EC-1(Measurement and Instrumentation)Unit 1 Notes (I)

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<u>MPHYEC – 1F Measurement and Instrumentation (5 Credits)</u>

Course Objectives:

1. To make the student familiarize with the basics of experimental physics.
2. To make the student familiarize with the basics of electronics.
3. To enable the student to explore the concepts involved in the oscillators.
4. To allow the student to understand the fundamentals of instruments involved

Unit 1: Basic Principles

Measuring Instruments: Accuracy, precision, sensitivity and resolution; Scale, standards and calibration; Uncertainties of measurements and errors, propagation of errors, statistical treatment of random errors, Distribution functions their derivation and properties

INSTRUMENTATION

Instrumentation is the science and technology of complete systems with which physical quantities are measured so as to obtain data which are transmitted to recording or display devices or to control devices.

Introduction: Measurement has always occupied an important place in Science and Technology. The advances of Science can be correlated with the improvements in Measurement technology. Many of the major breakthroughs in our Knowledge took place in an attempt to explain small discrepencies between theoretically predicted values and experimentally obtained ones as a result of better instrumentation. Instrumentation deals with design and construction of modern instruments built for various types of measurements.

Measurement of any physical quantity is based on some physical phenomenon in which a feature of the measuring device is used for comparing the value of the property of the system under consideration with a standard value. So depending on the nature of measurement, the measuring instrument can be mechanical, optical, electrical, etc. In recent time, practically All modern instruments have been made electronics based because such instruments have several advantages compared to the traditional measuring instruments. Following are some of the advantages of electronic measuring instruments.

(i) It is possible to design very sensitive as well as practically non-obstrucive instruments because even very small signals output from sensors can be electronically amplified for convenient recording or display.

(ii) An electronic signal can be easily processed for conversion to a useful and meaningful form. The different mathematical operatins required can be carried out either on the signals directly or processed digitally by attached microcontrollers or computers.

(iii) The measurement signals in electrical form cal be transmitted through short or long distances as per need. The basic instrument can thus be physically separated from processing devices as required. Thus the measurements by several devices can all be displayed on a single panel for convenience.

(iv) Many measurements can be carried out rapidly or simultaneously in real time. The data obtained can be processed sufficiently fast to be updated as soon as changes occur.

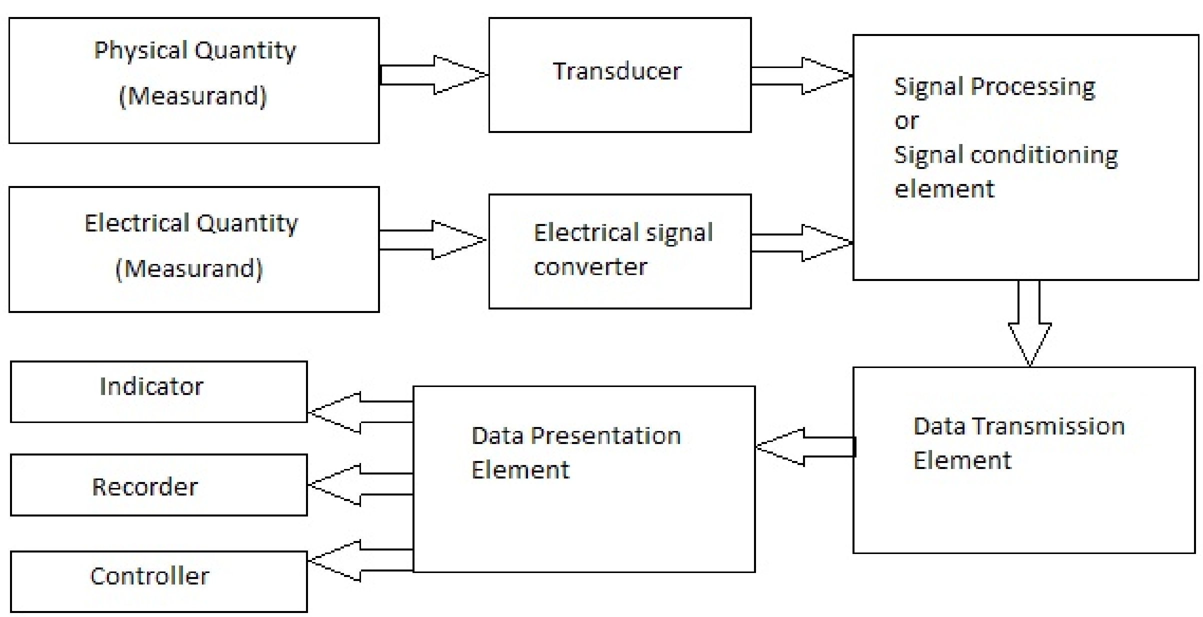
(v) Very small to very large values in measurands can be handled with good accuracy in modern electronic instruments.

