4. Proportional counter
5. Semiconductor counter

The electrical signal obtained from a radiation detector is conditioned by an electronic processing unit and the processed signal is displayed by an indicator or recorder.

### 1.4.5 Semiconductor Sensors

The classical transducers (macrosensors) are developed from materials such as conductors, crystals, dielectric, magnetic, and optical fibers, where the sensor principle relies on some physical or chemical properties shown by them. There is one more type of material—semiconductor—which is also used to make sensors. Semiconductor can be used in two levels—as material or as device. Whatever may be the level of use, semiconductor sensors are gaining importance for two reasons. First, they lead to microsensors, which are possible to be manufactured by micromachining in mass production with low cost. The second reason is that single-chip integration of signal processing along with the sensor is possible. The second concept leads to intelligent or smart sensor (microsensor).

#### *1.4.5.1 Semiconductor Thermal Sensors*

A good example of the semiconductor sensor is the integrated circuit (IC) thermal sensor. The basic concept of a semiconductor thermal sensor is that the forward characteristic of a *p*–*n* junction diode is temperature sensitive and of the order of −2 mV/°C for silicon diode. A better dependency in respect of linearity is observed in base emitter voltage $v_{BE}$ of a transistor supplied with a constant collector current $I_C$. The expression for $v_{BE}$ is given by

$$v_{BE} = \frac{KT}{q} \ln \frac{I_C}{BT^3} + V_{q0} \tag{1.3}$$

where

$K$ is Boltzmann's constant = $1.3807 \times 10^{-23}$ J/K
$V_{q0}$ is the band gap voltage = 1.12 V at 300 K for silicon
$B$ is the constant that depends on geometry and doping level and is independent of temperature
$T$ is the absolute temperature
$q$ is the charge on an electron
$I_C$ is the collector current

Equation 1.3 shows the dependence of temperature; however, it also depends on collector current. This is the reason why a single transistor is not attractive to be used as a temperature sensor. The alternative is a single sensor, having two identical transistors with different collector currents but

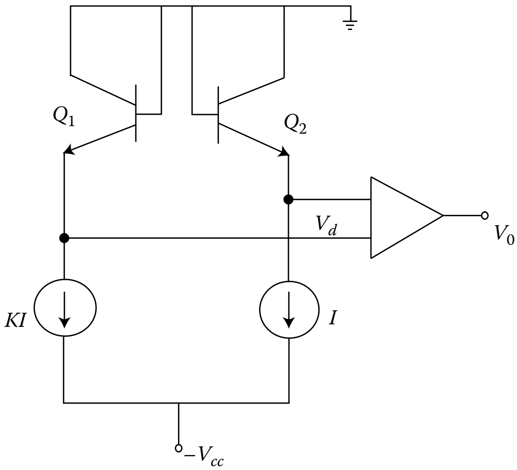


**FIGURE 1.2**
Dual transistor thermal sensor.

constant emitter current densities, as shown in Figure 1.2. At temperature $T$ for both transistors, the difference voltage is given by

$$v_d = v_{BE1} - v_{BE2} = \frac{KT}{q}\ln\frac{I_{C1}}{BT^3} + V_{q0} - \frac{KT}{q}\ln\frac{I_{C2}}{BT^3} + V_{q0} \tag{1.4}$$

$$v_d = \frac{KT}{q}\ln\frac{I_{C1}}{I_{C2}} \tag{1.5}$$

If $(I_{C1}/I_{C2})$ is constant, $v_d$ is directly proportional to only $T$.

IC thermal sensors are commercially available in a variety of forms in the range of −55°C to 150°C. These are generally available in metal (TO-52) or plastic (TO-92) packages. Analog Devices (Norwood, MA) manufactures the AD590 and AD592, which are two terminal currents proportional to absolute temperature (IPAT) sensors. The supply voltage for the AD series of thermal sensors is 4–30 V and when properly calibrated, outputs a current of 273.15 μA at 0°C and 298.15 μA at 25°C. By using an output load resistor of 1 kΩ, the sensitivity obtained is 1 mV/°C; however, an offset of 0.273 mV (at 0°C) is required to be nullified using an operational amplifier.

Similar ICs are manufactured by the National Semiconductor Corporation (Santa Clara, CA); however, these ICs are designed as voltage proportional to absolute temperature (VPTAT). LM34, LM35, LM134, LM135, LM234, LM235, and LM335 series of ICs of the National Semiconductor Corporation provides a sensitivity of 10 mV/°C over a range −55°C to 150°C. In these ICs, the offset of 2.73 mV (at 0°C) should be nullified while amplifying. These IC sensors are suitable for ambient temperature sensing and temperature compensation in other sensors.

#### 1.4.5.2 Semiconductor Pressure Sensors

Most pressure sensors are resistive strain gauge based, where the strain gauges are bonded over a diaphragm strained due to the application of pressure. The strain gauges are connected in Wheatstone bridge configuration and the output leads of Wheatstone bridge are connected to an external circuitry. But semiconductor pressure sensors utilize strain gauge technology fabrication in miniature sizes. In a design of IC Sensors Inc., Milpitas, CA, four piezoresistive strain gauges are diffused into the surface of a single crystal diaphragm of silicon to form the Wheatstone bridge.

