Chapter 1: Introduction to Measurement and Instrumentation

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Contents

1. General Concepts

- **Measurement:** The process of determining the amount, degree, or capacity by comparison (direct or indirect) with the accepted standards of the system unites being used.
  - Result: Number + measured unit
    E.g.: 10 V
- **A measurement system:** is a system that converts an unknown quantity being measured to a numerical unit using an instrument.

- **Instrument:** A device or mechanism used to determine the present value of the quantity under measurement.
- Two types of Instruments:
  1. Analog Instrument: a deflection type instrument with a scale and movable pointer.
  2. Digital Instrument: display in decimal (digital) from the value of the quantity being measured.

General Concepts

- **Electronic Instrument:** is based on electrical or electronic principles for its measurement functions.
- **Data:** Information obtained from the instrumentation/measurement system as a result of the measurements made of the physical quantities.
- **Resolution:** The smallest change in a numerical variable to which an instrument will respond.
- **Sensitivity:** The ratio of the change in output of the instrument to a change of input or measured variable.

$$Sensitivity = \frac{\Delta y}{\Delta x} \tag{1}$$

where;

Δy is the change in output value

Δx is the change in input value.

Example 1

A wheatstone bridge require change of 7 ohm in the unknown arm of the bridge to produce a change in deflection of 3 mm of the galvanometer. Determine the sensitivity.

Example 2

The following resistance values of platinum resistance thermometer were measured at 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

2. Measuring Things

- Discovering physics $\Rightarrow$ by learning how to measure the quantities involved in physics.
- Among these quantities are length, time, mass, temperature, pressure, and electric current.
- Measuring each physical quantity in its own units $\Rightarrow$ by comparison with a standard.
- The unit is a unique name is assigned to measures of that quantity.
  - Length: meter (m)
  - Time: seconds (s)
  - Mass: kilograms (kg)
- The standard corresponds to exactly 1.0 unit of the quantity.

3. System of Units

Unit: is a standard or reference by which a dimension can be expressed numerically.

1. International System of Units (SI):
   - Length (L): meter (m)
   - Time (T): seconds (s)
   - Mass (M): kilograms (kg)

2. cgs units:
   - Length (L): centimeter (cm)
   - Time (T): seconds (s)
   - Mass (M): grams (g)

3. English units:
   - Length (L): foot (ft) $\quad 1\text{m} = 3.28$ ft
   - Time (T): seconds (s)
   - Mass (M): slug (sl), $\quad 1$ kg $= 0.068$ slug

1. Fundamental Units

- The SI system: is the French International System of Units, and popularly known as the metric system of units.

Quantity	Symbol	Unit	Unit Abbreviation	Dimension Symbol
Length	l	meter	m	L
Mass	m	kilogram	kg	M
Time	t	second	s	T
Temperature	T	degree kelvin	$^{\circ}$K	θ
Luminous intensity		candela	cd	J
Electric current	I	ampere	A	I

Table: Six Fundamental Quantities of the SI System

2. Secondary Units

- The product/multiple/derivative of fundamental units are known as secondary units.
- For example:
  - **Multiple:** Area (m^2), Volume (m^3).
  - **Product:** Speed (ms^{-1}), Charge (As).
  - **Derived units:** Newton(N), Joule (J), Power (W), Frequency (Hz).
- Six electrical quantities are of concern when we make electrical measurements, which are:
  1. Electric charge (Q)
  2. Electric current (I)
  3. Electromagnetic force or potential difference (V)
  4. Resistance (R)
  5. Inductance (L)
  6. Capacitance (C)

Electrical Units

- The fundamental quantities of the SI system of units and a few of the electrical quantities that can be derived from these units.

Quantity	Symbol	Unit	Unit Abbreviation	Dimension Symbol
Electromagnetic force	V	volt	V	$ML^2T^{-3}I^{-1}$
Quantity of charge	Q	coulomb	C	IT
Electrical resistance	R	ohm	Ω	$ML^2T^{-3}I^{-2}$
Capacitance	C	farad	F	$M^{-1}L^{-2}T^4I^2$
Inductance	L	henry	H	$ML^2T^{-2}I^{-2}$

Table: Some Derived Quantities of the SI System

Prefixes

- To express the very large and very small quantities we can use scientific notation, which employs powers of 10

$$3560000000m = 3.56 \times 10^9 m$$

$$0.000000492s = 4.92 \times 10^{-7} s$$

- Scientific notation on computers sometimes takes on an even briefer look, as in 3.56 E9 and 4.92 E-7, where E stands for "exponent of ten".
- When dealing with very large or very small measurements, we use the prefixes.
- Each prefix represents a certain power of 10, to be used as a multiplication factor.