(vi) The processes for a large variety of systems and parameters can be handled by instruments that are electronically very similar in principle.

(vii) As digital technology has improved, more and more digital electronic instruments are being manufactured which have better capabilities and user interface.

Block Diagram of a generalized measuring system:

The figure below depicts a block diagram of a typical modern instrument.



Block Diagram of a General Instrumentation System

Components of the measuring system:

Following is a brief description of different components of an electronic measuring system:

1. **Measurand:** Measurand is a physical or electrical quantity that the instrument has to measure. Examples of physical Measurands are Position, Displacement, Acceleration, Temperature, Intensity of Light, strain, Magnetic Field, etc. Examples of Electrical Measurands are Voltage, Current, Frequency of A.C., Resistance, etc. For making any measurement, we must also know the measurand characteristics. These include the nature of measurand and the range of values that the measurand is suppose to cover during the measurement.
2. **Transducer**: A transducer is a device that converts the measurand into an electrical parameter that can be utilized in the instrument for further processing. Such a parameter can be a voltage, a current, resistance or some other type of signal.
3. **Signal processing or conditioning element:** The output of the transducer is an electrical signal. Before it can be displayed, or transmitted to the next stage, it has to be further processed so as to convert it into a form that is required by the next stage. This activity is called signal conditioning. The electronic circuits that carry out this function are called signal processing or signal conditioning elements.
4. **Data transmission element:** The transducer and associated circuits are often physically separated from the front end circuits where the information is displayed or recorderd. So suitable arrangement has to be made so that the signal reaches its destination without loss of information. Data may have to be sent through a carrier signal using wire or radio link or converted into digital form for reliable transmission. The related circuitary is termed as Data transmission element.
5. **Data presentation element:** The signal may have to be further processed before it is displayed, or recorder for further analysis, or used for control purposes. The data presentation element processes the signal to make it compatible with the relevant front end devices (Recorder, Display device, Controller, Computer, etc.)
6. **End element:** At the front end there can be some display device, recorder, or a computer or microcontroller based interface which communicates the information to the user in a human interpretable format. Alternately, it can supply this information in a digital form suitable for computer based applications.

Basic Terminology

Measurement: Measurement is a process through which the magnitude of a physical quantity (property that can be quantified) is obtained for a particular system by comparison with a standard magnitude of that quantity called “unit“.

Measurand: The physical quantity that we want to measure is called the measurand.

Measuring Instrument: A measuring Instrument is a device or a setup using which we carry out a measurement. Very few measurements are done directly. The modern trend is to convert the physical quantity to be measured into an electrical parameter through some transducer and then process that electrical signal to get the measurement value. In instrumentation we study ifference how this is done.

Static and Dynamic characteristics of an instrument: Characteristics of an instrument refer to its salient properties or features. The static characteristics of a measuring instrument are its characteristic features as obtained under steady state condition or when the instrument settles down. Dynamic characteristics are related to how the instrument copes with situations where the measurand changes value with real time.

Static characteristics: Some of the important static characteristics are described below.

Accuracy: The exact value of any continuous variable cannot be determined through measurement. This is mainly because of the limitations of the instrument which can make comparison only to a certain limit. Accuracy of any measurement is an estimate of the closeness of a measured value to the exact value. When we make any measurement and express the measured value, we also include an estimate of the accuracy of the measurement. For example, when we write T = $80^oC \pm 0.5^oC$ we mean that the measured temperature can lie between 79.5^oC and 80.5^oC. The mean value is and 80^oC and the accuracy is $\pm$ 0.5^oC. The accuracy of an instrument can also be expressed as percentage. Then it denotes percentage the corresponding full scale range. Suppose the range of a particular thermometer is 0 to 100^oC. Then a reading of $80^oC \pm 0.5\%$ will mean an accuracy of $\pm 0.5\%$ of 100^oC i.e. $\pm 0.5^oC$.