Motorola Semiconductors manufactures another IC, MPX series of pressure sensors where a single *p*-type diffused silicon strain resistor is deposited on an etched single crystal silicon diaphragm. Additionally, a patented X-shaped four-terminal resistor is deposited with two current taps and two voltage taps. In this configuration, when a current is passed through the current terminals and a pressure is applied at a right angle to the current direction, a transverse electric field is developed across the voltage terminals giving rise to an emf. Motorola µPX 3100 series sensors comprise of an additional signal conditioning circuit with four operational amplifiers and laser-trimmed resistors on the margin of the silicon wafer base. In a further enhanced series, µPX 2000, five laser-trimmed resistors and two thermistors are also deposited on the margin of the silicon chip that provides temperature effect.

#### 1.4.5.3 Semiconductor Magnetic Sensors

When a magnetic field is placed perpendicular to the direction of charge carrier in a *p-n* junction diode, the carriers are deflected by the magnetic field due to Lorentz force. If the carriers can be deviated to a high recombination region, the *I–V* characteristic of a diode can be controlled by magnetic field intensity. This makes the diode a magnetodiode, providing magnetic sensitivity. Similarly, this magnetic sensitivity can be obtained from a magnetotransistor, which consists of a base, an emitter, and two collectors. A magnetic field unbalances the two collectors resulting in unbalanced collector currents. The difference between the collector currents is proportional to the applied magnetic field intensity.

However, the above devices are found commercially unsuitable due to poor repeatability, poor sensitivity, and high offset error.

#### 1.4.5.4 Hall-Effect Sensors

Lorentz force is defined as the force on electrons when a magnetic field $H$ is applied to a current-carrying conductor and is given by

$$F = ev \times H \tag{1.6}$$

where
  $e$ is the charge on electron
  $v$ is the electron velocity

$e$ is given by

$$e = -q = -1.6 \times 10^{-19}\ \mathrm{C}$$

The force causes some electrons to deviate from their paths and the electrons drift to one side of the conductor. This phenomenon gives rise to a noticeable increase in electronic resistance, termed as "magnetoresistive effect." In semiconductors, this magnetoresistive effect can be manifold, say, 10–$10^6$ on application of a magnetic field of a few tesla.

On the basis of the above effect, Edwin H. Hall demonstrated in 1879 that an electric potential ($V_H$) is generated in a current-carrying semiconductor, while a magnetic field was applied perpendicular to the direction of current (Figure 1.3). The Lorentz force can be shown by a vector equation as

$$F = q(V \times B) = \{q\,|\,v\,|\,|\,B\,|\sin\theta\}u \quad \text{Nw} \tag{1.7}$$

The force direction is given by right-hand screw rule. If electrons are the carriers, then

$$-qE_y = -qv_nB_z \tag{1.8}$$

$$E_y = v_nB_z \tag{1.9}$$

In $n$-type semiconductor, the average drift velocity $v_n$ of electron is given by

$$v_n = -\frac{J_x}{qn} \tag{1.10}$$

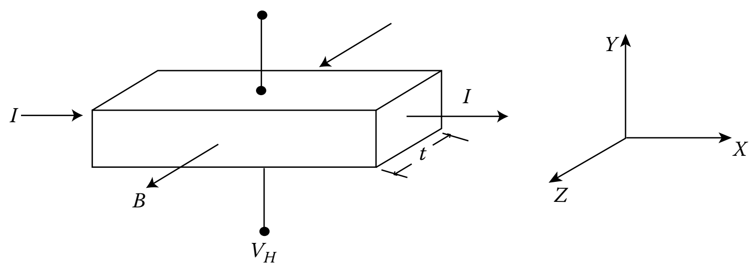


**FIGURE 1.3**
A Hall effect sensor.

where
$J_x$ is the current density in $x$-direction
$n$ is the electron doping density

From Equations 1.9 and 1.10 we can write

$$E_y = -\frac{J_x B_z}{qn} \tag{1.11}$$

The current density in $x$-direction

$$J_x = \frac{I}{t} \tag{1.12}$$

The Hall voltage developed

$$V_H = E_y = -\frac{IB_z}{(qnt)}$$

$$= R_H \frac{IB_z}{t} \tag{1.13}$$

where $R_H = -(1/qn)$ is called Hall coefficient.
Similarly, for $p$-type semiconductor

$$R_H = +\frac{1}{qn} \tag{1.14}$$

Hence, the Hall voltage depends on the current $I$, the applied magnetic field $B$, the thickness $t$ of the material, and the Hall coefficient. The Hall coefficient describes the electrical properties of the material and doping density.

Other interfering factors to the Hall sensor are temperature and piezoresistivity. The temperature effect can be compensated by using a constant current source instead of a voltage source.