Prefixes

Factor	Prefix	Symbol
10^{15}	peta-	P
10^{12}	tera-	T
10^{9}	giga-	G
10^{6}	mega-	M
10^{3}	kilo-	k
10^{-2}	centi-	c
10^{-3}	milli-	m
10^{-6}	micro-	μ
10^{-9}	nano-	n
10^{-12}	pico-	p

Table: Prefixes for SI Units

Dimension Analysis

- It is necessary for every equation to be balanced dimensionally.
- Dimension of physical quantity:
  - Force $=$ mass $\times$ acceleration $=$ MLT^{-2}
    Unit for force $=$ N $=$ kgms^{-2}
  - Charge $=$ Current $\times$ time $=$ IT
    In base units: As
- **Example 3:** The unit of voltage is volt (V). Express the dimension of voltage using only base units.

- **Example 4:** The unit of power is watt (W). Express the dimension of power using only base units.

- **Example 5:** The unit of resistance is ohm (Ω). Express the dimension of resistance using only base units.

4. Measurement Standards

- Before we can measure something, we must define its dimension and provide some standard, or reference unit, in terms of which the quantity can be expressed numerically.
- **A standard:** An instrument or device having a recognized stable value that is used as a reference.
- A known accurate measure of physical quantity is termed as a standard.
- These standard are used to determine the values of other physical quantities by the comparison method.
- There are different types of standard of measurement classified by their function and application in the following categories:
  1. International Standards
  2. Primary Standards
  3. Secondary Standards
  4. Working Standards

Measurement Standards

1. International Standards

- Defined on the basis of international agreement.
- Have the highest possible achieved accuracy.
- Periodically evaluated and checked.
- Not available to ordinary users, maintained at International Bureau of Weights and Measures at Sevres, Paris.

2. Primary Standards

- Maintained by national standard laboratories.
- Not available for use outside the national labs.
- Constructed to have highest possible accuracy.
- Main function is to check the accuracy of secondary standards.

Measurement Standards

3. Secondary Standards

- Used in industrial measuring labs.
- For calibrating equipment and components.
- Verifying the accuracy of working standard.
- Checked periodically by institutions maintained the primary standards.

4. Working Standards

- Principal tools of measurement lab.
- Used to check general laboratories instrument for their accuracy and performance.

6. Error in Measurement

- **Error:** The deviation of a reading from the expected value of measured variable.

1. True Value or Expected Value

- The most probable value that calculations indicate you should expect to obtain.
- It is almost impossible to obtain in practice.
- For example: Light speed = 299792458.63 m/s

2. Measured Value

- Measured value: Value of a measurand as indicated by an instrument.
- It should always be followed by its uncertainty in measurement.
- For example: $m = (5.5 \pm 0.1)$ gm
  $l = (2.4 \pm 0.1)$ cm
  $R = (200.5 \pm 0.2)\ \Omega$

3. Nominal Value

- Nominal Value: Value of the quantity specified by the manufacturer.
- It is followed by tolerance level.
- For example: l = 5.5 cm $\pm$ 1%
  R = 10 kΩ $\pm$ 5%
  (The True value is between 9.5 kΩ and 10.5kΩ)

4. Absolute Error

- Absolute Error: The difference between the expected value and the measured value of the quantity.

$$e = Y_n - X_n \tag{2}$$

e: Absolute error
Y_n: Expected value
X_n: Measured value

5. Relative Error

- Relative Error: The ratio of absolute error to the true value
- Relative Error (e_r) (as a fraction):

$$e_r = \frac{\text{Absolute Error}}{\text{Expected Value}} = \frac{e}{Y_n} = \frac{Y_n - X_n}{Y_n} \tag{3}$$

- Relative Percentage Error (% Error) (as Percentage %)

$$\%Error = \frac{\text{Absolute Error}}{\text{Expected Value}} \times 100\% = \frac{e}{Y_n} \times 100\% = \left| \frac{Y_n - X_n}{Y_n} \right| \times 100\% \tag{4}$$

6. Relative Accuracy

- **Accuracy:** The degree of exactness of a measurement when compared to the expected value of the variable being measured.
- Example: Assume the true value, m = 5.90 kg
  - Reading from instrument A, m = 5.82 kg
  - Reading from instrument B, m = 5.91 kg
  - **Conclusion: Instrument B is more accurate.**

- It is frequently more describe to express measurements in terms of **Relative Accuracy (A)** rather than error,

$$A = 1 - \left| \frac{e}{Y_n} \right| = 1 - \left| \frac{Y_n - X_n}{Y_n} \right| \tag{5}$$

- Accuracy expressed as **percent accuracy (a)**, is

$$a = 100\% - \text{Relative Percentage Erorr} = 100\% - \%Error \tag{6}$$

$$a = A \times 100\% \tag{7}$$

7. Precision

- **Precision:** A measure of the consistency or repeatability of measurements.
- Example: given a fixed value of quantity, precision is a measure of **the degree of agreement** within a group of measurements.