Precision: Precision is a term that describes an instrument's degree of freedom from random errors. If a large number of readings are taken of the same quantity by a high precision instrument then the spread of readings will be very small. Such an instrument will be able to discriminate or distinguish between two close-by values with better reliability. The repeatability of an instrument refers to the closeness of measured values when same measurement is repeated over short period of time. Another related term is reproducibility. Reproducibility describes the closeness of output readings for the same input when there are changes in the method of measurement, observer, measuring instrument, location, conditions of use and time of measurement.

Tolerance: Tolerance is not a property of measuring instrument but is a term that is closely related to accuracy and defines the maximum error that is to be expected in some supplied value. Tolerance is generally provided by the manufactures and expresses the maximum deviation of the actual value from the quoted value. For instance, if we have a 1.5 KΩ resistor whose tolerance is 10% then its value can be expected to lie within 10% of 1.5 KΩ. Sometimes the accuracy of an instrument is quoted as a tolerance figure.

Span: The *range* or *span* of an instrument defines the minimum and maximum values of a quantity that the instrument is designed to measure.

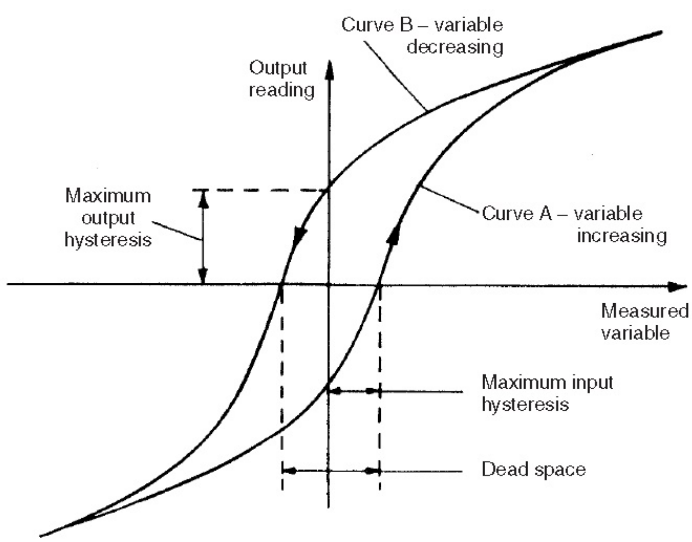
Linearity: In most of the instruments the output reading is linearly proportional to the quantity being measured. The non-linearity of the instrument is then defined as the maximum deviation of any of the output readings from a linear function (straight line fit: y = m x + c). Non-linearity is usually expressed as a percentage of full-scale reading.

Sensitivity: The sensitivity of measurement is a measure of the change in instrument output that occurs when the quantity being measured changes by a given amount. Thus, sensitivity is the ratio of scale deflection and the value of measurand producing this deflection. The sensitivity of measurement is therefore the slope of the straight line drawn between the scale deflections (y axis) and the corresponding measurand values (x axis).

Threshold: If the input to an instrument is gradually increased from zero, the instrument output reading is detectable only when the input reaches a certain minimum level. This minimum level of input is known as the threshold of the instrument.

Resolution: The resolution of an instrument refers to the minimum change in the measurand that will produce distinctly different reading in the instrument.

Sensitivity to disturbance: The specifications of an instrument are valid only under controlled environmental conditions (temperature, pressure etc.) These standard ambient conditions are usually defined in the instrument specification. When variations in these conditions occur, some of the static instrument characteristics change. The sensitivity to disturbance is a measure of the magnitude of this change. The environmental changes affect instruments mainly in two main ways: zero drift and sensitivity drift. Zero drift is also known by the alternative term, bias. Zero drift describes the situation when the zero reading of an instrument is modified through a change in ambient conditions. This causes a constant error that appears over the full range of measurement of the instrument. Zero drift is expressed in terms of zero drift coefficients, one for each environmental parameter. Sensitivity drift (or scale factor drift) defines the amount by which an instrument's sensitivity of measurement varies as ambient conditions change. It is expressed in terms of sensitivity drift coefficients that define the amount of drift per unit change in each environmental parameter that the instrument characteristics are sensitive to.



