Instrumentation, Quality Control & Improvement

For Science and Engineering Students

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PREFACE

This book aims to provide learners fundamentals of measuring, transmitting, and recording electrical quantities, temperature, pressure, flow, force, displacement, and velocity. The course will also cover statistical tests to evaluate quality of measurements, standard methods of characterizing measurement results, and methods for characterizing measurement system response.

Measurement is the basis for quality control and improvement. This book provides a brief introduction of quality control and improvement techniques.

Contents

Chapter 1
MEASURING INSTRUMENTS AND MEASUREMENT SYSTEMS

After completing this unit you would be able to:-

- define and classify instruments
- define measurement system
- identify basic components of a measurement system and
- classify measurement system

Introduction

In your previous courses of measurement science you have studied the importance of measurement in most facets of human civilization. The act of measurement implies the presence of a device (an artifact) used, known as measuring instrument.

Measuring instruments have important vital applications in our everyday lives, whether at home, in our vehicles, offices or factories.

We use measuring devices in buying commodities from sellers. We assume that the measuring devices are accurate, and we assume that we are all referring to the same units (e.g., kilogram, metre, litreĚ). The consequence of inaccurate measuring devices in this case leads to financial losses on our part.

Medical practitioners check the temperature of their patient and assume that the thermometers reading the temperature are accurate. If not, then the temperature will be either high or low, leading to incorrect decisions that may cause inconvenience even health risks.

We pay for our water consumption in units of m^3 and we assume that the flow meter is accurate and faithfully records the correct volume of water that we have used. We pay for the electricity we consume in kWh, and we also assume that the electricity meter is correctly measuring the electrical energy we used. In this case as well, the error will lead to financial loss.

The accuracy of the measurement systems mentioned above is very important, but is more critical in some applications than others. For example, a pharmacist preparing a medication is reliant on the accuracy of his/her scales to make sure he/she includes the correct amounts of ingredients in the medication. Another example is the manufacturing of present-day integrated circuits and photo-masks that requires a high degree of accuracy. Certain chemical reactions require high accuracy in the measurement and control of temperature.

1.1 Measurement Systems

After completing this section you would be able to:-

- define Measurement systems in general,
- classify classify measurement systems,
- state sub-systems in a measuring system
- understand main function in each sub-system
- understand the basic properties of measurement systems

Measurement involves the use of instruments as a physical means of determining quantities or variables. Because of modular nature of the elements within it, it is common to refer the measuring instrument as a *MEASUREMENT SYSTEM*.

A measurement system maps the value of a measurand to a specified set of numbers or symbols.

1.1.1 Variables that are measured: an overview

The most widely measured quantities are described below

Electrical parameters: The basic seven parameters are: voltage, current, resistance, capacitance, inductance, frequency and phase shift. Other electrical parameters that are effectively derived from these in terms of measurement are: power and power factor.

Magnetic: One of the magnetic parameters that can be directly measured is the magnetic flux density.

Environmental variables: Temperature, pressure and humidity.

Mechanical Mass, force, torque, length, area, volume/capacity, angle and surface roughness.

Fluid measurements such as: Viscosity, level measurement and flow measurement.

Motion measurement such as: Translational motion and rotational motion.

Others: Sound pressure, gas sensing and PH in solutions.

1.1.2 Elements of Measurement System

Measurement systems consists of five elements. These elements could all be in one item or could be all in separate five items. They could be adjacent to each other or they could be separated by a distance. In simple cases, the system can consist of only a single unit that gives an output reading or signal according to the magnitude of the unknown variable applied to it. However, in more complex measurement situations, a measuring system consists of several separate elements as shown in Figure 1.1.

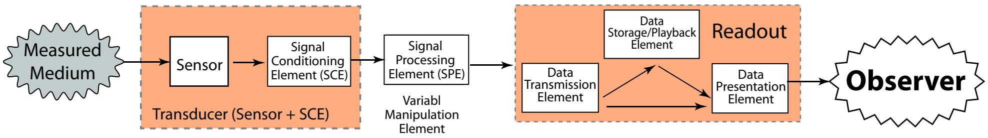

Figure 1.1 Elements of a measurement system

These components might be contained within one or more boxes, and the boxes holding individual measurement elements might be either close together or physically separate. The term measuring instrument is commonly used to describe a measurement system, whether it contains only one or many elements, and this term will be widely used throughout this course.Some simple systems might not contain all of the components. The components of a typical system are shown in figure 1.1. part or all of four general stages:

Sensor: The quantity under measurement makes its first contact with the primary sensing element of a measurement system.

The primary function of the sensor is to detect or to sense the physical variable (Measurand) and performs either a mechanical or an electrical transformation to convert the signal into a more usable form. The sensor is a physical element that employs some natural phenomenon by which it senses the variable being measured.

The sensor gives an output that is proportional to the input applied to it. In general the output is in an electrical format as this is the most suitable format for later use (in processing, transmission and storage). The input format depends on the variable to be measured (e.g., temperature, pressure, humidity, pH, speed, acceleration, lightĚ). Sensors usually have a near linear relationship, although this is not always the case.

Signal Conditioning Element (SCE): This is also referred to as a *variable conversion element*: When the output variable of a primary sensor is in an unsuitable (or inconvenient) format, a signal conditioning element is used to convert it to a suitable form. For example, the change in resistance of a strain gauge cannot be directly measured and thus a deflection type bridge circuit is used to convert it to a suitable voltage. Bridge circuits are examples of signal conditioning elements and are discussed in more detail in a Chapters xx and xx. Another example is the amplification of a very weak signal such as a biomedical signal (such as that used in an electrocardiogram ECG).

The combination of the sensor and the signal conditioning element (SCE) is called the transducer. By definition, a transducer is a device that converts one form of energy to another form.

Signal Processing Element (SPE): SPE is needed to improve the quality of the signal. A very common example is filtering a signal that contains mains frequency noise (i.e., 50 Hz). Some of the examples of signal processing elements as used in a measurement system are:

- Remove the mean value from an a.c. signal (i.e., dc shift).
- Filter out induced noise (example 50 Hz hum/pick-up).
- Convert an analogue signal to a digital format.
- Convert a time signal into voltage (e.g., an ultrasonic level sensor).