#### *1.4.5.5 Photodiodes and Phototransistors*

The energy of optical radiation can raise the electrodes of a $p$–$n$ junction semiconductor from valence to conduction band. Thus, it can generate an electric voltage of its own, which is called a photovoltaic effect. When the radiation energy is greater than band gap, it generates an additional electron–hole pair. The accumulation of electron in $n$ region and of holes in

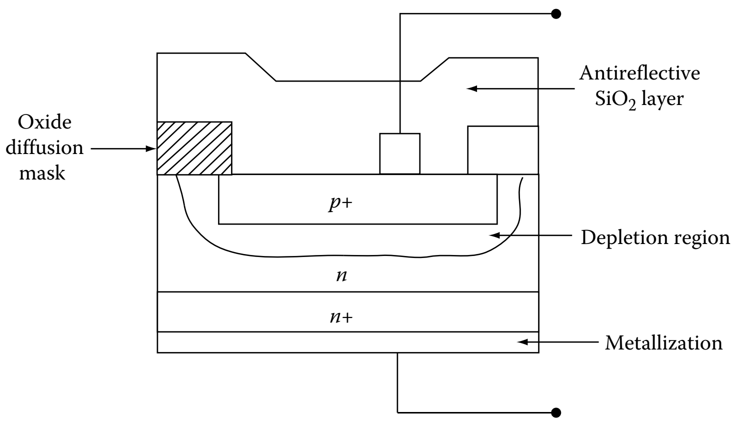


**FIGURE 1.4**
Layout of a photodiode.

*p* region causes a potential across the load connected to output leads of the *p*–*n* junction. Higher the radiation intensity, greater is the potential with a limitation to the band gap energy. This device is a self-generating device; however, an external reverse bias voltage is applied to increase the width of the depletion layer to provide a faster response and a current multiplication proportional to the incident radiation. Figure 1.4 shows the layout of a photodiode.

The sensitivity and spectral bandwidth of photodiode can be improved by placing an intrinsic semiconductor layer between *p* and *n* regions forming a *p*–*i*–*n* diode. The incident photons are absorbed in the intrinsic region causing a lower recombination rate.

Spectral selectivity of a photodiode can be obtained by using different materials in the absorption window for the semiconductor material. For example, silicon is transparent to radiation with a wavelength higher than 1100 nm, but a short wavelength radiation penetrates only to a low depth; therefore, the *p*-doped zone is made very thin.

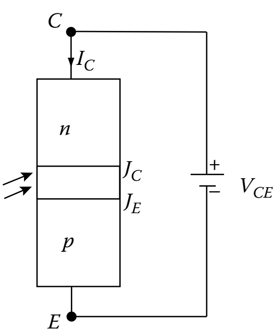


**FIGURE 1.5**
A phototransistor.

On the other hand, the window can be used as a filter such that, say, plastic window for $850\,nm < \lambda < 100\,nm$, and germanium for $800\,nm < \lambda < 1800\,nm$. Most commercial photodiodes are available for wavelength ranging for 0.2–2 μm.

The phototransistor (also called photodiode) is obtained by combining a photodiode and an *n*–*p*–*n* transistor. The phototransistor is usually connected in common-emitter configuration with the base open for radiation to strike it. Figure 1.5 shows a phototransistor biased in common-emitter configuration. The junction $J_E$ is slightly forward biased; due to the open base and junction, $J_C$ is reverse biased. Under unexcited condition, thermally generated electrons cross the base to the collector and holes cross the collector to the base. This produces collector current due to the reverse saturation current. When the light is incident on the base, minority carriers are generated to increase the reverse saturation current. Phototransistors are many times sensitive than photodiodes.

### 1.4.6 Array-Based Sensors

Till now, the sensors discussed above are considered to work alone or in tandem to perform a particular sensing operation. These sensors are mainly used to generate a signal function proportional to the measurand; however, they are not capable of deriving statistical metrics, signal features, and patterns as any human or animal sentience can do.

The human or animal sentience—sight, hearing, smell, touch, and taste—perform differently to a stand-alone and dumb sensor. For example, human olfactory system is an array of hundreds of olfactory receptor neurons of the nose and produces a pattern of signal that is transmitted to the brain. Each olfactory receptor neuron contains 8–20 cilia that receive the molecular odorants and convert it to electrical stimuli. The brain recognizes the pattern of the signal rather than their magnitudes. The pattern becomes a signature of the odorant because the olfactory receptors have different sensitivity to different odors. This technique of human or animal olfactory system is mimicked by the electronic nose. E-nose comprises of an array of gas sensors, each with different sensitivity to different odorant molecules. The signal generated is fed to a computer (or a microcomputer) to discriminate the class with the help of an intelligent software such as artificial neural network (ANN) or fuzzy logic.

Signal detection using an array of sensor elements is an attractive solution to overcoming sensitivity and the dimensionability limitation of a single sensor element. The three important stages of array-based signal processing and pattern recognition are

1. Preprocessing
2. Feature extraction
3. Classification and decision making

#### *1.4.6.1 Preprocessing*

Different sensors in an array respond to the physical signal in different ways, say, in case of chemoresistive and polymer sensors, there is a change in conductivity, whereas in the case of a quartz crystal microbalance (QCM) or a surface acoustic wave (SAW), sensors are frequency sensitive. Therefore, in the first type of sensors, resistive circuits are used and in the second type of sensors, oscillator circuits are used. The preprocessing unit performs smoothing, normalization, and drift correction of the data. The preprocessed data is then stored in the computer for analysis.

#### 1.4.6.2 Feature Extraction

This stage adopts software techniques to extract some hidden information from the data. Features are some unique signature of a class of data. Supervised linear transformations such as principal component analysis (PCA) are mostly used for feature extraction. Nonlinear transforms such as Kohonen self-organizing maps are also used in many cases.

