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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHATRONICS ENGINEERING

UNIT - I - Measurements of Systems - SMR1302

SMR1302 SENSORS AND INSTRUMENTATION

UNIT 1 MEASUREMENT SYSTEMS

TOPICS:

Generalized Measurement System – Performance Characteristics: Static and Dynamic Characteristics – Errors in Measurements – Calibration and Standards – Generalized Performance of Zero Order, First Order and Second Order Systems – Classifications of Transducers - General working principles of Resistive, capacitive and inductive type transducers with governing equations.

INTRODUCTION

Instrumentation is a collective term for measuring instruments that are used for indicating, measuring and recording physical quantities. The term has its origins in the art and science of scientific instrument-making.

- **Instrumentation is the branch of engineering that deals with measurement and control.**
- **According to ISA or known as Instrumentation and Systems Automation Society formerly known as Instrument Society of America, the official definition of Instrumentation –**

➢ **Instrumentation is a collection of Instruments and their application for the purpose of Observation, Measurement and Control.**

➢ **Reference: ISA std. S 51.1 – (Instrument Society of America)**

INSTRUMENT

Measuring Instrument:
It may be defined as a device for determining the value or magnitude of a quantity or variable.

➢ **An instrument is a device that measures/manipulates process physical variables such as flow, temperature, level, or pressure etc.**

➢ **Instruments include many varied contrivances which can be as simple as valves and transmitters, and as complex as analyzers.**

➢ **Instruments often comprise control systems of varied processes. The control of processes is one of the main branches of applied instrumentation.**

➢ **Control instrumentation includes devices such as solenoids, valves, circuit breakers, and relays. These devices are able to change a field parameter, and provide remote or automated control capabilities.**

➢ **Transmitters are devices which produce an analog signal, usually in the form of a 4–20 ma electrical current signal, although many other options using voltage, frequency, or pressure are possible.**

➢ This signal can be used to control other instruments directly, or it can be sent to a PLC, DCS, SCADA system, or other type of computerized controller, where it can be interpreted into readable values and used to control other devices and processes in the system.

➢ Instrumentation plays a significant role in both gathering information from the field and changing the field parameters, and as such are a key part of control loops.

Measurement

➢ Instrumentation can be used to measure certain field parameters (physical values):

➢ These measured values may include: pressure, either differential or static, flow, temperature, level, density, viscosity, radiation, process instrumentation etc

Control

➢ In addition to measuring field parameters, instrumentation is also responsible for providing the ability to modify some field parameters.

Instrumentation technologists and mechanics

- **Instrumentation technologists, technicians and mechanics specialize in troubleshooting and repairing and maintenance of instruments and instrumentation systems.**
- **This trade is so intertwined with electricians, pipe fitters, power engineers, and engineering companies, that one can find him/herself in extremely diverse working situations.**
- **An over-arching term, "Instrument Fitter" is often used to describe people in this field, regardless of any specialization.**

Modern Automation World :

- **In today's modern world, the top target of every plant management or plant ownership is to achieve the safest and maximum production out of their equipment, machinery and devices.**
- **In order to reach that target, one of the major steps it follows is to install good instrumentation in the plant.**
- **When we walk through a modern day plant, we find many transmitters, gauges, trolls, control valves, motors, solenoid valves etc. This is all nothing but Instrumentation.**
- **But the fact is, that instrumentation can't do anything alone. It needs some brain that can constantly monitor the readings provided by it and takes actions accordingly to operate the final control elements like valves, motors etc.**
- **At the same time, these actions must ensure to operate these devices at optimal parameters as to ensure their health and long-life. This is where the world of control comes in.**
- **Control System enables the instrumentation to operate in a way to give you the safest and optimum production. Nowadays, it is fully automatic. Once configured, it brings your whole plant over the screens of control room.**

Introduction to Metrology

Metrology is the science of measurement of lengths and angles and all related quantities like width, depth, diameter and straightness with high accuracy. Metrology demands pure knowledge of certain basic mathematical and physical principles. The development of the industry largely depends on the engineering metrology. Metrology is concerned with the establishment, reproduction and conservation and transfer of units of measurements and their standards. Irrespective of the branch of engineering, all engineers should know about various instruments and techniques.

TYPES OF METROLOGY:

1.Legal Metrology

'Legal metrology' is that part of metrology which treats units of measurements, methods of measurements and the measuring instruments, in relation to the technical and legal requirements.
The activities of the service of 'Legal Metrology' are:
(i) Control of measuring instruments;
(ii) Testing of prototypes/models of measuring instruments;
(iii) Examination of a measuring instrument to verify its conformity to the statutory requirements etc.

2. Dynamic Metrology

'Dynamic metrology' is the technique of measuring small variations of a continuous nature.
The technique has proved very valuable, and a record of continuous measurement, over a surface, for instance, has obvious advantages over individual measurements of an isolated character.

3. Deterministic metrology

Deterministic metrology is a new philosophy in which part measurement is replaced by process measurement. The new techniques such as 3D error compensation by CNC (Computer Numerical Control) systems and expert systems are applied, leading to fully adaptive control. This technology is used for very high precision manufacturing machinery and control systems to achieve micro technology and nanotechnology accuracies.

MEASUREMENTS:

The measurement of a given quantity is essentially an act or the result of comparison between the quantity (whose magnitude is unknown) & a predefined Standard. Since two quantities are compared, the result is expressed in numerical values.
Measurement is defined as the process of numerical evaluation of a dimension or the process of comparison with standard measuring instruments. The elements of measuring system include the instrumentation, calibration standards, environmental influence, human operator limitations and features of the work-piece. The basic aim of measurement in industries is to check whether a component has been manufactured to the requirement of a specification or not.

Practical terms related with measurement:

- Errors in measurements
- Methods of measurements
- Measuring Instruments
- Units of measurement and their standards
- Industrial inspection and its different techniques
- Measuring instruments and accuracy

Basic Requirements of Measurement:

i) The standard used for comparison purposes must be accurately defined & should be commonly accepted

ii) The apparatus used & the method adopted must be provable.

Needs

To ensure standards
Meet the interchangeability
To provide Customer satisfaction
No faults in the product
Coordination
Repair of minor defects

Objectives

Accuracy at Minimum cost
Minimize the cost of maintenance and rejection & rework
Process capability
Evaluation of new products

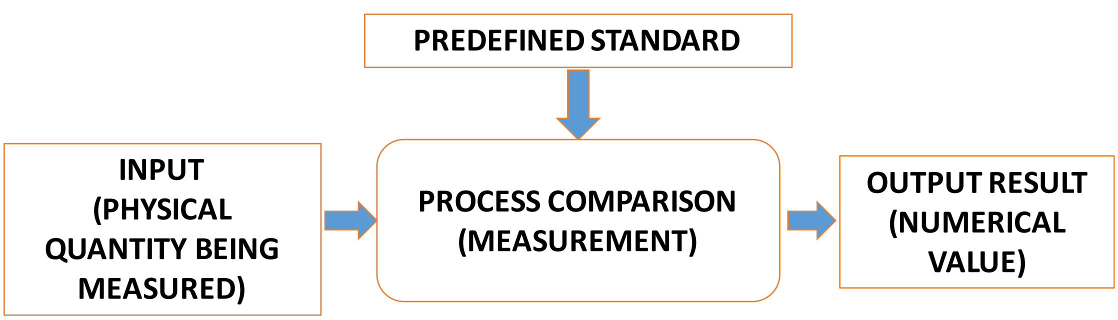


Figure : Basic Process of Measurement

Methods of measurements are broadly classified into two basic categories.