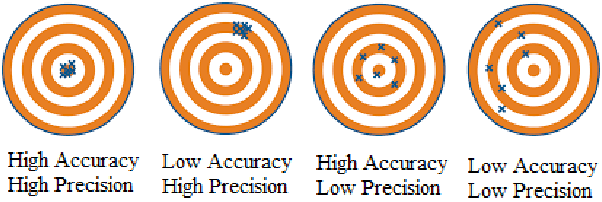
Error in Measurement

- It is composed of 2 characteristics:
  - Conformity
  - Number of significant figures

- Example: Suppose;
  Instrument A, l = 5.32, 5.32, 5.31, 5.32
  Instrument B, l = 5.32, 5.34, 5.33, 5.30
  Conclusion: Instrument A is more precise.

- Example: Suppose; True value, m = 4.50 kg
  Instrument A, m = 4.475 kg
  Instrument B, m = 4.49 kg
  Conclusion: **Instrument A is more precise.**
  Instrument B is more accurate.

Error in Measurement



- Precision can be expressed in a mathematical sense, or quantitatively, as

$$Precision = 1 - \left| \frac{X_n - \overline{X}_n}{\overline{X}_n} \right| \tag{8}$$

X_n: the value of the n^{th} measurement.
$\overline{X}_n$: the average of the set of n measurements.

Example 6

The expected value of the voltage across a resistor is 50 V; however, measurement yield a value of 49 V. Calculate:

1. The absolute error.
2. The percent error.
3. The relative accuracy.
4. The percent of accuracy.

Example 7

The following set of ten measurements was recorded in the laboratory. Calculate the precision of the fourth measurement.

Measurement Number	**Measurement Value X_n (volts)**
1	98
2	102
3	101
4	97
5	100
6	103
7	98
8	106
9	107
10	99

Example 8

The following table of values represents a meter output in terms of the angular displacement of the needle, expressed in degrees, for a series of identical input currents. Determine the worst case precision of the readings.

I_{in} (μ**A**)	**Output Displacement (degrees)**
10	20.10
10	20.00
10	20.20
10	19.80
10	19.70
10	20.00
10	20.30
10	20.10

7. Sources of Error

The source of error, other than the inability of a piece of hardware to provide a true measurement, are as follows:

1. Insufficient knowledge of process parameter, irregularities, upsets. etc.
2. Poor design.
3. Poor maintenance.
4. Change in process parameter, irregularities, upsets. etc. ...
5. Certain design limitations.
6. Errors caused by person operating the instrument or equipment.

8. Types of Static Error

- The static error of a measuring instrument is the numerical difference between the true value of a quantity and its value as obtained by measurement.
- Static errors are categorised as:

1. Gross Errors or Human Errors.
2. Systematic Error
    1. Instrumental Errors.
    2. Environmental Errors.
    3. Observational Errors.
3. Random Error

Types of Static Error

1. Gross Errors or Human Errors

- Refer to errors due to human mistake in reading instruments and recording and calculating measurement results.
- Examples:
  - Read the length of wire as 21.3 cm while the actual reading is 11.3 cm
  - Read 21.3 cm but record as 23.1 cm
  - 5 - 1 = 6 instead of 4
- **Prevention:**
  - Read and record carefully.
  - Take the average of several readings (at least 3 readings).

Types of Static Error

2. Systematic Error

2.1 Instrumental Errors.

1. Due to inherent shortcomings of the instruments
    - Inherent due to their mechanical structure.
    - May be due to improper calibration, construction.
    - Due to faulty instrument.

    Prevention:
    - Re-calibrate carefully.
    - Apply correction factor after determining the instrumental errors.
    - Proper maintenance, use and handling of instruments.
2. Due to misuse of instrument.
    - Failure to adjust the zero of instrument (calibrate).
    - Using leads of too high resistance (when measuring low R value).

    Prevention:
    - Recalibrate system carefully.
    - Use a right instrument for a particular application.

2.2 Environmental Errors.

- Effect due to temperature, pressure, humidity, dust, vibration or external magnetic or electrostatic fields.
- **Prevention:**
  - Keep the surrounding conditions as constant as possible.
  - Use equipment which not affected by these effects.
  - Employ techniques which eliminate the effects of disturbances.
  - Apply computed correction.