#### 1.4.6.3 Classification and Decision Making

In supervised learning, known features are assigned to known classes and the unknown sample is placed on the class assignment. The classification stage assigns to the set of data a class label to identify the signal by comparing its features with those compiled during training. The tools available for performing classification are K-nearest neighbors (KNN), Bayesian classifiers, and ANN. Accordingly, the classifier takes a decision whether the data "falls within the class" or "does not fall," etc.

### 1.4.7 Biosensors

Micro/nanofabricated biochemical sensor technology has become popular recently. Such devices couple a molecular recognition process to a physiochemical microsensor that results in a sensitive signature of a molecular event [2]. With the advent of micro/nanofabricated technology, the miniaturization of the macroscale biosensors has become possible. Major applications of such devices are in low-cost medical diagnostic equipment, drug recovery, and proteomics research. The advantages of micro/nanofabricated biosensors are smaller in size, lower manufacturing cost per unit, improved sensitivity, batch manufacturing, lower energy consumption, capacity to handle smaller sample volume, scalability to large arrays, label-free detection, shorter analysis time, extended measurement bandwidth, differential measurement, and suitable construction of experimental controls.

Examples of such microsensors are ISFETS, micro/nanomechanical cantilevers, magnetic bead technologies, carbon nanotube sensors, and holographic sensors [1].

### 1.4.8 Actuating Devices

An actuator is a kind of inverse transducer since it converts back an electrical control signal to a mechanical form to produce a physical effect or action to actuate the final control element, such as a pneumatic or hydraulic effect such as pneumatic and hydraulic actuators. Actuators are designed and manufactured in a variety of sizes to generate force for different sizes of actions. Hence, it is important to select the right type of actuator for a specific application. The following points should be kept in mind to make the selection of the actuator simpler [1]:

1. Type of power source (electrical, pneumatic, or hydraulic)
2. Reliability required
3. Mechanical power (torque or thrust) required
4. Control functions (on/off, PID, etc.)
5. Cost

The following two types of actuators are very commonly used.

#### *1.4.8.1 Electrical Solenoids*

Solenoids can generate mechanical energy using the principle of magnetodynamics. In its basic form, a coil is excited by the electrical signal, which produces electromagnetism. The magnetic force moves a plunger where the plunger may be freestanding or spring loaded. The electrical voltage or current signal applied to the coil generates a rectilinear motion in the plunger to make a valve open or close. A solenoid is designed based on voltage or current it receives and the force required to move the assembly connected to the plunger. The duty cycle of the plunger motion (percentage of motion time to total time) is also important for considering plunger thermal constraints.

#### *1.4.8.2 Electrical Motors*

Various types of control machines like conveyors, blowers, stirrers, mixers, and pumps are run by electric motors. Sizes and types of such motors depend on the speed and torque required by the process operation. Moreover, all motors cannot be controlled with the same precision; therefore, the motor employed depends upon the precision of control. Any motor used to control some mechanical action can be said to be an actuating motor.

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# 2

# *Sensor Performance Characteristics*

## 2.1 Introduction

The successful operation of a transducer depends on its performance characteristics. When a transducer is designed, the design parameters are chosen so as to meet the desired input–output amplitude relationship; however, similar attention should also be given to meet other factors like linearity, hysteresis, lag, temperature effect, etc. Many traditional sensors designed with high sensitivity (output/input) might show poor linearity, high hysteresis, high lag, or high temperature effect.

For example, low current rating of a resistive potentiometer for displacement can be obtained by choosing a high value of resistance of the potentiometer, but a high resistance decreases the linearity of the potentiometer. On the other hand, an increase in input voltage increases the sensitivity, which in turn increases the current drawn by the potentiometer. Therefore, a compromise has always to be made to achieve the optimum characteristics.

Researchers and transducer manufacturers always try to tune transducers to the best characteristics within the scope of practical design parameters. Improvement in the performance characteristics of instrumentation system is a matter of concern for instrumentation engineers. Hence, it is imperative to study the performance characteristics of a transducer.

An instrument should always work satisfactorily under various operating conditions. The conditions relate both to the measured and to the interfering inputs. The instrument should pick up the measurand with highest sensitivity but should respond least to the interfering inputs. For example, a strain gauge should vary fairly well with the applied strain, but the changes in the gauge resistance due to temperature change should be as low as possible. Some of the transducer characteristics relate to the measurand of interest, while some are related to the interfering inputs, or to both.

Since a measurand can be quantified in two domains, i.e., static domain and dynamic domain, the performance characteristics are also based on these two factors—static and dynamic. The characteristics associated or relevant to a signal under steady or static conditions are static characteristics. Hence, the characteristics associated with an instrument that works with a measurand, which does not vary with time, are called static characteristics. On the other hand, the factors that signify the functioning of an instrument for a measurand of time varying with nature are called dynamic characteristics. Although the characteristics are grouped under these two categories, some of the static characteristics may also be applicable in dynamic conditions. For example, *resolution* is a term categorized as a static performance, but when the system works under a dynamic condition, the term *resolution* is also equally applicable. Similarly, sensitivity of a transducer in a dynamic condition refers to the sensitivity over a range of input frequency, while static sensitivity is fixed for a particular transducer. In some cases, the dynamic sensitivity may be equal to the static sensitivity for a specific range of frequencies. There are still limitations for certain instrumentations that are designed for use in static conditions only and will not show good performance in dynamic condition. All such characteristics together are of distinct importance for intelligent signal processing systems.