Hysteresis: In some instruments, the readings for the same magnitude of the measurand are different when it is increasing and when it is decreasing. The reading appears to lag behind the actual value as shown in the figure. This lagging behind is called hysteresis.

Dead space: Dead space is defined as the range of different input values over which there is no change in output value. The instruments that show hysteresis also display dead space, as shown in above Figure. Backlash error in gears is also an example of dead space error.

Dynamic characteristics: The dynamic characteristics of a measuring instrument describe its behavior between the time a measured quantity changes value and the time when the instrument output attains a steady value in response. For a step change in measurand, the response can be expressed as

$$a_n \frac{d^n q_0}{dt^n} + a_{n-1} \frac{d^{n-1} q_0}{dt^{n-1}} + \cdots + a_1 \frac{dq_0}{dt} + a_0 q_0 = b_0 q_i$$

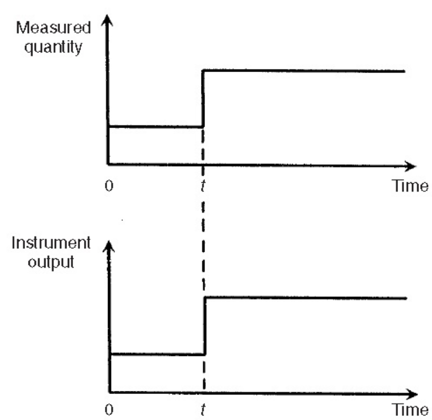
where qi is the measured quantity, q0 is the output reading and a0 . . . an, b0 are constants.

Zero order instrument: If all the coefficients a1 . . . an other than a0 in the above equation are assumed to be zero, then

$$a_0 q_0 = b_0 q_i \text{ and so } q_0 = b_0 q_i / a_0 = K q_i$$

where K is a constant known as the instrument sensitivity.

Any instrument that behaves according to the above equation is said to be of zero order type. If there is a step change in the measured quantity at time t, the instrument output moves immediately to the corresponding new value at the same time instant t.

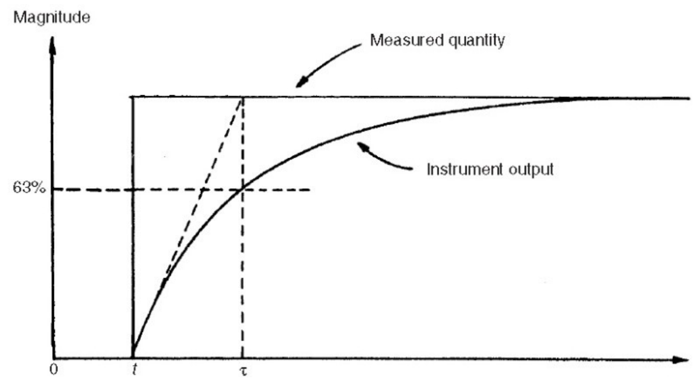


Zero order response

First order instrument: If all the coefficients $a_2 \ldots a_n$ except for a_0 and a_1 are assumed zero in equation (1) then

$$a_1 \frac{dq_0}{dt} + a_0 q_0 = b_0 q_i$$

If this equation is solved analytically, the output quantity q_0 in response to a step change in q_i at time t varies with time in the manner shown in Figure below. The time constant τ of the step response is the time taken for the output quantity q_0 to reach 63% of its final value.



Second order Instrument:

Measurement Scale: Modern measuring instruments are based on electronics. The common trend is to use some device (called sensor) that is sensitive to the physical parameter that we want to measure and outputs an electrical signal that is a function of the required parameter. This function can be linear or non linear depending on the nature of the sensing device. If we know the functional relation between the measurand and the electrical signal that our device outputs, then we can use this knowledge to obtain measurement value of the measurand when we obtain a particular value for the electrical signal from the device. The relation that exists between the measurand and the electrical parameter for the particular device is called the measurement scale.