***1)* Direct method of measurement.**

Direct methods are common for the measurement of physical quantities like length, mass and time. For Example, to measure the length of an iron bar, we compare the length of an iron bar with a standard ruler. The unit length is metre. An iron bar is so many times long because that many units on our standard having the same length as the bar. Here we have determined the length of paper by direct comparison with standard ruler.

- Direct methods are also less sensitive.
- Indirect methods are used in industries for accurate measurements.

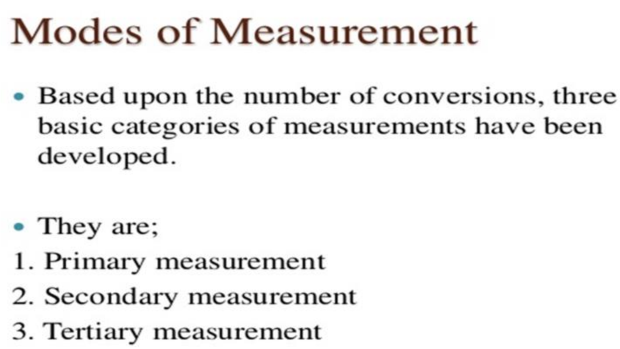
Example, Temperature measurement using thermocouple in industries.

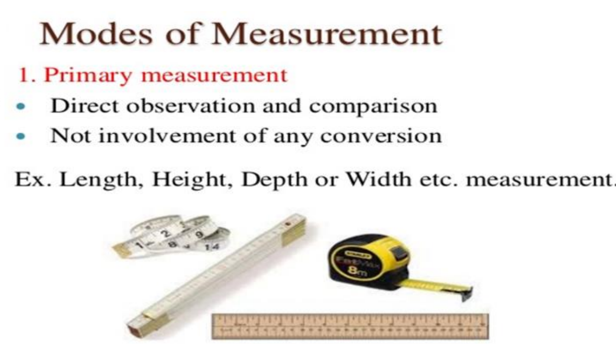
Direct methods are not always possible, feasible and practicable. Most of the cases inaccurate because they involve human factors. Hence direct methods are not preferred for accurate measurements and are rarely used.

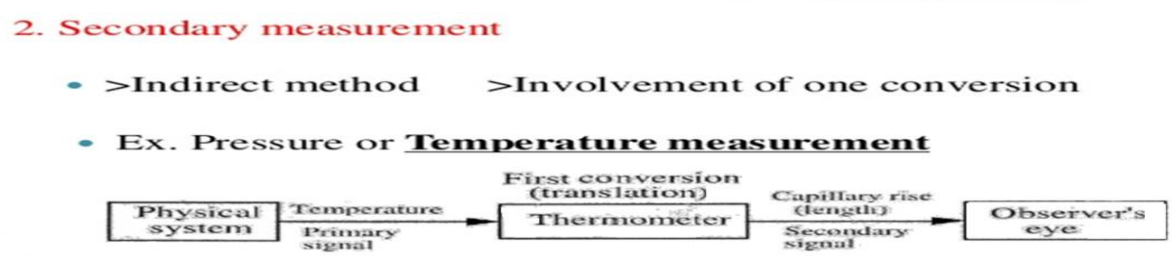
2) **Indirect method of measurement.**

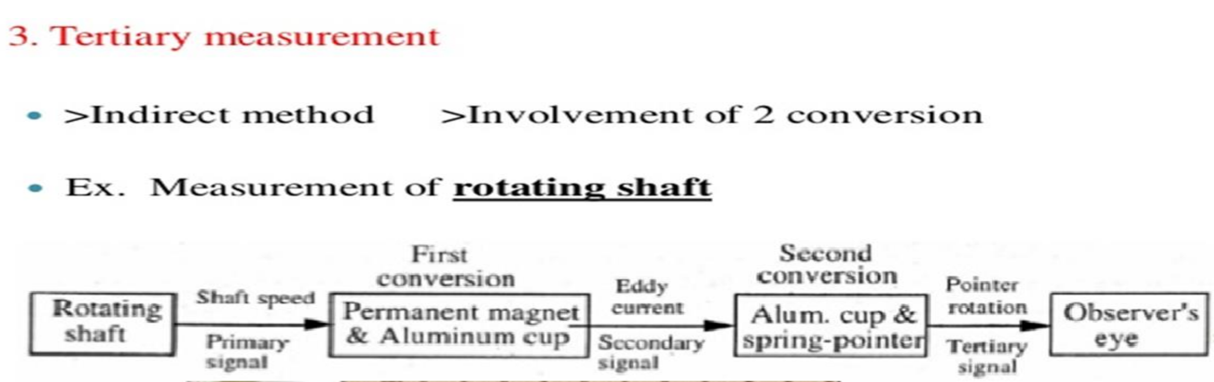
In Direct method of measurement, Unknown Quantity (measurand) is directly compared with predefined standard. The result is expressed as a numerical value and a unit. In indirect method, the physical parameters to be measured is compared with the predefined standard through the use of a calibrated system. (Calibration is the process of checking the accuracy of instrument by comparing the instrument reading with a standard or against a similar meter of known accuracy)

- ✓ Indirect methods are used is industries for accurate measurements.
- ✓ Example, Temperature measurement using thermocouple in industries.







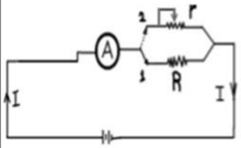
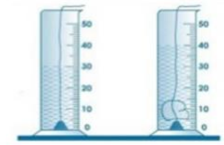


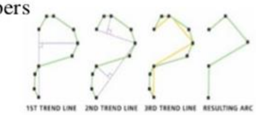
Methods of Measurement

DIRECT	INDIRECT
1)Unknown quantity is measured comparing directly with primary or secondary standards	1)unknown magnitude is measured by comparing with a standard indirectly through the use of a calibrated system
2)human senses are very much necessary for measurement	2)Consists of a chain of devices which form a measuring system
3)Results obtained from direct comparison are not that dependable	3)this consists of a detector element to detect ,a transducer to transducer and a unit to indicate or record the processed signal
4)Not always accurate	4)Fairly accurate .

Methods of Measurement

Type of Method	Technique to measure
With contact	Instrument is placed in contact with the object. For ex. vernier calliper
Without contact	Instrument not placed in contact with the object. (use of sensor)
Absolute or Fundamental	Based on the measurements of base quantities entering into the definition of the quantity.
Comparative	Based on the comparison of the value of a quantity to be measured with a known value of the same quantity.
Null measurement	Here, difference between measurand value and known value of same quantity with which it is compared is brought to zero.