## 2.2 Static Characteristics

As already stated, static characteristics are related to the amplitude of the response or the output of the system when the measurand or input does not vary with time. Compared to static, dynamic systems are less in number since most signals vary very slowly; hence, static characteristics alone suffice for analyzing the performance of these systems.

### 2.2.1 Accuracy and Precision

*Accuracy* can be defined as the capacity of an instrument system that gives a result that is near to the *true* or *ideal* value. The *true* or *ideal* value is the standard against which the system can be calibrated. The measured value of most systems fails to represent the true value either due to the effects inherent to the system or other interfering inputs such as temperature, humidity, vibration, etc. The accuracy of a system can be mathematically expressed as

$$A = 1 - \left| \frac{Y - X}{Y} \right| \tag{2.1}$$

where

$X$ is the measured value

$Y$ is the true or ideal value

Accuracy is generally expressed in percentage form as

$$\%A = A \times 100 \tag{2.2}$$

**Example 2.1**

In a strain gauge of resistance 120 Ω, the change in resistance of the gauge for three consecutive strain readings measured by a very accurate measuring instrument is as follows:

| | | | |
|---|---|---|---|
| Strain $(\varepsilon) \times 10^{-6}$ | 100 | 150 | 200 |
| Change in resistance $(\Delta R)$, Ω | 0.025 | 0.037 | 0.047 |

The gauge factor of the strain gauge is 2.0. Determine the accuracy of the three readings.

**Solution**

The resistance of the gauge $= R = 120\ \Omega$
The gauge factor $= \lambda = 2.0$
From the equation of the gauge factor of a strain gauge

$$\lambda = \frac{\Delta R/R}{\varepsilon} = \frac{\Delta R}{\varepsilon R}, \text{ where } \varepsilon \text{ is applied strain}$$

$$\therefore \Delta R = \lambda \varepsilon R$$

From the gauge factor, the change in resistance $\Delta R$ for the given strain value (first reading) can be found as

$$\Delta R = 2.0 \times 100 \times 10^{-6} \times 120$$
$$= 0.024\,\Omega$$

Similarly, the values of $\Delta R$ for the other two readings are 0.036 and 0.048 Ω, respectively. These three values of $\Delta R$ are the true or ideal values, while the values given in the problem are the measured values. Therefore, the accuracy of the first reading is calculated as

$$A_1 = 1 - \left|\frac{0.024 - 0.025}{0.024}\right|$$
$$= 1 - \frac{1}{24} = \frac{23}{24}$$

and

$$\% A_1 = 95.83\%.$$

Similarly, the accuracies of the other two readings are

$$\% A_2 = 97.22\%$$

$$\% A_3 = 97.91\%$$

In the above example, it is observed that the accuracy gradually increases as the transducer is used at higher values of its operating range. Although a transducer shows different values of accuracies, at different operating points as in the above example, its accuracy is generally rated as a maximum likely deviation from the true value. Therefore, the strain gauge of the above example has an accuracy of 95.83%, which corresponds to a reading that shows a maximum percentage deviation from the true value.

If we want the percentage deviations of the three readings from their true values, they can be calculated as

$$\text{First reading:}\quad \frac{0.024-0.025}{0.024}\times 100 = -4.16\%$$

$$\text{Second reading:}\quad \frac{0.036-0.037}{0.036}\times 100 = -2.77\%$$

$$\text{Third reading:}\quad \frac{0.048-0.047}{0.048}\times 100 = +2.08\%$$

It is observed that the deviation may be either positive or negative with respect to the true value. Since the percentage deviation indicates the accuracy, it is also alternatively used to represent accuracy. Therefore, this accuracy of the strain gauge for the above example can also be ±4.16%.

*Precision* is a characteristic of a measuring system that indicates how closely it repeats the same values of the outputs when the same inputs are applied to the system under the same operating and environmental conditions. Although there is very less likelihood that the output response is exactly repeated, the closeness of repetition can be considered by taking a cluster of the repeating points. The degree of this precision is expressed as *the probability of a large number of readings falling within the cluster of closeness*. However, such closeness may not have closeness to the true value. Hence, an accurate system is also precise but a precise system may not be accurate.

Let us take $N$ readings of the measurements of which the mean value is

$$\bar{X}_n = \frac{1}{N}\sum_{n=1}^{N} X_n \quad N = \text{Number of data} \tag{2.3}$$

The precision of a measurement is given by

$$P = 1 - \left|\frac{X_n - \bar{X}}{\bar{X}}\right| \tag{2.4}$$

Let us consider the same strain gauge discussed in Example 2.1 for each of the three strain values, following repeated sets of $\Delta R$ values obtained:

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Strain $(\varepsilon)\times10^{-6}$ | 100 | | | | | | | | | |
| Change in resistance $(\Delta R)$ Ω | 0.025 | 0.0252 | 0.0251 | 0.0248 | 0.0247 | 0.0253 | 0.0250 | 0.0250 | 0.0251 | 0.0249 |

The mean of the readings is 0.02501 Ω. In the above set of readings, the precisions calculated using Equation 2.4 are 99.96%, 99.24%, 99.64%, 99.16%, 99.76%, 98.84%, 99.96%, 99.96%, 99.64%, and 99.56%.