The output signal from the SPE could be in a number of formats: voltage, current, frequency or on/off (such as in a switch). In other words, the information about the variable to be measured will be contained in the voltage of the output signal, its current or its frequency. It could also just be a yes/no output signal (for example as given by a thermostat that gives a signal stating whether the variable measured is more or less than a set value). In the case of frequency for example, the value of the measured variable would be represented as a certain frequency deviation from a certain mean frequency.

The voltage and current output usually follow a standard format (e.g. 0-10 V in case of voltage and 4-20 mA in case of current). Use of voltage, current or frequency has implication in terms of the effect of noise. The effect of noise on current transmission and voltage transmission is discussed in more detail in a Chapter xx.

Signal Transmission: The signal is then transmitted to the final location where it is needed. Most modern measurement system could be distributed over a wide area, and hence transmission in this case is necessary. There are three reasons why the signal needs to be transmitted to a remote location:

1. Convenience: It is easier for example to locate the final equipment in a warm office than on a the roof of the building where the transmitter is located.
2. Inaccessibility: The transmitter may sometimes be located in an area that cannot be accessed or reach. The measured variable could be inaccessible because it is located in a narrow tunnel if it is located in a high position.
3. Hazardous location: The transmitter might be located in an area that is accessible, but hazardous to humans. An example of the hazardous situation is where the measured variable is in a chemical or nuclear plant, or in an area with very high temperatures.

Transmission can be done by a number of methods, some of which are: Cable Transmission, Fibre optics, Wireless transmission.

Display, recording or analysis (D/R/A): D/R/A or use in automatic feedback systems is where the final signal is utilized. One of the following action is taken:

- It is either fed into the automatic feedback system.

- The signal is displayed, recorded or analysed: The signal can either be displayed on a screen or industrial display, it could be recorded on a hard-disk for example over a period of days or months and it could be analysed to understand trends or draw conclusions.

Both actions can be taken simultaneously as well: We can feed the signal into an automatic feedback system and display it on a screen or record it.

☞ Not all measurement system will contain all of the five elements. In some cases it is difficult to identify the boundaries between different elements.

Example 1.1 **mercury-in-glass thermometer as a measurement system**

A simple measurement system is the mercury-in-glass thermometer.

Solution:
In mercury-in-glass thermometer all the items are within the same instrument and it is in fact difficult to separate one component from another. The system only contains a sensor (effectively the mercury in the tube) and a display component (the scale on the glass). There is neither an SCE, SPE or transmission system.

Example 1.2 **A computer controlled remote system in a chemical plant**

In the case of a computer controlled remote system, in a chemical plant, all the five components can be clearly identified.

Solution:
The system is distributed, and thus the transmission element in this case is necessary due to the distance between the variable of the process to be measured and the receiver (e.g., a computer). The computer receiving the signal would display it, record it and keep available for later analysis if needed. The signal could also be fed into an automatic control system (e.g., temperature control of the chemical reaction).

1.2 Classification of Measurement Systems

Having introduced the components of a measurement system in section 1.1.2, we now look at the various classifications of measurements systems. The classification is important in understanding how different systems work and comparing their performance later on. Further, classification of measurement systems allows general rules and conclusions to be drawn about measurement systems in terms of their accuracy, ease of use and suitability for various applications.

Measurement systems can be classified in accordance to a number of criteria. Seven criteria are discussed below:

1.2.1 Gauge systems vs measurement systems

Figure 1.2 Stepped gauge used to check gaps.

In certain cases (especially in quality control processes in manufacturing) we are only interested in knowing if a variable is within a certain value. This is especially true for mechanical products. In these cases a gauge can be produced that can be applied to the product. If the product passes through the gauge, then we know it is within range; if it does not then it can be rejected. Rather than measuring each product and finding the exact value, this saves a considerable amount of time. An example of a gauge used to check the gap between escalator steps and the side of the escalator is shown in Figure 1.2.

Another example of a gauge measurement system is the battery tester. When a battery is tested the user is only interested in knowing whether the battery is good or weak (rather than knowing the actual voltage that it produces). Gauge systems can also be referred to as *go/no-go systems*.

1.2.2 Active and passive measurement systems

Passive systems are usually characterized by not having a power supply, and thus are not able to carry out any significant processing on the signal or amplification1. Resolution measurement is limited in passive type measurement systems, and they have an undesirable loading effect on the electrical circuits they measure. However, their main advantage is that they are generally simpler and thus can be more reliable. A simple example of a passive measurement system is a float in a water tank that rotates around a pivot point, and that has a pointer on a scale. Another example is the permanent magnet moving coil ammeter that measure the current in an electrical circuit and that does not need an internal power supply.

In active measurement systems the power source is mainly electrical (although it could also be pneumatic or hydraulic). The signal can be amplified, transmitted to a different location and the resolution is better than passive devices. Active devices produce less interference with the measured circuit compared to passive device. However, the resolution in active devices cannot be increased infinitely for safety reasons and heating. The comparison between the two types of systems is a balance between resolution requirements, minimising interference with the measured circuit, simplicity, reliability and cost.

1.2.3 Null type and deflection type systems

In null type measurement systems a control variable is changed until is balances (nulls) the effect of the second variable (i.e., the variable to be measured). At the point of balance (null condition) the variable to be measured is equal to the variable being altered to achieve the balance condition.

In the deflection type measurement systems, the value of the variable to be measured is shown immediately on a scale or reading.

Figure 1.3 Balance scale used by a fruit grocer

Examples of the two devices are scales: The balance scale is a null type device and uses calibrated weights (an example of which is shown in Figure 2). The normal type scale that we use at home for weighing ourselves is a deflection type device. Deflection type measurement systems are more convenient as they do not require the lengthy process of changing weights and checking for null conditions. Null type measurement systems are more accurate than deflection type measurement systems as they can be better calibrated (e.g., a scientific scale comes with a box of accurately calibrated weights). Null type systems however, require time before a reading is available, and thus are limited to measurement of slowly changing variables.