Type of Method	Technique to measure
Substitutional Method 	Quantity to be measured is replaced by a known value of the same quantity, so selected that the effects produced in the indicating device by these two values are the same (a type of direct comparison).
Complementary Method 	The value of quantity to be measured is combined with known value of the same quantity. Ex: Volume determination by liquid displacement.
Transposition Quantity to be measured is first balanced by a known value and then balanced by an other new known value. 	Value of quantity measured is first balanced by an initial known value A of same quantity, then measured by quantity is put in place of this known value. Then, it is balanced again by another value B. If the position of element in equilibrium.

Coincidence	Measurements coincide with certain lines and signals. Ex. Callipers 
Deflection 	The value of the quantity to be measured is directly indicated by the deflection of a pointer on a calibrated scale

Measurement systems

A measurement system is defined as the system (Group of physical components) which is used for making measurements. It has as its input the quantity being measured and its output the value of that quantity. Generally, a measurement system is used to know the unknown value of a quantity or a variable.

- Measurement involves the use of instruments as a physical means of determining quantities or variable.
- In simple measurement, a measuring instrument consists of a single unit which gives an output reading according to the unknown input quantity applied to it.
- In complex measurement, a measuring instrument may be consisting of several separate elements like sensor/ transducer, signal conditioner and display. Because of this modular nature of the elements within it, it is common to refer the measuring instrument as a Measurement system.

FUNCTIONS OF MEASUREMENT SYSTEMS:

Functional Elements of an Instrument - Operation and the performance of measuring instruments

- **Operation : The operation can be described in terms of the functional elements of instrument systems**
- **Performance: The performance is defined in terms of the static and dynamic performance characteristics**

***i)* Indicating Function (Indicating measurement system)**

Instruments and systems use different kind of methods for obtaining information concerning the input unknown quantity under measurement. Mostly this information is obtained as a deflection of pointer of a measuring instrument. In this way the instruments perform a function which known as indicating function. Example, the speed of automobile is indicated by deflection of pointer of a speedometer, Ammeter, Voltmeter and Wattmeter.

***ii)* Recording Function (Recording measurement system)**

In many cases the system makes a written record on the paper according to given input unknown quantity under measurement against time or against some other variable. Thus, system or instrument performs a recording function**.**

Example, Monitoring of instantaneous values of temperature records using potentiometric strip chart recorder with respect to time, monitoring of pressure and temperature relationship record for boiler and compressor using X-Y recorder**.**

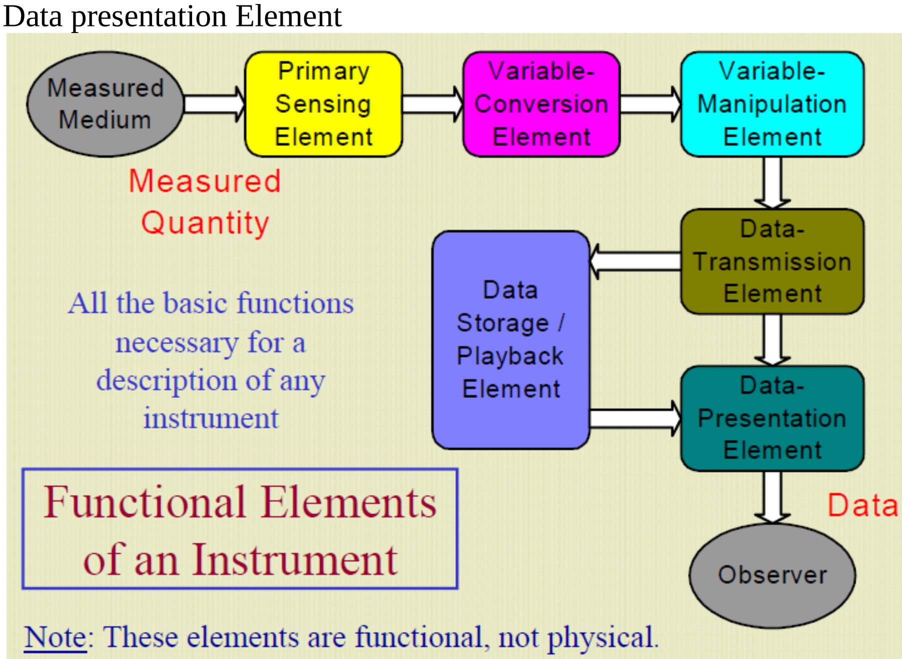
***iii)* Controlling Function (Controlling measurement system)**

In this case, the information is used by the instrument or the system to control the original measured input unknown quantity. This controlling function is one of the most important functions used in the field of industrial control processes.

ELEMENTS OF A GENERALIZED MEASUREMENT SYSTEM:

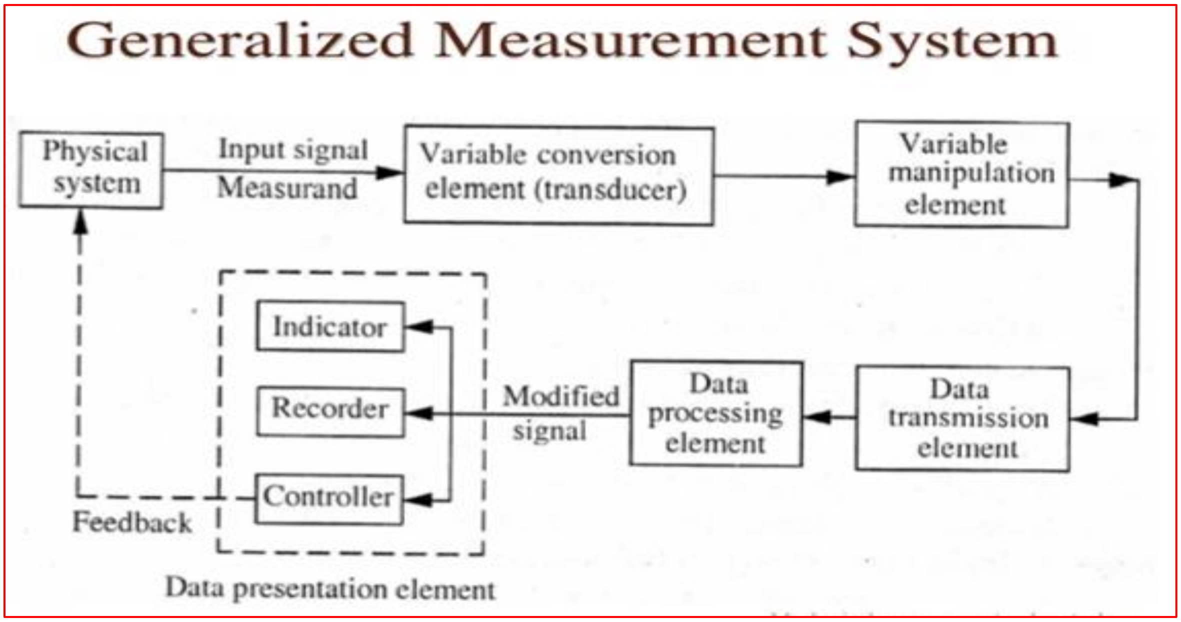
Most of the measurement systems contain three main functional elements are