If the accuracies for all readings are determined, their mean value is found as 95.41%. Hence, although the readings are not accurate, they are precise. Let us consider an accurate set of readings for repeated input strain of $200\times10^{-6}$.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Strain $(\varepsilon)\times10^{-6}$ | 200 | | | | | | | | | |
| Change in resistance $(\Delta R)$ Ω | 0.047 | 0.049 | 0.050 | 0.044 | 0.048 | 0.045 | 0.046 | 0.051 | 0.052 | 0.052 |

The mean of the readings is 0.048 Ω. The precisions calculated using Equation 2.4 for each of the readings are 97.91%, 97.91%, 95.83%, 91.66%, 100%, 93.75%, 95.83%, 93.75%, 91.66%, and 91.66%. It is evident that the accuracy for the set of readings is high, yet the precision is lower than the previous set of readings. Here we have examined the two sets of readings from which it is clear that the accuracy brings the readings closer to the true value, while precision makes the system capable of repeating the outputs more closely.

### 2.2.2 Error, Correction, and Uncertainty

The deviation of the output or response of a measurement system from the true or ideal value is called an error of the system. The error is calculated by taking the difference of the measured value and the true value. This is called absolute error. Sometimes, the error is calculated as a percentage of the full-scale range or with respect to the span of the instrument. Therefore, the error is expressed as

$$\varepsilon = X - Y \tag{2.5}$$

and

$$\%\,\varepsilon = \frac{X - Y}{Y_{FS}} \times 100 \tag{2.6}$$

where, $Y_{FS}$ = true or ideal full-scale value.

In common cases, the percentage error is expressed with respect to the true value as

$$\%\,\varepsilon = \frac{X - Y}{Y} \times 100 \tag{2.7}$$

This is called relative error.

Revisiting the strain gauge problem, the ideal and measured values of change in resistance ($\Delta R$) for the second readings are

$$Y = 0.036\,\Omega$$

$$X = 0.037\,\Omega$$

Therefore, the absolute error is

$$\varepsilon = (0.037 - 0.036)\,\Omega$$

$$\varepsilon = 0.001\,\Omega$$

and the relative error is

$$\%\,\varepsilon = \frac{0.001}{0.036} \times 100$$

$$= 2.77\%$$

Now let us consider the third reading of 200 μ strain and the full-scale operating range of the strain gauge, this relative error with respect to the true maximal value is

$$\%\,\varepsilon = \frac{0.001}{0.048} \times 100$$

$$\%\,\varepsilon = 2.08\%$$

But if the relative error is calculated with respect to the true value of the span of the strain gauge, taking the first reading as the minimal value

$$\text{Span} = (0.048 - 0.024)\,\Omega$$

$$= 0.024\,\Omega$$

Hence

$$\%\varepsilon = \frac{0.001}{0.024} \times 100$$

$$\%\varepsilon = 4.16\%$$

During the calibration of an instrument, the error has to be compensated using a calibrating circuit, a microprocessor or a microcomputer used to implement in software. The *correction* is the value to be added with the measured value to get the true value. Hence, the correction can be expressed as

$$\text{Correction}(r) = Y - X$$
$$= -\varepsilon \quad (2.8)$$

Depending upon the polarity of deviation from the true value, the correction may be either positive or negative. For the first and second readings of the strain gauge, the correction $(r) = -0.001\ \Omega$, while for the third reading the correction $(r) = +0.001\ \Omega$.

*Uncertainty* is a term similar to error, which is used to express the deviation of the instrument from the true value. Uncertainty is the range of the deviation of the measured value from the true value. In a set of readings, uncertainty indicates the range of errors. For the strain gauge of the problem, the maximum error is 0.001 Ω and in all the three readings; however, the direction of deviation is positive in the first and second readings, while it is negative in the third reading. Therefore, the uncertainty is ±0.001 Ω. Hence, the uncertainty can be expressed as a range: $-r_{max}$ to $+r_{max}$ or $\pm r_{max}$

Uncertainty is also alternatively defined as a limiting error; however, it is expressed as a percentage of full-scale reading.

### 2.2.3 Repeatability, Reproducibility, and Hysteresis

*Repeatability* of an instrument signifies the degree of closeness of a set of measurements for the same input obtained by the same observer with the same method and apparatus under the same operating condition, but for a short duration of operation. Quantitatively, it is the minimum value by which the absolute value of the difference between two successive repeated measurements exceeds with a specific probability. If not specifically mentioned, the probability is considered to be 95%.

In the first set of readings for the strain gauge problem for a strain of $100 \times 10^{-6}$, the absolute value of difference between the successive measurements is calculated as 0.0002, 0.0001, 0.0003, 0.0001, 0.0006, 0.0003, 0, 0.001, and 0.0002 Ω.

Let the expected probability of repetition be 90%. Hence, eight out of nine pairs of successive readings should possess the difference of 0 Ω. The minimum value of deviation required to fulfill this target is 0.0003 Ω. If the expected probability is reduced to 30%, the repeatability is also reduced to 0.0002 Ω. A smaller quantitative value of repeatability increases the degree of repeatability.

*Reproducibility* is the same as repeatability, but the measurement operation is considered for a large span of time, carried out by different people at different places, and even with different instruments.