Measurement standards: For measuring any physical quantity (measurable property), we require a unit in terms of which any measured value is expressed.

Measured value = number X unit (of the particular physical quantity)

A Fundamental principle of Scientific investigation is that the measured value is independent of the unit used. Different units have been adopted for the same physical quantity (i.e. Length, Mass, Time, etc.) at different times in different civilizations. Whatever be the unit adopted, the process of measurement is expected to give a value that does not depend on the unit adopted. Gradually the units have been standardized based on international agreement.

A Standard has been defined as an Object system or experiment that bears a well defined verifiable relation with a unit of measurement of a physical quantity. Modern measurements are defined in relationship to internationally standardized reference objects, which are used under carefully controlled laboratory conditions to define the units of length, mass, electrical potential, and other physical quantities.

S.I. Units: As of today, a uniform system of units has been adopted known as S.I. (Systeme internationale). It is based on a choice of seven fundamental physical quantities (and two auxiliary quantities). All other physical quantities as well as their units can be expressed in terms of these seven by considering the Laws of Physics and definitions of those (derived) quantities.

Table 1.1 Definitions of standard units

Physical Quantity	Standard unit	Definition
Length	metre	The length of path travelled by light in an interval of 1/299 792 458 seconds
Mass	kilogram	The mass of a platinum–iridium cylinder kept in the International Bureau of Weights and Measures, S`evres, Paris
Time	second	9.192631770 d 109 cycles of radiation from vaporized caesium-133 (an accuracy of 1 in 1012 or 1 second in 36 000 years)
Temperature	kelvin	The temperature difference between absolute zero and the triple point of water is defined as 273.16 kelvin
Current	ampere	One ampere is the current flowing through two infinitely long parallel conductors of negligible cross-section placed 1 metre apart in a vacuum and producing a force of 2 d 10_7 newtons per metre length of conductor
Luminous intensity	candela	One candela is the luminous intensity in a given direction from a source emitting monochromatic radiation at a frequency of 540 terahertz (Hz d 1012) and with a radiant density in that direction of 1.4641 mW/steradian. (1 steradian is the solid angle which, having its vertex at the centre of a sphere, cuts off an area of the sphere surface equal to that of a square with sides of length equal to the sphere radius)
Matter	mole	The number of atoms in a 0.012 kg mass of carbon-12

Table 1.2 Fundamental and derived SI units
(a) Fundamental units

Quantity	Standard Unit	Symbol
Length	metre	M
Mass	Kilogram	Kg
Time	Second	S
Electric current	Ampere	A
Temperature	Kelvin	K
Luminous Intensity	Candela	Cd
Matter	mole	Mol

(b) Supplementary Fundamental units

Quantity	Standard Unit	Symbol
Angle	radian	Rad
Solid Angle	steradian	Sr

(c) Derived units

Quantity	Standard Unit	Symbol
Area	Square meter	m^2
Volume	Cubic meter	m^3
Velocity	Meter per second	m/s
Acceleration	Meter per second squared	m/s^2
Angular velocity	Radian per second	rad/s
Angular Acceleration	Radian per second squared	rad/s^2
Density	Kilogram per cubic meter	Kg/ m^3
Specific Volume	Cubic meter per kilogram	m^3/kg
Mass flow rate	Kilogram per second	Kg/s
Volume flow rate	Cubic meter per second	m^3/s
Force	Newton	N (kg m/s^2)
Pressure	Newton per square meter, Pascal	Pa (N/m^2)
Torque	Newton meter	Nm
Momentum	Kilogram meter per second	Kg m/s
Moment of Inertia	Kilogram meter squared	Kg m^2
Kinematic viscosity	Square meter per second	m^2/s
Dynamic viscosity	Newton second per square meter	N s/m^2
Work, Energy, Heat	Joule	J (N m)
Specific Energy	Joule per cubic meter	J/m^3
Power	Watt	J/s
Thermal conductivity	Watts per meter kelvin	W/mK
Electrical Charge	Coulomb	Coul (As)
Voltage, emf, Pot. Diff.	Volt	V (W/A)
Electric Field	Volt per meter	V/m
Electric resistance	Ohm	Ω (V/A)
Electric capacitance	Farad	F (As/V)
Electric Inductance	Henry	H (Vs/A)
Electric Conductance	Siemens	S (A/V)
Resistivity	Ohm meter	Ωm
Permittivity	Farad per meter	F/m
Current density	Ampere per square meter	A/m^2
Magnetic Flux	Weber	Wb (Vs)
Magnetic Flux density	Tesla	T (Wb/m^2)
Frequency	Hertz (Cycles per second)	s^{-1}
Luminous Flux	Lumen	lm (cd sr)
Luminance	Candela per square meter	cd/m^2