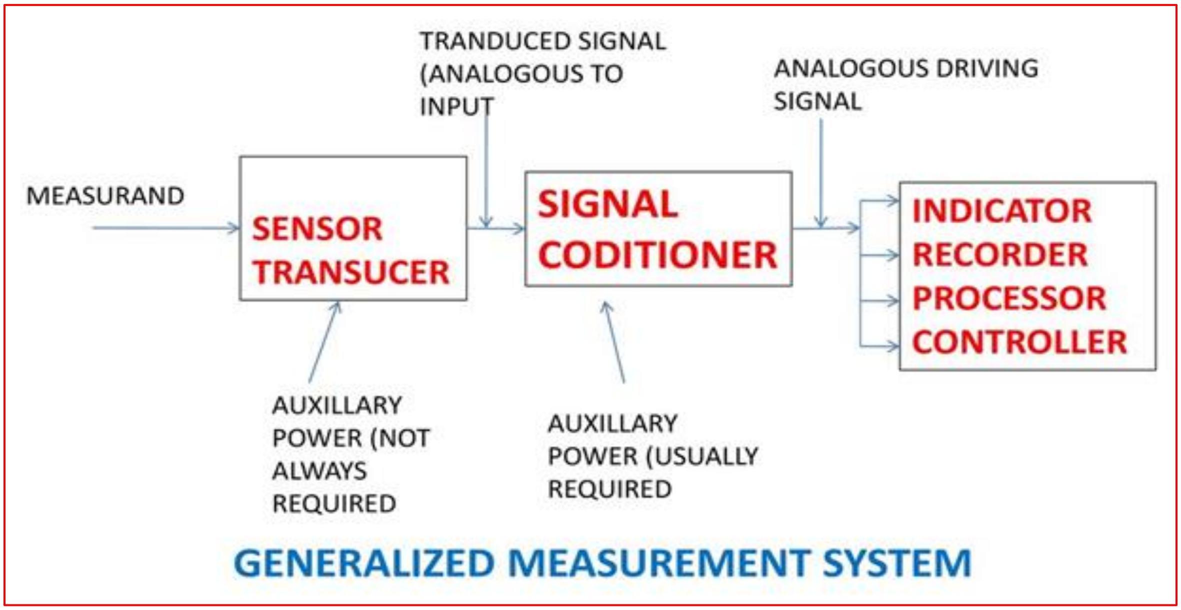
i) Primary sensing element
ii) Variable conversion element
iii) Data manipulation element.
iv) Data Transmission Element
v) Data storage and playback element
vi) Data presentation Element



A possible arrangement that includes all the *basic functions,*

▫ **It is a vehicle for presenting the concept of functional elements, and not as a physical schematic of a generalized instrument.**





1.Primary sensing element:

The quantity or the variable which is being measured makes its first contact with the primary sensing element of a measurement system i.e., the measurand- (the unknown quantity which is to be measured). The measurement is thus first detected by primary sensor or detector. The measurement is then immediately converted into an analogous electrical signal. This is done by a transducer. Though a transducer in general, is defined as a device which converts energy from one form to another. But in measurement systems, this definition is limited in scope. A transducer is defined as a device which converts a physical quantity into an electrical quantity. The output of the sensor and detector element employed for measuring a quantity could be in different analogous form. This output is then converted into an electrical signal by a transducer. This is true of most of the cases but is not true for all. In many cases, the physical quantity is directly converted into an electrical quantity by a detector transducer. The first stage of a measurement system is known as a detector transducer stage.

2.Transducer stage Variable conversion element:

The output of the primary sensing element may be electrical signal of any form; it may be voltage, a frequency or some other electrical Parameter. For the instrument to perform the desired function, it may be necessary to convert this output to some other suitable form.

3.Variable manipulation element:

The function of this element is to manipulate the signal presented to it preserving the original nature of the signal. It is not necessary that a variable manipulation element should follow the variable conversion element.

Examples,

1. Voltage amplifier acts as variable manipulation element. Voltage amplifier accepts a small voltage signal as input and produces the voltage with greater magnitude. Here numerical value of voltage magnitude is increased.

2. Attenuator acts as variable manipulation element. It accepts a high voltage signal and produces the voltage or power with lower magnitude. Here numerical value of voltage magnitude is decreased.

Linear process manipulation elements: Amplification, attenuation, integration, differentiation, addition and subtraction etc.,

Nonlinear process manipulation elements: Modulation, detection, sampling, filtering, chopping and clipping etc.

These are performed on the signal to bring it to desired level to be accepted by the next stage of measurement system. This process of conversion is called signal conditioning. The combination of variable conversion and variable manipulation elements are called as Signal Conditioning Element

4. Data Transmission Element

The elements of measurement system are actually physically separated; it becomes necessary to transmit the data from one to another. The element which is performs this function is called as data transmission element.

Example, Control signals are transmitted from earth station to Space-crafts by a telemetry system using radio signals. The combination of Signal conditioning and transmission element is known as Intermediate Stage of measurement system.

5. Data storage and playback element

Some applications require a separate data storage and playback function for easily to rebuild the stored data based on the command. The data storage is made in the form of pen/ink and digital recording. Examples, magnetic tape recorder/ reproducer, X-Y recorder, X-t recorder, Optical Disc recording etc.

6. Data presentation Element

The information about the measured physical quantity is to be presented to a person handling the instrument in the proper form for monitoring, control and analysis purposes. This function is done by data presentation element. If the data is to be monitored then visual display devices are used as data presentation element.

These devices may be analog or digital instruments like ammeter, voltmeter, camera, CRT, printers, analog and digital computers. Computers are used for control and analysis of measured data of measurement system. This Final stage of measurement system is known as Terminating stage.

Signal conditioning: Some non-linear processes like modulation, detection, sampling, filtering, chopping etc., are performed on the signal to bring it to the desired form to be accepted by the next stage of measurement system. This process of conversion is called '**signal conditioning**.' The term signal conditioning includes many other functions in addition to Variable conversion & Variable manipulation. In fact, the element that follows the primary sensing element in any instrument or measurement system is called signal conditioning element'. When the elements of an instrument are actually physically separated, it becomes necessary to transmit data from one to another. The element that performs this function is called a '**data transmission element'**. The information about the quantity under measurement has to be conveyed to the personnel handling the instrument or the system for monitoring, control, or analysis purposes. This function is done by **data presentation element**. In case data is to be monitored, visual display devices are needed. These devices may be analog or digital indicating instruments like ammeters, voltmeters etc. In case data is to be recorded, recorders like magnetic tapes, high speed camera & TV equipment, CRT, printers may be used. For control & analysis purpose microprocessor or computers may be used. The final stage in a measurement system is known as '**terminating stage'.**

EXAMPLE OF GENERALIZED MEASUREMENT SYSTEM

Example 1. Bourdon Tube Pressure Gauge:

The simple pressure measurement system using bourdon tube pressure gauge is shown in figure. The detail functional elements of this pressure measurement system is given below. In this measurement system, bourdon tube acts as primary sensing and variable conversion element. Bourdon tube senses the input pressure and on account of input pressure the closed end of the tube is displaced. Pressure in converted into small displacement. The closed end of bourdon tube is connected through mechanical linkage to a gearing arrangement. The gearing arrangement amplifies the small displacement and makes the pointer to rotate through large angle. The mechanical linkage acts as a data transmission element while the gearing arrangement acts as a data manipulation element. The final data presentation stage consists of pointer & dial arrangement which gives an indication of the pressure signal applied to the bourdon tube. The schematic diagram of this measurement system is given in Fig.