Many sensors with primary sensing devices made of elastic members show a difference between the two output readings for the same input, depending upon the direction of successive input values—either increasing or decreasing. This difference in output values is known as *hysteresis*. It is not that, hysteresis is a characteristic of mechanical or magnetic elements only, but many chemical and biochemical devices also show hysteresis. A ferromagnetic material shows hysteresis effect upon magnetization and subsequently demagnetization. Many chemical sensors upon being exposed to the chemicals get their sensitivity deformed and show a hysteresis effect.

### 2.2.4 Sensitivity, Offset, and Dead Band

When a measuring instrument is used to measure an unknown quantity $x$, we need to know how the instrument relates the amplitude of input $x$ with the amplitude or output or response $y$. This input–output relationship is called *sensitivity*. Quantitatively, the sensitivity at any measuring point $i$ is given by the slope

$$S_i = \frac{dy_i}{dx_i} \tag{2.9}$$

where $x_i$ and $y_i$ are the input and output at the measuring point $i$. It is desirable that a sensor has a constant sensitivity so that

$$\frac{dy_i}{dx_i} = K \quad \text{for } i = 1, 2, 3, \ldots, n \tag{2.10}$$

where $n$ is the measuring point of the highest operating range.

Revisiting the same problem of strain gauge discussed earlier, where the input to the strain gauge is strain (ε) and output is the change in resistance ($\Delta R$), the sensitivity of a strain gauge is determined by its gauge factor, which is given by

$$\lambda = \frac{\Delta R/R}{\varepsilon}$$

hence the true or ideal sensitivity is given by

$$\frac{\Delta R}{\varepsilon} = \lambda R = 2 \times 120 = 240\ \mu\Omega/\mu \text{ strain}$$

For the three readings of the strain gauge, the sensitivities at three different points are

$$S_1 = \frac{0.025\,\Omega}{100\,\mu} = 200\,\mu\Omega/\mu \text{ strain}$$

$$S_2 = \frac{0.037\,\Omega}{150\,\mu} = 246.66\,\mu\Omega/\mu \text{ strain}$$

$$S_3 = \frac{0.047\,\Omega}{200\,\mu} = 235\,\mu\Omega/\mu \text{ strain}$$

It is observed that although the strain gauge is expected to have a constant value of sensitivity, the three sensitivity values are different.

In many cases, the average or mean value of a set of sensitivity readings is taken as the working sensitivity. Alternatively, a best fit curve by least square method may also be plotted and the slope be taken as the sensitivity, as shown in Figure 2.1, for the three readings of the strain gauge. The slope of the best fit line is calculated graphically and the sensitivity is found as 200 Ω/strain.

In Figure 2.1, it is observed that the best fit line does not pass through the origin and the intercepts at 0.007 Ω of the $\Delta R$ axis. Hence, the equation of the line is given by

$$y = 200x + 0.007$$

This equation is of the form $y = mx + c$, where $m$ is the slope and $c$ is the intercept. The component $+c$ of the calibration equation of a measurement system is called the *offset*. Offset is the value that is developed in a measuring instrument even when no input is applied. This is also termed as zero error. Alternatively, the component $-c$ is a negative component produced in the system even when no input is applied. Due to this negative component, the system does not produce positive output up to a certain input level. This input level is given by

$$x = \frac{y + c}{S} \tag{2.11}$$

This quantity is called the *threshold*.

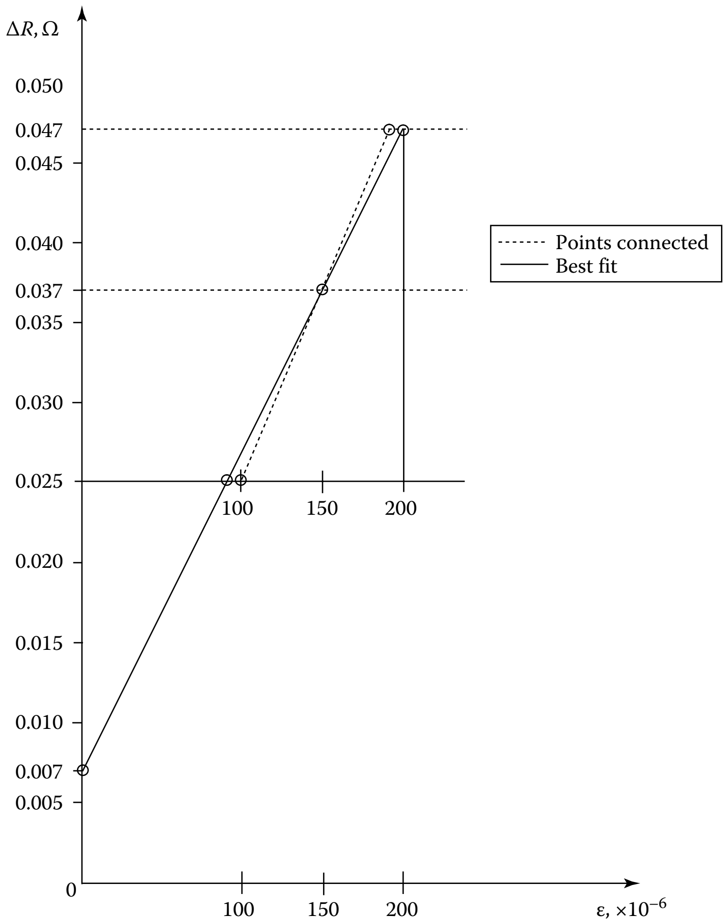


**FIGURE 2.1**
Sensitivity characteristics for the problem in Example 2.1.

In some instruments, the nonavailability of output right from zero level is not due to such a negative offset component, but due to some inherent reason of the system. The largest change in the input quantity to which the system does not respond is called *dead band*. The dead band is due to static friction, backlash, or hysteresis.