Another example of the two types is the electrical bridge circuit (discussed in a future chapter). Electrical bridges can be used as either null type or deflection type circuits.

In addition to the classification of deflection and null type, a third type is the substitution measurement systems or methods (Gregory, 1981).

1.2.4 Analogue vs digital measurement systems

Analogue variables have an infinite number of possible values, but in practice the eye can only discriminate between a limited number of positions. The discrimination depends on how large the scale is and how finely it is divided. The human operator is a source of error if he/she is not aware of parallax (reads the pointer at an angle) and also when interpreting the position of the pointer on the scale. So the main disadvantages of analogue measurement systems are:

a) The difficulty that human observer has in interpreting the position of the pointer on the scale.
b) The error that could be caused by parallax.

c) The inability to process analogue signals using digital processing units (e.g., microprocessors).

Digital measurement systems use discrete variables that have a finite number of levels and change in discrete steps. This fact results in an error called the quantization error. We can increase the number of levels (and hence reduce the quantization error) by increasing the number of levels, which can be done by increasing the number of bits (e.g., 8 bits= 256 levels; 12 bits=4096 levels). Most A/D converters use 10 or 12 bits.

The main motivation for using digital systems is that the variable is in a suitable format for processing by a microprocessor. The human error in reading/interpreting the output is eliminated, as the output is generally presented in a multi-digit 7-segment display format. There are two disadvantages in using digital systems:

a) Analogue to Digital (A/D) D conversion is needed and this introduces an error (called quantization error). The quantization error can be understood by taking an example. Let us say that a measurement system uses 8 bits for internally representing the value of the measured variable. This provides 256 levels. The resolution of the system would be the smallest required change in the input for the output to change, which in this case would be 1/256= 0.39%. So in effect we have an inaccuracy caused by quantization of 0.39%. The actual quantization error depends on how the system assigns discrete values to analogue input. In certain cases the quantization error will be *half* the step size (i.e., $\frac{1}{2}$, $\frac{1}{2^n}$ů) where n is the number of bits; in other conventions it is taken as the full step size $\frac{1}{2^n}$.
b) The A/D conversion also requires time and can introduce a time delay into the system2. The time delay can have an effect on the closed loop feedback control system into which the measurement system is feeding the signal, and can lead to oscillations. A real life example of an oscillatory response caused by a time delay is when we try to arrive at the optimum water temperature for a shower. If there is time delay between changing the tap setting and the water temperature changing, the temperature of the emerging water will oscillate as we ŚoverreactŠ to the changes in the water temperature by making large changes to the tap settings.

1.2.5 Absolute instruments

Absolute instruments give the magnitude of the quantity being measured in terms of the constants of the instruments. For example, a *tangent galvanometer*, as it measures current in terms of the tangent of the angle of deflection produced by the current, radius and number of turns of the galvanometer and the horizontal component of the earthŠs magnetic field. In practice, we seldom use an absolute instrument.

1.2.6 Secondary instruments

The deflection of such instruments directly give us the magnitude of the quantity being measured. These have to be calibrated by comparison with an absolute instrument or with another secondary instrument which has already been calibrated beforehand. Such instruments are in most common use in laboratories, industries and power stations, etc. Secondary instruments are further divided into three groups vis (i) Indicating instruments (ii) Recording instruments (iii) Integrating instruments

Indicating instruments

These instruments given the magnitude of the quantity at the time when it is being measured. The measurement is indicated by a pointer moving over a marked (graduated) dial. Ordinary voltmeters, ammeters, wattmeters belong to this group.

Recording instruments

These instruments give a continuous record of the quantity being measured over a given period. The variations of the quantity being measured are recorded by a pen. This inked pen lightly touches a sheet of paper wrapped over a drum. The drum rotates slowly at uniform speed. The pen is deflected by the magnitude of the quantity being measured. Thus, a curve is traced. Such an instrument is used by doctors to give ECG (Electro-Cardio-Gram) of a patient.

Integrating instruments

Such instruments give total amount of quantity being measured over a period of time. The summation given by such an instrument is the product of time and an electrical quantity. Ampere-hour meter, watt-hour (energy) meter and odometer in a car (which measures the total distance covered) are examples of this category. The summation value is generally given by a register consisting of a set of pointers and dials, or an electronic digital display.

1.3 Measuring Instruments: Applications

Measurement of a given quantity is essentially an act or result of comparison between the quantity (whose magnitude is unknown) and predetermined or predefined standards. Two quantities are compared the result is expressed in numerical values.

After completing this section you would be able to:-

- identify basic requirements for measurement,
- describe areas of applications of instruments and measurement systems,
- classify instruments and,
-

Measuring instruments and measurement systems, in general, can be used in three major areas. These are the uses in *regulating trade*; in *knowledge seeking and problem solving*; in *monitoring functions* and use of as part of *automatic feedback control systems.*

1.3.1 Regulating Trade

Applying instruments that measure physical quantities such as length, volume and mass in terms of standard units is one of the applications.

1.3.2 Knowledge Seeking and Problem Solving

A second application that is widely used in research laboratories is that of knowledge seeking and problem solving. We use measurements to enhance our knowledge about various systems and understand how different variables interact.

1.3.3 Monitoring Functions

Information from monitoring functions of instruments enable humans to take some prescribed action. For example the information on the temperature measuring device, attached to a boiler, is used to decide whether to keep on heating or otherwise of the boiler. Regular study of a barometer allows us to decide whether we should take our umbrellas if we are planning to go out for a few hours.

Although uses of instrumentation in our normal domestic lives are important and common, the majority of monitoring functions exist to provide the information necessary to allow a human being to control some industrial operation or process. In a chemical process for instance, the progress of chemical reactions is indicated by the measurement of temperatures and pressures at various points, and such measurements allow the operator to take correct decisions regarding the electrical supply to heaters, cooling water flows, valve positions etc.

Monitoring instruments are also used in calibrating the instruments used in the automatic process control systems which is the third area where instruments are used.