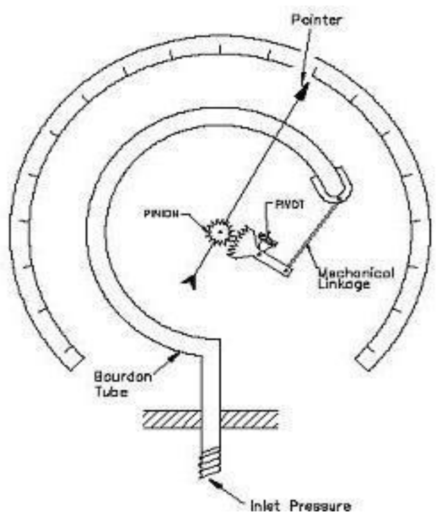


Figure: Bourdon tube pressure gauge

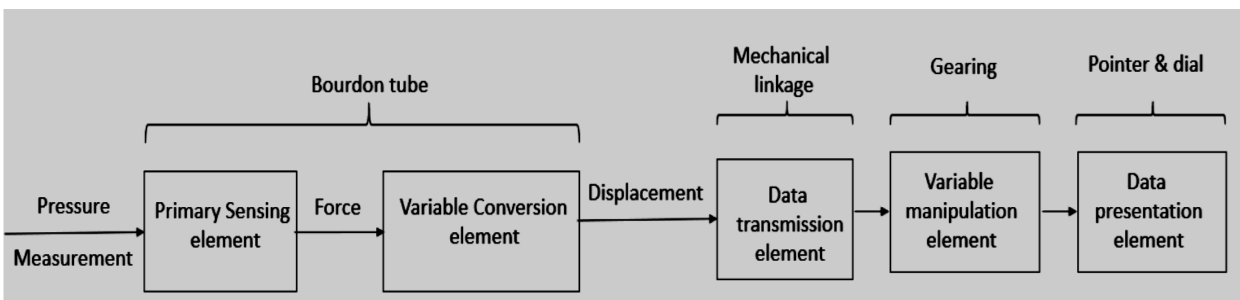
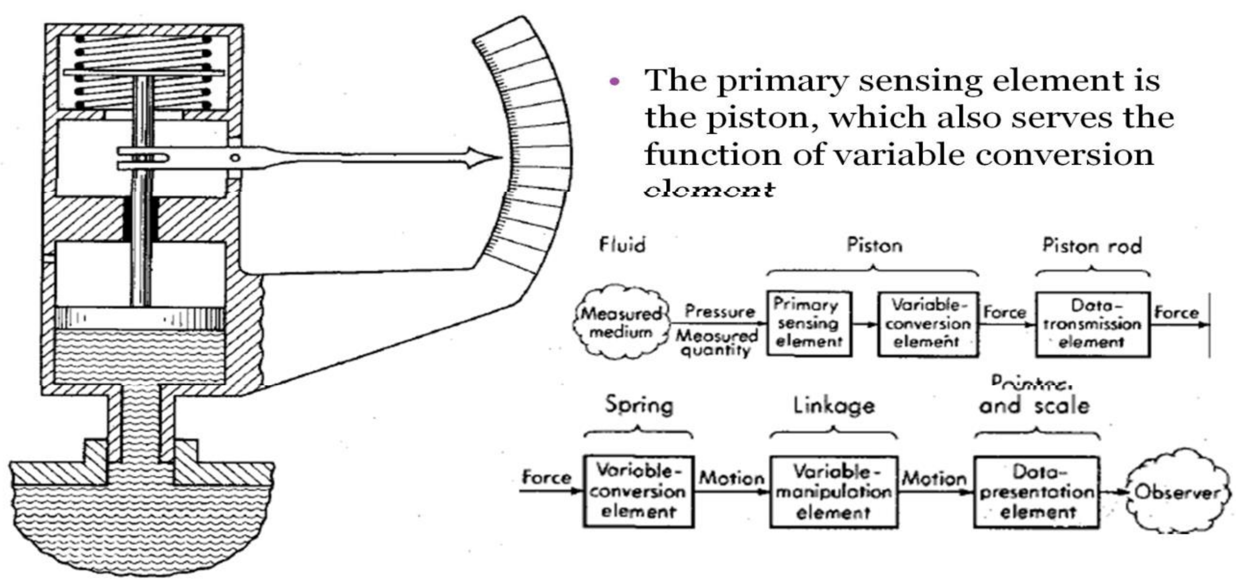


Figure: Schematic diagram of a Bourdon tube pressure gauge



Pressure gage

Performance Characteristics of Measuring Instruments

The response of an instrument to a particular input is the guiding factor to decide its choice out of the available options. The input to the instrument can be constant or varying with time. These performance characteristics of an instrument are very important in their selection. Therefore, performance characteristics can be headed into two types as:

1. **Static Characteristics:** Static characteristics of an instrument are considered for instruments which are used to measure an unvarying process condition. Performance criteria based upon static relations represent the static Characteristics. (The static characteristics are the value or performance given after the steady state condition has reached).

2. **Dynamic Characteristics:** Dynamic characteristics of an instrument are considered for instruments which are used to measure a varying process condition. Performance criteria based upon dynamic relations represent the dynamic Characteristics.

1. STATIC CHARACTERISTICS:

Static Performance of Instrument:

The static characteristics of instruments are related with steady state response. The relationship between the output and the input when the input does not change, or the input is changing at a slow rate.

The quantity to be measured by an instrument could be either constant or rapidly varying with time. The quantities to be measured by an instrument which are either constant or vary very slowly with time, the quantities are termed as static could be either constant or rapidly varying with time.

(i) Range and Span

Range : The region between which the instrument operate is called range.

Example: An ammeter whose scale reads from 0 to 1 mA is said to have a range from 0 to 1m A.

Span is the algebraic difference between the upper and lower limits of the instrument range.

Example: span :1mA

For a thermometer calibrated between 200degree centigrade to 500 degree centigrade, the span is 300 degree centigrade.

(ii) Accuracy

It is the degree of closeness with which the reading approaches the true value of the quantity to be measured. It determines the closeness to true value of instrument reading. The accuracy can be expressed in following ways:

a) Point accuracy: This is the accuracy of the instrument only at one point on its scale.

b) Accuracy as percentage of scale range: When an instrument as uniform scale, its accuracy may be expressed in terms of scale range.

Eg: Accuracy of an instrument is specified by ±5% for the range of 0 to 200ºC in the temperature scale means the reading might be within + or -10ºC of the true reading.

c) Accuracy as percentage of true value: The best way to conceive the idea of accuracy is to specify it in terms of the true value of the quantity being measured. Eg 5% of true value

(iii) Precision

Precision is the degree of repeatability of a series of the measurement. Precision is measures of the degree of closeness of agreement within a group of measurements are repeatedly made under the prescribed condition.