2.3 Observational Errors.

- Observational error are those errors introduced by the observer.
- There are two common types of observational errors:
  - Parallax error: Error due to wrong observation angle/position.
  - The error of estimation: when obtaining a reading from a meter scale.

3. Random Error

- Random errors are those that remain after the gross and systematic errors have been substantially reduced.
- These are error due to unknown causes.
- These are unavoidable errors. Even though the devise been calibrated.
- **Prevention:**
  - More reading need to be taken.
  - Using statistical means to obtain the best approximation to the true value.

1. The Arithmetic Mean

- Suppose an experiment were repeated many, say n, times to get, x_1, x_2, ... , x_n
- **The arithmetic mean ($\overline{x}$)** is the sum of a set of numbers divided by the total number of pieces of data.

$$\overline{x} = \frac{x_1 + x_2 + x_3 + ... + x_n}{n} \tag{9}$$

where;
$\overline{x}$: Arithmetic mean.
x_n : n^{th} reading taken.
n: total number of readings.

2. Deviation

- **Deviation (d)** is the difference between each piece of test data and the arithmetic mean.

$$d_1 = x_1 - \overline{x} \tag{10}$$

$$d_2 = x_2 - \overline{x} \tag{11}$$

$$d_i = x_i - \overline{x} \tag{12}$$

- The algebraic sum of the deviation of a set of numbers from their arithmetic mean is **zero**.
- The average deviation may be used as an expression of the precision of measuring instrument.
- A low value for average deviation indicates a precise instrument.

3. The Average Deviation

- The average deviation is an indication of the precision of the instrument used in measurement.
- Average deviation is defined as the sum of the absolute values of the deviation divided by the number of readings.
- **The average deviation (D_{avg})** of a set of numbers is;

$$D_{avg} = \frac{|d_1| + |d_2| + |d_3| + \dots + |d_n|}{n} \tag{13}$$

where;
D_{avg}: The average deviation.
$|d_1|, |d_2|, \dots, |d_n|$: Absolute value of deviations.
n: Total number of reading.

4. The Standard Deviation

- The standard deviation for a set of values is the degree to which the values vary about the average value.
- The standard deviation is also known as root mean square deviation.
- **The Standard Deviation (σ)** of a set of n numbers is

$$\sigma = \sqrt{\frac{d_1^2 + d_2^2 + ... + d_n^2}{n}} \tag{14}$$

where; σ is the standard deviation.

- For small reading ($n < 30$), the denominator is frequently expressed as (n-1) to obtain more accurate value for the standard deviation.

Example 9

For the following data compute:

1. The arithmetic mean.
2. The deviation of each value.
3. The algebraic sum of the deviations.
4. The average deviation.
5. The standard deviation.

$$X_1 = 50.1$$
$$X_2 = 49.7$$
$$X_3 = 49.6$$
$$X_4 = 50.2$$

5. Limiting or Guarantee Errors

- Manufacturer must always guarantee a certain accuracy of their product **numerically** to ensure the quality of their instrument.
- The manufacturer specifies the **deviations from the nominal value** of a particular quantity defined as limiting errors or guarantee errors.
- For example, manufacturer of a certain voltmeter may specify the instrument to be accurate with $\pm$ 2% with full-scale deflection.
- The limiting error means that a full-scale reading is guaranteed to be within the limits of 2% of perfectly accurate reading.
- However, with readings that are less than full-scale, the limiting error will increase.
- It is important to obtain measurements as close as possible to full-scale.
- The limiting error obtained for **the worst possible combination** by direct sum of all possible Errors.

Example 10

A 150V voltmeter has a guarantee accuracy of 1% at full-scale reading. The voltage measured by this instrument is 83V.

1. Calculate the limiting error
2. Calculate Actual value.

Example 11

A voltmeter and an ammeter are to be used to determine the power dissipated in a resistor. Both instruments are guaranteed to be accurate within $\pm$ 1% at full-scale deflection. If the voltmeter reads 80 V on its 150 V range and the ammeter reads 70 mA on its 100 mA range. Determine the limiting error for the power calculation.

1. **Transducer:** converts a nonelectrical signal into an electrical signal. It is required only if the quantity to be measured is nonelectrical.

2. **Signal Modifier:** is required to process the incoming electrical signal to make it suitable for application to the indicating device. The signal may need to amplified until it is of sufficient amplitude or reduce the amount of signal applied to the indicating device.

3. **Indicating Device:** is generally a deflection type meter for such general purpose instruments as voltmeters, current meters.