1.3.4 Use as Part of Feedback Control Systems

The fourth application of measurement systems is the use to feed the measured value to an automatic feedback control systems. In the last application, the human being was monitoring the value of a variable and taking appropriate action. By closing the loop, the measurement system becomes part of the automatic feedback control system and this obviates the need for human intervention.

An example is a level measurement system that measures the water level in a tank and opens a valve to fill it up whenever the water level drops below a certain preset value. The accuracy and resolution of a measured variable is very important. The control system that uses the output of the measurement system cannot be more accurate that the accuracy of the measurement system itself. In effect, a poor measurement system becomes the weakest link in the control system and causes a deterioration of performance.

As another example, of instruments form a part of automatic feedback control systems, suppose there is a device that maintains the room temperature at a comfortable temperature (T_c). Suppose the room temperature is $T_a \neq T_c$. The value of T_a is measured by a temperature measuring device and is compared to the the reference value T_c. The value $T_a - T_c$ is sent as signal to the device. Then the device acts until $T_a - T_c = 0$

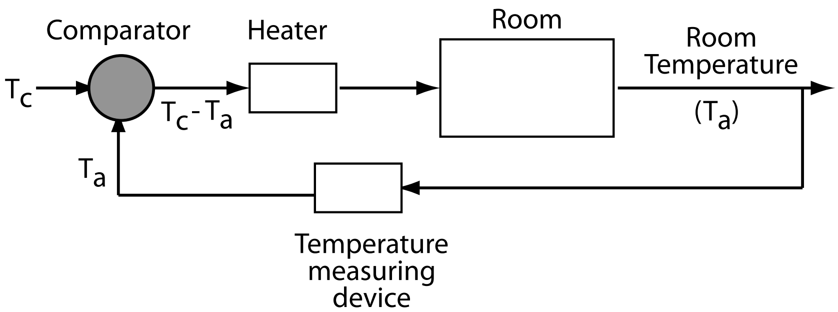

Figure 1.4 Simple Closed Loop Control System.

1.3.5 Basic requirements of Measurement

For a meaningful measurement the following two requirements should be fulfilled

- Standard used for comparison purposes must be accurately defined and should be commonly accepted.
- Apparatus used and the method adopted must be provable (verifiable).

1.3.6 Methods of measurement

Measurement methods can be categorized into two broad categories. These are Direct and indirect methods:

Direct Methods:- In these methods, the unknown quantity (called the measurand) is directly compared against a standard.

Indirect Methods:- Measurements by direct methods are not always possible, feasible and practicable. In engineering applications measurement systems are used which require need of indirect method for measurement purposes.

1.3.7 Evolution of instruments

Instruments are classed as Mechanical, Electrical and Electronic.

Mechanical Instruments:- These instruments are very reliable for static and stable conditions. But their disadvantage is that they are unable to respond rapidly to measurements of dynamic and transient conditions.

Electrical Instruments:- It is faster than mechanical, indicating the output are rapid than mechanical methods. But it depends on the mechanical movement of the meters. The response is 0.5 to 24 seconds.

Electronic Instruments:- It is more reliable than other system. It uses semiconductor devices and weak signal can also be detected

1.3.8 Classification of Measuring Instruments

Instruments can be subdivided into separate classes according to several criteria. These subclassifications are useful in broadly establishing several attributes of particular instruments such as accuracy, cost, and general applicability to different applications.

Active and passive instruments Active instruments are those instruments on which the instrument output is entirely produced by the quantity being measured where as passive instruments are instruments in which the quantity being measured simply modulates the magnitude of some external power source.

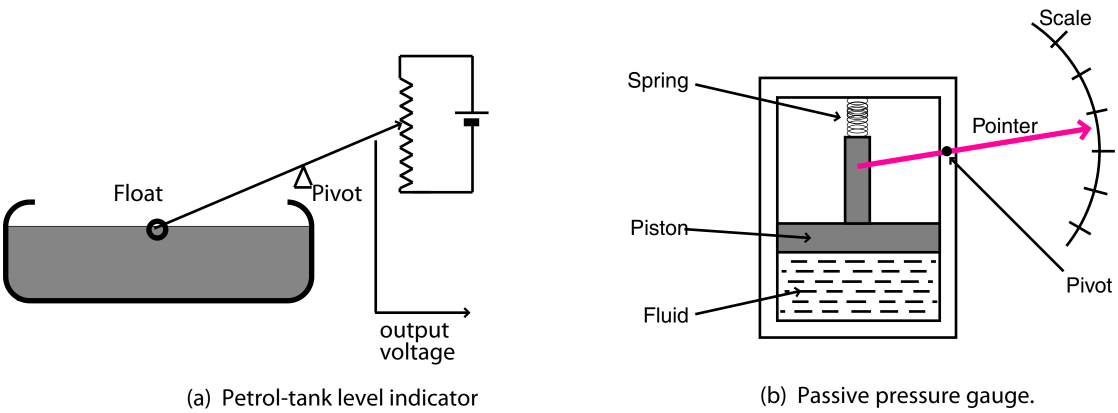

Figure 1.5 Examples of Active and Passive Instruments.

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1.4 Characteristics of Measuring Instruments

1.4.1 Static Characteristics of Measurement Systems

There are parameters of interest in the choice of instrument for a particular application. For example it is adequate if the the accuracy of a thermometer for measuring room temperature is ±0.5°C. Other parameters such as sensitivity, linearity and the reaction to ambient temperature changes are further considerations. These attributes are collectively known as the *static characteristics* of instruments, and are given in the data sheet for a particular instrument.

In considering static characteristics of instruments, the construction and the working principle of the instrument is unimportant. We consider the instrument as a black box.

The various static characteristics are defined in the following paragraphs.

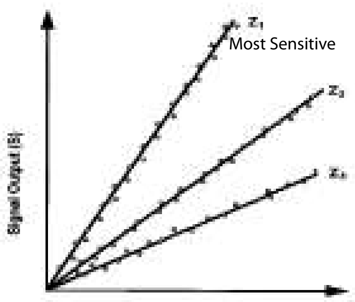

Figure 1.6 Physical Variable vs signal output

Range:

The working range of a measuring instrument is an important static property, where x_{min} is the lower limit and x_{max} is the upper limit of the range.