Precision is used in measurements to describe the stability or reliability or the reproducibility of results.

The precision is composed of two characteristics:

a) Conformity: Consider a resistor having true value as 2385692ohm, which is being measured by an ohmmeter. But the reader can read consistently, a value as 2.4 M ohm due to the nonavailability of proper scale.

b) Number of significant figures: The precision of the measurement is obtained from the number of significant figures, in which the reading is expressed. The significant figures convey the actual information about the magnitude & the measurement precision of the quantity. More significant figures greater is the precision of an instrument. Eg: 210 V, 210.1V,210.04V.

Comparison between accuracy and precision.

S.No	Accuracy	Precision
1.	It refers to degree of closeness of the measured value to the true value.	It refers to the degree of agreement among group of readings
2.	Accuracy gives the maximum error that is maximum departure of the final result from its true value.	Precision of a measuring system gives its capability to reproduce a certain reading with a given accuracy

***iv)* Static Error**

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

True value:It is the error free value of the measured variable.

True value= Measured value – Static error

***v)* Sensitivity:**

Sensitivity is defined as the ratio of change in output signal (response) to the change in input signal (measurand). It is the relationship indicating how much output changes when input changes.

Sensitivity = change in output /change in input

Sensitivity = $\Delta qo / \Delta qi$

If the sensitivity is constant then the system is said to be linear system. If the sensitivity is variable then the system is said to be non linear system.

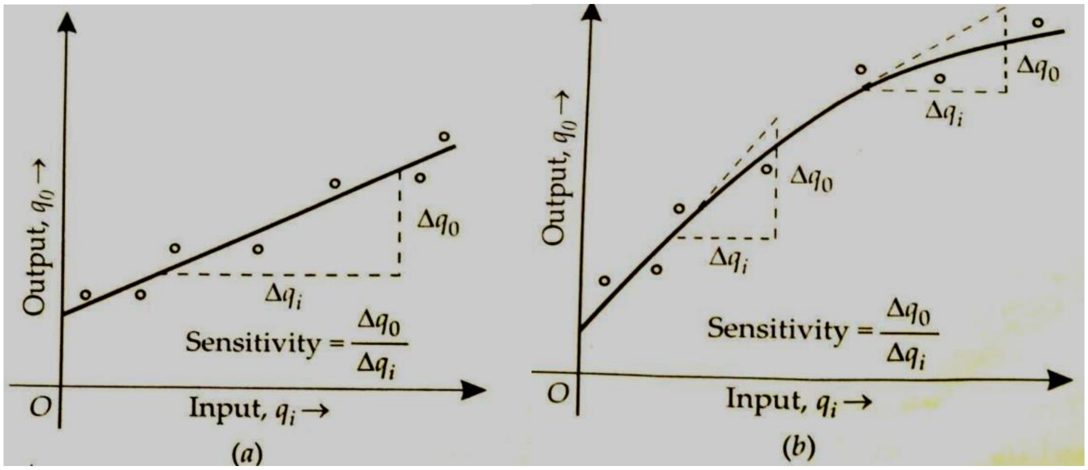
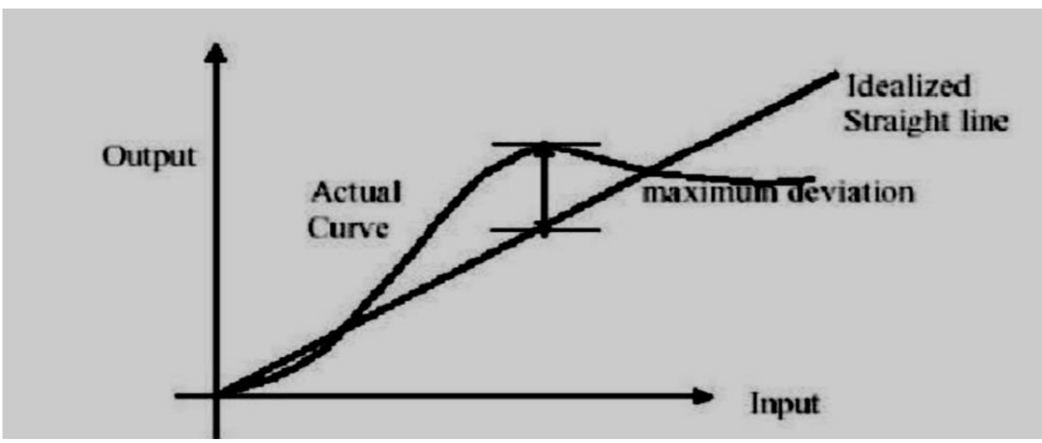


Figure: Definition of sensitivity for (a) Linear and (b) Non- linear instrument

When the calibration curve is linear as in figure 1.5a the sensitivity of the instrument can be defined as in slope of the calibration curve. In this case sensitivity is constant over the entire range of instrument. If the curve is not normally straight line or nonlinear instrument sensitivity varies with the input or varies from on range to another as in figure.

(vi) **Linearity**

- Linearity is the best characteristics of an instrument or measurement system.
- Linearity of the instrument refers to the output is linearly or directly proportional to input over the entire range of instrument.
- So the degree of linear (straight line) relationship between the output to input is called as linearity of an instrument.



Nonlinearity: The maximum difference or deviation of output curve from the Specified idealized straight line.

$$\text{Non linearity} = \frac{\text{Maximum deviation of output from the idealized straight line}}{\text{Actual reading or response}} \text{ X } 100$$

(vi) Repeatability

- Repeatability is defined as the ability of an instrument to give the same output for repeated applications of same input value under same environmental condition.

- It is the closeness between successive measurements of the output quantity for the same value of input under the same operating conditions.

(vii) Reproducibility

- Reproducibility is defined as the ability of an instrument to reproduce the same output for repeated applications of same input value under different environment condition.

- In case of perfect reproducibility, the instrument satisfies no drift condition

(viii) Drift

- Drift is an undesirable change in output over a period of time that is unrelated to change in input, operating conditions. (value of input variable, operating conditions does not change)

- Drift is occurred in instruments due to internal temperature variations, ageing effects and high stress etc.

Drift may be classified into three categories:

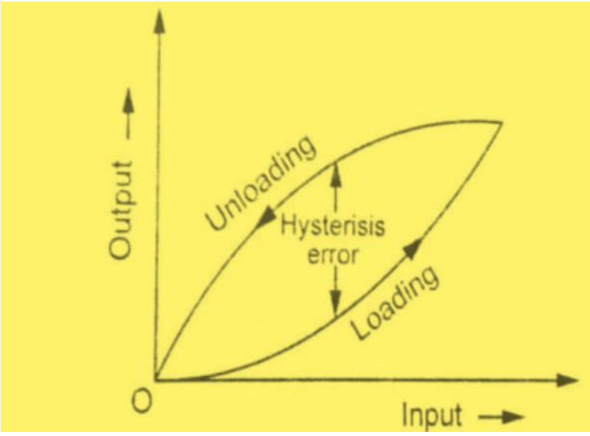
1. **Zero drift:** If the whole calibration gradually shifts due to slippage, permanent set, or due to undue warming up of electronic tube circuits, zero drift sets in.