Illumination	Lux	lx (lm/m^2)
Molar volume	Cubic meter per mole	m^3/mol
Molarity	Mole per kilogram	Mol/kg
Molar energy	Joule per mole	J/mol

S.I. Prefixes: In many situations the S.I. Unit may be too big or too small for practical usage. Then the units are scaled up or scaled down by attaching appropriate prefixes. These prefixes are listed below.

Prefix	Multiple	symbol
Atto	10^{-18}	a
Femto	10^{-15}	f
Pico	10^{-12}	p
Nano	10^{-9}	n
Micro	10^{-6}	µ
Milli	10^{-3}	m
Centi	10^{-2}	c
Deci	10^{-1}	d
Deca	10^{1}	da
Hecto	10^{2}	h
Kilo	10^{3}	K
Mega	10^{6}	M
Giga	10^{9}	G
Tera	10^{12}	T
Peta	10^{15}	P

Hierarchy of standards: Although the S.I. units are well defined, it is not possible to have these in day to day usage. So additional standards are required. The following types of standards have been defined in order to maintain uniformity in magnitude as well as to meet widespread needs.

(i) Primary Standards: These are devices that conform to the internationally agreed legal specifications of the different fundamental units. The International Primary Kilogram is a one kilogram mass of a platinum iridium alloy maintained by the International Bureau of Weights and Measures (BIPM) in Sèvres, France. Currently the volt is defined in terms of the output of a Josephson junction which bears a direct relationship to fundamental physical constants. In 1983, the standard meter was redefined as the distance that Light travels in vacuum during 1/299792458 of a second.

(ii) Secondary/Reference standards: The Primary standards are not very practical for calibration work. So many major national measuring laboratories maintain secondary reference standards that are very close approximations of primary reference standards. These are periodically calibrated against the primary standards and each other.

(iii) Working standards: For day to day usage, people use standards that are easy to handle and moderately accurate. These are replicas that have been verified in standard laboratories or verified with other replicas certified by Standard laboratories. In India, the National Physical Laboratory at New Delhi maintains the reference standards and verifies the working standards.

Calibration: In any indirect measurement the measurand value has to be correlated with the value of the transducer output so that correct measurement values are inferred. This is done by help of some other instrument that is known to give accurate measurement. The process of comparison with a standardized instrument is called calibration and is a very important step in instrumentation. Calibration is also necessary from time to time to ascertain whether the instrument parameters has drifted or not. This is quite possible because of aging effect.

Instrument Performance characteristics

In order to ascertain whether a particular instrument is suitable for given application, a knowledge of its behavior is essential. The performance of the instrument is conveyed through its performance characteristics. These can be divided broadly into the following categories.

- **(i) Measurand characteristics:** This includes the range of values of the measurand over which the instrument operates.
- **(ii) Electrical design characteristics:** These characteristics usually include information such as output levels, input and output impedances, grounding and insulation, and other instrument characteristics
- **(iii) Static performance characteristics:** The static characteristics of a measuring instrument are its characteristic features as obtained under ideal condition when the instrument settles down. Some of the important static characteristics have been discussed earlier.
- **(iv) Dynamic performance characteristics:** The dynamic characteristics of a measuring instrument are its characteristic features when the measurand undergoes rapid variations and the instrument simultaneously tries to settle down. The dynamic characteristics have been discussed earlier.
- **(v) Environmental characteristics:** These refer to specifications related to external conditions such as temperature, humidity under which the instrument is to be run and external conditions such as shock, vibration, dust, heat, etc. To which the instrument might get exposed during transport andhandling.
- **(vi) Reliability characteristics:** This refers to the instrument behavior such as precision, accuracy, repeatability, reproducibility, life, and exposure to harsh operating conditions.