Sensitivity

The sensitivity (deflection over the change in the variable) of an instrument is given by the response at the output to the unit change in the input signal.

The expression of the sensitivity S is defined as the ratio of the magnitude of the output response to that of input response.

$$S = \left(\frac{\partial y}{\partial x}\right)_{x_\circ} \tag{1.1}$$

The index $x_\circ$ indicates that the sensitivity may vary with the input signal x.

- If the sensitivity of the instrument is independent of the input signal the instrument is linear. It is preferable to use a linear instrument, but unfortunately it is not possible to make such one in all cases. Figure 1.7(a) represents an instrument that is linear in a limited range.

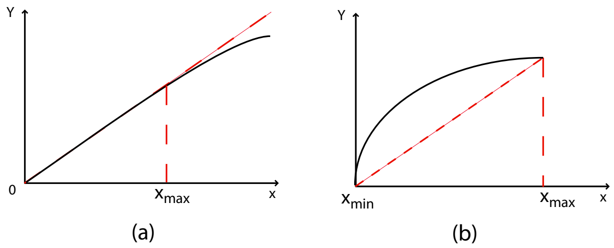

Figure 1.7

- There are instruments that are nonlinear in the full working range (Figure 1.7(b)). The nonlinearity of an instrument in its working range is given by the maximum of the relative deviation from the linearity:

$$\left(\frac{\Delta y}{y}\right)_{\max} \tag{1.2}$$

Example 1.3 Sensitivity of a resistance thermometer

The following resistance values of a platinum resistance thermometer were measured at a range of temperatures. Determine the measurement sensitivity of the instrument in ohms/°C.

Resistance (Ω)	*Temperature (°C)*
307	*200*
314	*230*
321	*260*
328	*290*

Solution:

If these values are plotted on a graph, the straight-line relationship between resistance change and temperature change is obvious.
For a change in temperature of 30°C, the change in resistance is 7Ω. Hence the measurement sensitivity =7/30 = 0.233 Ω/°C.

Accuracy

Accuracy (measurement uncertainty) is the closeness an instrument reading approaches the true value of the quantity being measured.

The *True value* of quantity may be defined as the average of an infinite number of measured values.

In practice, it is more usual to quote the inaccuracy figure rather than the accuracy figure for an instrument. Inaccuracy is the extent to which a reading might be wrong, and is often quoted as a percentage of the full-scale (f.s.) reading of an instrument. If, for example, a pressure gauge of range 0–10 bar has a quoted inaccuracy of ±1.0% f.s. (±1.0 % of full-scale reading), then the maximum error to be expected in any reading is 0.1 bar. This means that when the instrument is reading 1.0 bar, the possible error is 10% of this value. For this reason, it is an important system design rule that instruments are chosen such that their range is appropriate to the spread of values being measured, in order that the best possible accuracy is maintained in instrument readings. Thus, if we were measuring pressures with expected values between 0 and 1 bar, we would not use an instrument with a range of 0–10 bar. The term *measurement uncertainty* is frequently used in place of inaccuracy.

Accuracy is typically expressed as:

1. **Percentage of full scale reading** (upper range value). Example: A 100 Kpa pressure gage having an accuracy of ±1% would be accurate of ± 1% Kpa over the entire range of the gage.

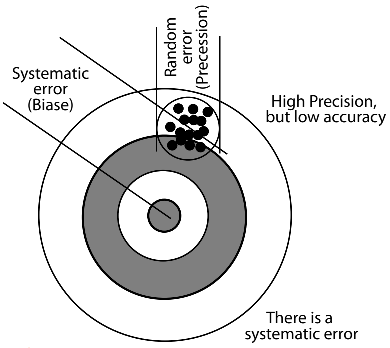

Figure 1.8 Accuracy vs Precision

2. **Percentage of span**. Example: A pressure gage has span of 200 Kpa, Accuracy of $\pm 0.5\%$.

   To one reading of 150 Kpa is taken, then the true value of measurement will be between $150 \pm \frac{0.5\times 200}{100} 150 \pm 1$ or 149 Kpa and 151 Kpa.
3. Measured Variable Accuracy of $\pm$ Kpa, over all ranges of the Instrument.
4. **Percentage of the actual reading**. Thus, for a $\pm 2\%$ of reading voltmeter, we would have an inaccuracy of ± 0.04 volts for a reading of 2 volts.

Precision

Precision (spread of readings, repeatability)

Notice that high accuracy means that the mean is close to the true value, while high precision means that the standard deviation σ is small.

Resolution

Another important static property of the instruments is the *resolution* or the *threshold*. The words resolution and threshold are almost synonyms. The threshold is the smallest detectable change $x_{\min}$ (the smallest step that can be distinguished) in the input signal around the zero input value. The resolution, however, is a similar change in the input signal at any input value. It may be seen that there is only a small difference between the two definitions, but the resolution is more general.

The problem is that we can not observe directly the input signal, only the output one of the instrument. Because of this the resolution has to be expressed by the signal observed at the output. There are two extreme cases. In the first case the noise on the output signal may be neglected. So we can determine the smallest detectable change ymin of the output signal (see Fig. 2.3) from which the resolution is

In the second case the noise is comparable to the signal (see Fig. 2.4). The noise is a random (or nonrandom) fluctuation which disturbs the output signal. Let us introduce the concept of signal-to-noise ratio in the following form

where n is the square root of the variance of noise (see Chapter 4). A widely used but rough estimation of n is

where npp is the noise peak-to-peak, the double of the maximum amplitude in the noise recorded in the time. The condition of the observability of the change in the output signal buried by noise is

From this the resolution is

if the noise level is high.

Static Error: It is defined as the difference between the measured value and true value of the quantity.

Reproducibility: is specified in terms of scale readings over a given period of time.

Drift: is an undesirable quality in industrial instruments because it is rarely apparent and cannot be maintained. It is classified as Zero drift; Span drift or sensitivity drift and Zonal drift.

Noise: spurious current or voltage extraneous to the current or voltage of interest in an electrical or electronic circuit is called noise.