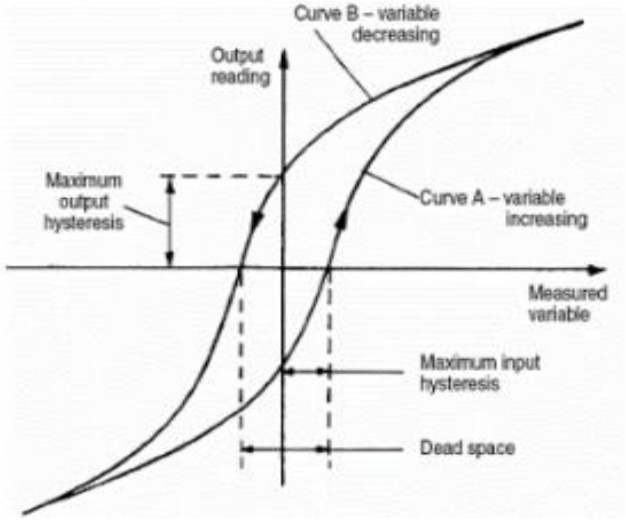
2. **Span drift:** If there is proportional change in the indication all along the upward scale, the drifts is called span drift or sensitivity drift.

3. **Zonal drift:** In case the drift occurs only a portion of span of an instrument, it is called zonal drift.

(ix) Hysteresis

Hysteresis is Non-coincidence of loading and unloading curves on output. When input of an instrument is slowly varied from zero to full scale and then back to zero, its output varies as shown in fig. If input is decreases from maximum value and output also decreases but does not follow the same curve, then there is a residual output when input is zero. This phenomenon is called Hysteresis. The difference between increasing change and decreasing change of output values is known as hysteresis error.





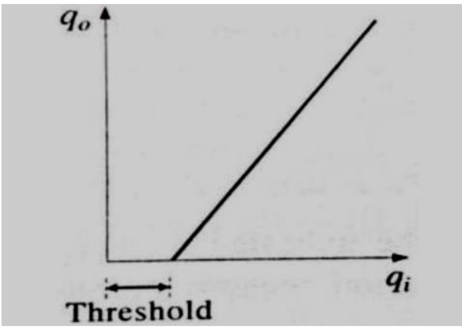
(x) Threshold

• The minimum value of input which is necessary to activate an instrument to produce an output is termed its threshold

• Threshold is the minimum value of the input required to cause the pointer to move from zero position

• If the input is increased very gradually from zero, there will be some minimum value below which no output change can be detected.

• This minimum value defines the threshold of an instrument.



(xi) Dead time: It is the time required by a measurement system to begin to respond to a change in the measurand.

(xii) Dead zone

• Dead zone or dead band is defined as the largest change of input quantity for which there is no output the instrument.

• The region upto which the instrument does not respond for an input change is called dead zone.

(xiii) Resolution

Resolution or Discrimination is the smallest change in the input value that is required to cause an appreciable change in the output. (The smallest increment in input or input change which can be detected by an instrument is called as resolution or discrimination). So, if a non-zero quantity is slowly increased, output reading will not increase until some minimum change in the input takes place. The minimum change which causes the change in the output is called discrimination.

(xiii) Loading Effect

• Loading effect is the incapability of the system to faith fully measure, record or control the input signal in accurate form

2. **DYNAMIC CHARACTERISTICS**

Dynamic characteristics of an instrument are considered for instruments which are used to measure a varying process condition. The set of criteria defined for the instruments, which are changes rapidly with time, is called ‘dynamic characteristics. As the input varies from instant to instant, output also varies from instant to instant. The dynamic behaviour of an instrument is determined by applying some standard form of known and predetermined input to its primary element (sensing element) and then studies the output.

Generally dynamic behaviour is determined by applying following three types of inputs.

1. Step Input.

- Step change in which the primary element is subjected to an instantaneous and finite change in measured variable and then remains constant

3. Linear Input

- Linear change, in which the primary element is, follows a measured variable, changing linearly with time.

3.Sinusoidal input

- Sinusoidal input: Sinusoidal change, in which the primary element follows a measured variable, the magnitude of which changes in accordance with a sinusoidal function of constant amplitude

The dynamic characteristics of an instrument are

(i) Speed of response (ii) Lag (iii) Fidelity (iv) Dynamic error

(i) **Speed of response**

• It is the rapidity with which an instrument responds to changes in the measured quantity.

• It gives information about how fast the system reacts to the changes in the input.

(ii) **Lag**

• It is the retardation or delay in the response of an instrument to changes in the measured variable. The measuring lags are two types:

Retardation type: In this case the response of an instrument begins immediately after a change in measured variable has occurred.

Time delay type: In this case the response of an instrument begins after a dead time after the application of the input quantity.

(iii) **Fidelity**

• It is the degree to which an instrument indicates the changes in the measured variable without dynamic error.

• faithful reproduction or fidelity of an instrument is the ability of reproducing an input signal faithfully (truly).

(iv) **Dynamic error**

• It is the difference between the true values of a quantity changing with time and the value indicated by the instrument, if no static error is assumed. It is also called as *Measurement Error*.

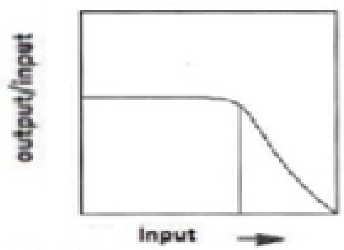
Aspect of dynamic response are :

(i) Fidelity/Faithfulness (ii) Speed of response and delay caused

Fidelity : It is system's ability to present faithfully the information in the measurand

Fidelity is defined in terms of :

1. Amplitude response
2. Frequency response
3. Phase response



1. Amplitude response

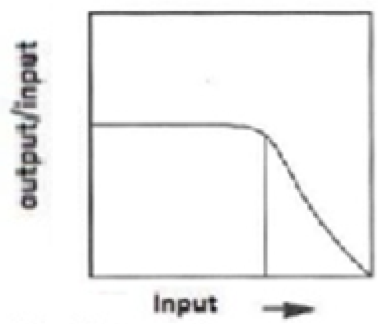
➢ It is the ability of the system to treat all input amplitudes equally and uniformly . Practically, it may not be possible. So, it is desired that for over a specified range of input amplitudes the ratio of output amplitude to input amplitude should remain constant.

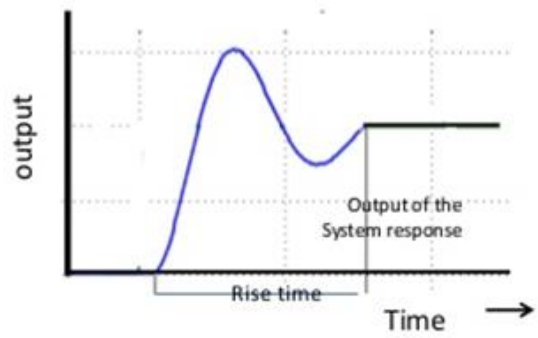
2. Frequency response

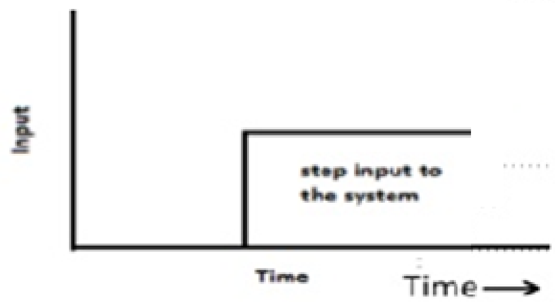
➢ It is the ability of the system to treat inputs of all frequencies equally and uniformly . Again, Practically it is desired that the ratio of output to input amplitudes should remain constant over some desired frequency range.