In the strain gauge of the problem, if the gauge operates satisfactorily within the range 100–200 μ strains, then the maximum input value of 200 μ strains is called the *range* or *full-scale* value of the gauge. The word "satisfactory" indicates that the instrument is not used beyond this range due to one or more reasons like nonlinearity, operationally not suitable, not applicable, etc.

The value of working range, i.e., 100 μ strain (200 − 100) is called the *span* of the strain gauge.

### 2.2.5 Resolution and Linearity

Theoretically, a measuring instrument produces the smallest output quantity on application of the smallest input; however, all smallest outputs are not practically detectable. The smallest input for which the system produces the detectable output is called its *resolution* (or discrimination). The resolution is mostly a characteristic inherent to the measuring system that depends on its geometry or structural factors.

In some measuring instruments, the input is restricted to discrete points only such as in a wire-wound potentiometer where displacement is restricted from turn to turn due to discontinuous contact of the wiper over the coil. Here, the resolution is determined by the distance between two turns. In some other instruments, although the input is linearly variable, the output is detectable only at discrete levels like a digital shaft encoder, where the detectable angle is restricted to the coded binary sequence only. Therefore, an angle between two successive binary numbers cannot be detected. Rarely, in few instruments only, both the input and the output are linearly variable to get an infinite resolution. In many measuring systems, the overall resolution is governed by the resolution of the measuring device like digital display, ADC, etc. With reference to the strain gauge discussed earlier, say, the smallest change in the resistance that can be measured by a measuring circuit is 0.001 Ω, then its corresponding strain value, i.e., $0.2 \times 10^{-6}$, is the resolution of the strain gauge. Again, let us consider that the measuring circuit used produces 1 μV for every 0.001 Ω resistance; however, the voltmeter connected to the output cannot read values smaller than 10 μV. Hence the resolution is now determined by the voltmeter and is reduced to a value of 0.01 Ω that corresponds to a strain of $2 \times 10^{-6}$.

If the output voltage of the measuring circuit is amplified using an amplifier and subsequently converted to digital output by a 12-bit ADC, the measurement system resolution will be determined by the resolution of the ADC. Assuming an amplifier amplifies the signal obtained from the strain gauge measuring circuit within the working range of 0–200 μ strain to a voltage of 0–5 V, a single bit of the ADC corresponds to $5/(2^{12})$ V, i.e., 1.22 mV that corresponds to a strain of $0.048 \times 10^{-6}$. Therefore, the resolution is increased on amplifying the signal. The resolution of many transducers are infinite; however, the indicating devices restrict the resolution of the transducer to a non-infinite value.

It was discussed in Section 2.2.1 that the measuring instruments possess some undesirable characteristics due to which the actual output deviates from the true or ideal values. The causes of deviation are various, including the inherent design characteristics and interfering inputs. Many instruments show a typical deviation from a trend of outputs even without interfering inputs making the system nonlinear. Such a characteristic of a measuring instrument is essential for calibrating the instrument by adopting various linearization techniques. In fact, when the sensitivity is constant over the operating range, the calibration characteristic is a straight line either passing through the origin or intercepting on any one of the axis. When the sensitivity changes or does not remain constant over the operating range, the instrument is said to be nonlinear. Linearity is a quantity that denotes the maximum deviation of the output from the true value as a percentage of the true value. The lesser this value is, higher is the linearity.

### 2.2.6 Statistical Characteristics

When an instrument is used to measure an input quantity, the output may be different from the true value due to errors. *Systematic errors* are those developed in the instruments and components of the measurement system, and are easy to be modeled, while *random errors* are produced due to the sources that cannot be specified and modeled. Due to the presence of random errors, the same instrument may show different outputs for the same inputs. The quality of such a set of measurements can be ascertained by certain statistical characteristics. Apart from the assessment of the data quality of an instrument, statistical characteristics are becoming popular for data classification using artificial neural network (ANN) techniques of sensor signal processing.

It is not that statistical analysis is useful for error analysis only. There are many systems that produce signals of random nature such as acoustics, seismology, structural vibration, etc., which need analysis by statistical methods. Statistical characteristics are used to describe all the three parameters of a signal-amplitude, frequency, and phase. The amplitude behavior is described by mean, root-mean-square, and probability density function (PDF) of the signal. These three characteristics are limited to the amplitude of the signal and are independent of frequency and phase of the signal. Similarly, the frequency behavior, which is independent of amplitude and phase of the signal, is described by the spectral density of the signal, while the phase or time behavior is described by the auto correlation function of the signal.

For a set of $N$ readings $X_1, X_2, X_3, \ldots, X_n$ of an instrument for the same input, the mean value of the measurements is given by Equation 2.3, which is simply the arithmetic mean of the readings. Thus, the random error is eliminated to some extent by taking the mean. Higher the number of readings ($N$), lesser is the error. *Deviation* $d_i$ is the departure of the $i$th reading from the arithmetic mean given by

$$d_i = X_i - \bar{X}_N \tag{2.12}$$

and average deviation is the mean of all the deviations obtained as