A remarkable static property is the input and output load of the instrument. The electronic instruments have an input and an output loops. Theirs impedances are defined as the ratio of the voltage and the current at the input as well as the output. The input and output values are different in the case of electronic instruments. The magnitude of the input impedances would be very different according to the detectors.

A good example is the measuring of pH. The determination of pH is based on the measuring the electromotive force (EMF) between a pH sensitive electrode and a reference one. The EMF of an electrochemical cell can be determined by a pH meter only if practically no current flows through the input and the electrochemical cell. Because of this the input impedance of the pH meter has to be as high as possible. Applying FET transistors at the input of the electronic, 100 Gohm impedance or higher can be achieved, thus the input current is reduced to some pAs, thus the load is some pwatts.

The output impedance and the output power requirements are specified by the display or the recorder. The output impedance of a pH meter is usually 10-100 ohms. Since the voltage amplification of the pH meters is 1, the power requirement is between 0.1 and 0.01 watts. The input-output power difference is supplied by the electric network. We speak about power amplification.

After completing this unit you would be able to:-

- understand dynamic Characteristics of Measurement Systems

1.4.2 Dynamic Characteristics of Measurement Systems

The static characteristics of measuring instruments are concerned only with the steady state reading that the instrument settles down to, such as the accuracy of the reading etc.

The dynamic characteristics of a measuring instrument describe its behaviour between the time a measured quantity changes value and the time when the instrument output attains a steady value in response. As with static characteristics, any values for dynamic characteristics quoted in instrument data sheets only apply when the instrument is used under specified environmental conditions. Outside these calibration conditions, some variation in the dynamic parameters can be expected.

In any linear, time-invariant measuring system, the following general relation can be written between input and output for time $(t) > 0$:

$$a_{\mathrm{n}}\frac{d^n q_\circ}{dt^n} + a_{\mathrm{n}-1}\frac{d^{n-1} q_\circ}{dt^{n-1}} + \cdot + a_1\frac{dq_\circ}{dt} + a_\circ q_\circ = b_{\mathrm{m}}\frac{d^m q_i}{dt^m} + b_{\mathrm{m}-1}\frac{d^{m-1} q_i}{dt^{m-1}} + \cdot + b_1\frac{dq_i}{dt} + b_\circ q_i \tag{1.3}$$

where q_i is the measured quantity, $q_\circ$ is the output reading and $a_\circ \cdots a_n$, $b_\circ \cdots b_m$ are constants.

If we limit consideration to that of step changes in the measured quantity only, then equation 1.3 reduces to:

$$a_{\mathrm{n}}\frac{d^n q_\circ}{dt^n} + a_{\mathrm{n}-1}\frac{d^{n-1} q_\circ}{dt^{n-1}} + \cdot + a_1\frac{dq_\circ}{dt} + a_\circ q_\circ = b_\circ q_i \tag{1.4}$$

Further simplification can be made by taking certain special cases of equation 1.4, which collectively apply to nearly all measurement systems.

Speed of response

It is defined as the rapidity with which a measurement system responds to changes in measured quantity. It is one of the dynamic characteristics of a measurement system.

Response time (fast response/high bandwidth)

Input impedance

Input impedance (loading effect)

Robustness

Robustness (noise, disturbance, or drift)

After completing this unit you would be able to:-

- define measurement error and their distribution
- use statistical parameters to describe errors
- describe factors influencing measurement errors

Measuring lag: It is the retardation delay in the response of a measurement system to changes in the measured quantity. It is of 2 types:

- Retardation type: The response begins immediately after a change in measured quantity has occurred.
- Time delay: The response of the measurement system begins after a dead zone after the application of the input.

Fidelity: It is defined as the degree to which a measurement system indicates changes in the measured quantity without any dynamic error.

Dynamic error: It is the difference between the true value of the quantity changing with time and the value indicated by the measurement system if no static error is assumed. It is also called measurement error. It is one the dynamic characteristics.

1.5 Instrumental Errors in Measurement

Example 1.4 Sensitivity of a resistance thermometer

The following resistance values of a platinum resistance thermometer were measured at a range of temperatures. Determine the measurement sensitivity of the instrument in ohms/°C.

Resistance (Ω)	*Temperature (°C)*
307	*200*
314	*230*
321	*260*
328	*290*

Solution:

If these values are plotted on a graph, the straight-line relationship between resistance change and temperature change is obvious.
For a change in temperature of 30°C, the change in resistance is 7Ω. Hence the measurement sensitivity $=7/30 = 0.233\,\Omega/°C$.

All measurements are subject to errors, due to a variety of reasons such as inherent inaccuracies of the instrument, human error and using the instrument in a way for which it was not designed.

Error is the difference between the result of the measurement and the true value of the quantity measured, after all corrections have been made. Error, which is not the same as uncertainty, has traditionally been viewed as being of two kinds: random error and systematic error. In general, although error always exists, its magnitude cannot be exactly known.

Example 1.5

A temperature transducer has a range of 20° to 250° C. A measurement results in a value of 55° C for the temperature. Compare the errors if the accuracy is:

a) $\pm 0.5\% FS$

b) $\pm 0.75\%$ *of span*

c) $\pm 0.8\%$ *of reading*

What is the possible temperature in each case?

Solution:

Solution:

a) Error $= \frac{0.5\%(250°C}{100\%} = \pm 1.25°C$
Thus, the actual temperature is in the range 53.75 °C and 56.25 °C.

b) Error $= \pm\frac{0.75\%(250-20)^{\circ}\mathrm{C}}{100\%} = \pm 1.725^{\circ}\mathrm{C}$
Thus, the actual temperature is in the range 53.75 °C and 56.725 °C.

c) Error $= \pm\frac{0.8\%(55)^{\circ}\mathrm{C}}{100\%} = \pm 0.44^{\circ}\mathrm{C}$
Thus, the actual temperature is in the range 54.46 °C and 55.44 °C.

Example 1.6

Two pressure instruments with a range of 0 to 100 psi are measuring a process value of 50 psi. The accuracy of both devices is ±1% FS. Data obtained from five measurements are listed in the following table; determine which instrument has a greater degree of repeatability.

Measurement	*Instrument A (psi)*	*Instrument B (psi)*
1	*49.9*	*49.9*
2	*49.7*	*49.6*
3	*50.1*	*50.4*
4	*49.8*	*49.7*
5	*50.2*	*50.5*

Solution:
From the measurements shown, it can be seen that the instrument A is more repeatable. The measurements from both instruments are within the tolerance expressed by the ±1% accuracy stated (±1% psi).

Example 1.7

A force sensor measures a range of 0 to 150 N with a resolution of 0.1% FS. Find the smallest change in force than can be measured.

Solution:
Because the resolution is 0.1% FS, we have a resolution of:
Resolution = = $\frac{0.1\,\%(150\,\mathrm{N})}{100\,\%} = 0.15\,\mathrm{N}$
Which is the smallest measurable change in force.

1.5.1 Statistics of Errors

Statistical analysis is frequently used in measurements and four concepts commonly used in measurements are: averages, dispersion from the average, probability distribution of errors, and sampling.

Averages

The most frequently used averaging technique is the '*arithmetic mean*'. If n readings are taken with an instrument, and the values obtained are $x_1, x_2, \ldots, x_\mathrm{n}$, then the arithmetic mean is given by

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \ldots + x_\mathrm{n}}{\mathrm{n}} = \frac{\sum_{\mathrm{r}=1}^{\mathrm{n}} x_\mathrm{r}}{\mathrm{n}} \tag{1.5}$$

Although the arithmetic mean is easy to calculate it is influenced unduly by extreme values, which could be false. An alternative averaging technique, called the geometric mean, is not overly affected by extreme values. It is often used to find the average of quantities that follow a geometric progression or an exponential law. The geometric mean is given by

$$x_\mathrm{g} = \sqrt[n]{x_1 \times x_2 \times x_3 \times \ldots \times x_\mathrm{n}} \tag{1.6}$$

Dispersion from average

The 'average' represents the mean Figure of a series of numbers. It does not give any indication of the spread of these numbers.

The three techniques most frequently used to measure dispersion from the mean are the *range*, *mean deviation* and the *standard deviation*.

The *range* is the difference between the largest and the smallest values.

The *mean deviation*, M, is found by taking the mean of the difference between each individual number in the series and the arithmetic mean, and ignoring negative signs. Therefore for a series of n numbers $x_1, x_2, \ldots, x_n$, having an arithmetic mean $\bar{x}$, the mean deviation is given by

$$M = \frac{\sum_{r=1}^{n} |x_r - \bar{x}|}{n} \tag{1.7}$$

Neither the mean deviation nor the range are suitable for use in statistical calculation. The standard deviation is the measure of dispersion that is most commonly used for this. The standard deviation of a series of n numbers $x_1, x_2, \ldots, x_n$ having a mean of $\bar{x}$, is given by

$$\sigma = \left(\frac{\sum_{r=1}^{n} (x_r - \bar{x})^2}{n} \right)^{\frac{1}{2}} \tag{1.8}$$

because the deviation from the mean is squared before summing, the signs are taken into account, so that the calculation is mathematically correct.

Example 1.8 Measures of Dispersion

Two voltmeters were used to measure a fixed voltage. The values read are 97, 98, 99, 100, 101, 102, 103V for the first voltmeter and the values for the second voltmeter were 90, 90, 95, 100, 100, 105, 110, 110.

Determine the Mean, Mean deviation and Standard Deviation of each measurement.

Solution:

For the first voltmeter:

$$\text{Mean} = \frac{97+98+99+100+100+101+102+103}{8} = 100\text{V}$$

$$\text{Range} = 103 - 97 = 6\text{V}$$

$$\text{Mean Deviation} = \frac{\sum_{r=1}^{n} |x_r - \bar{x}|}{n}$$

$$= \frac{3+2+1+0+0+1+2+3}{8} = 1.5\text{V}$$

$$\sigma = \left(\frac{\sum_{r=1}^{n} (x_r - \bar{x})^2}{n} \right)^{\frac{1}{2}}$$

$$= \left(\frac{9+4+1+0+1+4+9}{8} \right)^{\frac{1}{2}} = 1.87$$

For the second voltmeter:

$$\text{Mean} = \frac{90+90+95+100+100+105+110+110}{8} = 100\,\text{V}$$

$$\text{Range} = 110 - 90 = 20\,\text{V}$$

$$\text{Mean Deviation} == \frac{\sum_{\text{r}=1}^{\text{n}} |x_\text{r} - \bar{x}|}{\text{n}}$$

$$= \frac{10+10+5+0+0+5+10+10}{8} = 6.25\,\text{V}$$

$$\sigma = \left(\frac{\sum_{\text{r}=1}^{\text{n}} (x_\text{r} - \bar{x})^2}{\text{n}}\right)^{\frac{1}{2}}$$

$$= \left(\frac{100+100+25+0+0+25+100+100}{8}\right)^{\frac{1}{2}} = 7.5$$

Notice that

(i)the mean is the same in both cases

(ii) by comparing the mean deviation of the two sets of readings, one can deduce that the first set is more closely clustered around the mean, and therefore represents more consistent values.

Probability Distribution of Errors

If an event A, for example an error, occurs n times out of a total of m cases, then the probability of occurrence of the error is stated to be

$$p(A) = \frac{n}{m} \tag{1.9}$$

Probabilities vary between 0 and 1. If $p(A)$ is the probability of an event occurring then $1 - p(A)$, which is written as $p(\bar{A})$, is the probability that the event will not occur.

There are several mathematical distributions that are used to define the spread in probabilities. The *binomial, Poisson, normal, exponential* and *Wiebull* distributions are commonly used. The normal distribution is most commonly used. The normal distribution curve is bell shaped, and is shown in Figure 1.9.

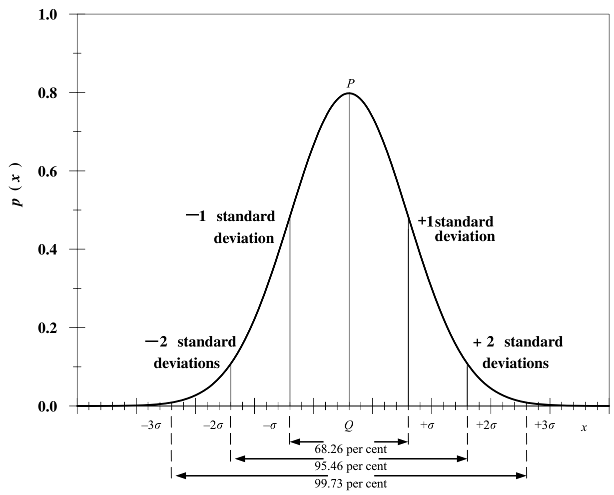

Figure 1.9 normal distribution

The x axis gives the event and the y axis gives the probability of the event occurring. If PQ represents the line of mean value $\bar{x}$ then the equation for the normal curve is given by

$$y = \frac{1}{(2\pi)^{1/2}} \exp -\omega^2/2 \tag{1.10}$$

1.5.2 Factors influencing measurement errors

Errors arise in measurement systems due to several causes, such as human errors or errors in using an instrument in an application for which it has not been designed. Definitions of factors that influence measurement errors are introduced below.

Accuracy

Accuracy refers to how closely the measured value agrees with the true value of the parameter being measured. For electrical instruments the accuracy is usually defined as a percentage of full scale deflection.

Precision

Precision means how exactly or sharply an instrument can be read. It is also defined as how closely identically performed measurements agree with each other. As an example, suppose that a resistor, which has a true resistance of 26 863Ω, is measured by two different meters. The first meter has a scale which is graduated in kΩ, so that the closest one can get to reading of resistance is 27 kΩ. The instrument is fairly accurate but it is very imprecise. The second instrument has a digital readout which gives values of resistance to the nearest ohm. On this instrument the same resistor measures 26 105Ω. Clearly this instrument has high precision but low accuracy.

Resolution

The resolution of an instrument is the smallest change in the measured value to which the instrument will respond. For a moving pointer instrument the resolution depends on the deflection per unit input. For a digital instrument the resolution depends on the number of digits on the display.

Range and bandwidth

The range of an instrument refers to the minimum and maximum values of the input variable for which it has been designed. The range chosen should be such that the reading is large enough to give close to the required precision. For example, with a linear scale an instrument which has 1 per cent precision at full scale will have 4 per cent precision at quarter scale.

The bandwidth of an instrument is the difference between the minimum and maximum frequencies for which it has been designed. If the signal is outside the bandwidth of the instrument, it will not be able to followchanges in the quantity being measured. A wider bandwidth usually improves the response time of an instrument, but it also makes the system more prone to noise interference.

Sensitivity

Sensitivity is the degree of response of a measuring device to the change in input quantity. The sensitivity of an instrument is defined as the ratio of the output signal of response of the instrument to the input signal or measured variable.

Uncertainty

Uncertainty is an estimate of the possible error in a measurement. More precisely, it is an estimate of the range of values which contains the true value of a measured quantity. Uncertainty is usually reported in terms of the probability that the true value lies within a stated range of values.

Measurement uncertainty has traditionally been defined as a range of values, usually centred on the measured value, that contains the true value with stated probability. A measurement result and its uncertainty traditionally were reported as

$$\text{quantity} = \text{value} \pm U \tag{1.11}$$

So the number usually reported and called ŚuncertaintyŠ was actually half the range defined here. The ISO Guide (?) redefines uncertainty to be the equivalent of a standard deviation, and thus avoids this problem.

Confidence interval and confidence level

When uncertainty is defined as above, the *confidence interval* is the range of values that corresponds to the stated uncertainty.

Confidence level is the probability associated with a confidence interval. For example one could indicate that the true value can be expected to lie within $\pm x$ units of the measured value with 99 percent confidence.

Repeatability

Repeatability is defined as the degree of agreement among independent measurements of a quantity under the same condition.

Reproducibility

Measurement reproducibility is the closeness of agreement between the results of measurements of the same measurand at different locations by different personnel using the same measurement method in similar environments.

Assessment Questions

Exercise 1.1*:* ***Questions for Homework***

1. Give one example of each class of instrument (Mechanical, Electrical and Electronic)
2. Give one example of each class of instrument (Indicating, Recording and Integrating) instrument.

Solution:
1.
2.

Exercise 1.2*:*

1. What is meant by measurement?
2. Mention the basic requirements of measurement.
3. What are the 2 methods for measurement?
4. Explain the function of measurement system.
5. Define Instrument.
6. List the types of instruments.
7. Classify instruments based on their functions.
8. Give the applications of measurement systems.
9. Explain the calibration procedure. Why calibration of instrument is important?
10. Define Calibration.

Solution:

1. Measurement is an act or the result of comparison between the quantity and a Pre-defined standard.

2. (1) The standard used for comparison purpose must be accurately defined and should be commonly accepted.
   (2)The apparatus used and the method adopted must be provable.
3. Direct method and Indirect method.
4. The measurement system consists of a transducing element which converts the quantity to be measured in an analogous form. the analogous signal is then processed by some intermediate means and is then fed to the end device which presents the results of the measurement.
5. Instrument is defined as a device for determining the value or magnitude of a quantity or variable.
6. The 3 types of instruments are: (1) Mechanical Instruments (2) Electrical Instruments and (3) Electronic Instruments.
7. (1)Indicating instruments (2)Integrating instruments (3) Recording instruments
8. The instruments and measurement systems are sued for (1) Monitoring of processes and operations (2)Control of processes and operations (3)Experimental engineering analysis
9. Calibration procedure involves a comparison of the particular instrument with either (i) A primary standard (ii) A secondary standard with a higher accuracy than the instrument to be calibrated or An instrument of known accuracy.

   The calibration of all instruments is important since it affords the opportunity to check the instrument against a known standard and subsequently to errors in accuracy
10. It is the process by which comparing the instrument with a standard to correct the accuracy.

Answers to Exercises

(Coleman et al., 2008)

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