3. Phase response

➢ It is the ability of the system to treat inputs of all frequencies uniformly in terms of causing time delay or causing a shift timewise.







ERRORS IN MEASUREMENTS AND THEIR STATISTICAL ANALYSIS

Errors:

The difference between the measured value of quantity and true value (Reference Value) of quantity is called as Error.

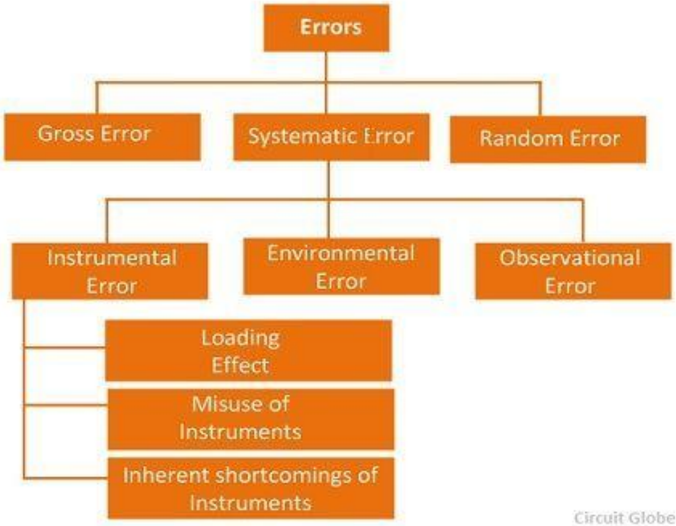
Error = Measured value - True Value

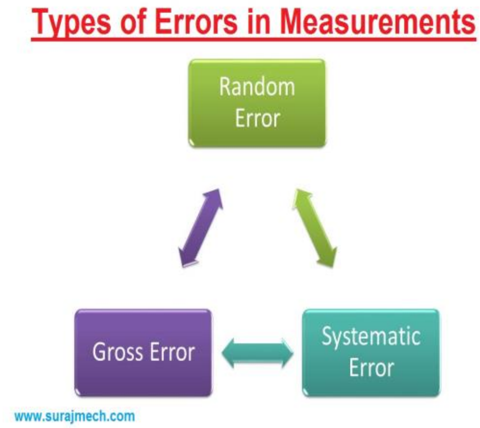
$\delta A = Am - At$

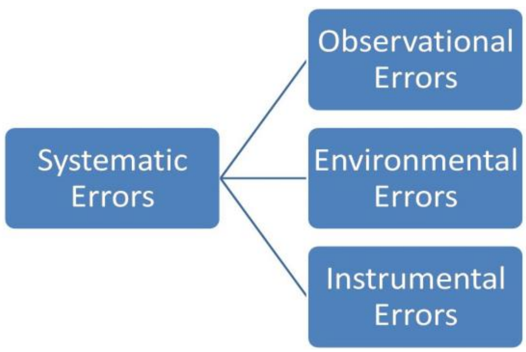
Classification of Errors:

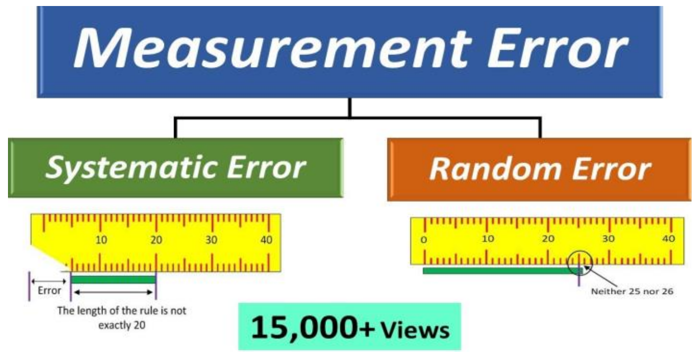
All measurement can be made without perfect accuracy (degree of error must always be assumed). In reality, no measurement can ever made with 100% accuracy. It is important to find that actual accuracy and different types of errors can be occurred in measuring instruments. Errors may arise from different sources and usually classified as follows, Classification of Error

1. **Gross Errors**
2. **Systematic Errors**
   a. Instrumental errors
      i. Inherent shortcomings of instruments
      ii. Misuse of instruments
      iii. Loading effects
   b. Environmental errors
   c. Observational errors
3. **Random Errors**









1.Gross Errors

• These gross errors mainly occur due to carelessness or lack of experience of a human being.

• The main source of Gross errors is human mistakes in reading or using instruments and in recording and calculating measured quantity.

• As long as human beings are involved and they may grossly misread the scale reading, then definitely some gross errors will be occurred in measured value.

Example,

(i)Due to an oversight, Experimenter read the voltage as 31.5 V, While the actual reading is 21.5 V

(ii) The reading may be transposed while recording. For example, 25.8 V actual reading may be recorded as 28.5 V.

• The complete elimination of gross errors is maybe impossible, one should try to predict and correct them.

• Some gross errors are easily identified while others may be very difficult to detect.

• The complete elimination of gross errors is not possible but one can minimize by the following ways.

• Great care should be taken in reading and recording the data.

• Two, three or even more readings should be taken for the quantity being measured by using different experimenters

• So, it is suitable to take a large number of readings as a close agreement between readings assures that no gross error has been occurred in measured values.

2.Systematic Errors

Systematic errors are divided into following three categories.

1. **Instrumental Errors :** a) Due to inherent shortcoming of instrument b) Due to misuse of the instruments, and c) Due to loading effects of instruments
2. **Environmental Errors**
3. **Observational Errors**

1. **Instrumental Errors**

These errors are arises due to following three reasons (sources of error).

(a) Inherent Shortcomings of instruments

These errors are inherent in instruments because of their mechanical structure due to construction, calibration or operation of the instruments or measuring devices.

These errors may cause the instrument to read too low or too high.

Example, if the spring (used for producing controlling torque) of a permanent magnet instrument has become weak, so the instrument will always read high. Errors may be caused because of friction, hysteresis .

Elimination or reduction methods of these errors,

- The instrument may be re-calibrated carefully.
- The procedure of measurement must be carefully planned. Substitution methods or calibration against standards may be used for the purpose.
- Correction factors should be applied after determining the instrumental errors.

(b) Misuse of the Instruments

- In some cases the errors are occurred in measurement due to the fault of the operator than that of the instrument.
- A good instrument used in an unintelligent way may give wrong results.
- Examples, Misuse of instruments may be failure to do zero adjustment of instrument, poor initial adjustments, using leads of high resistance and ill practices of instrument beyond the manufacturer’s instruction and specifications etc.
- Such things do not cause the permanent damage to the instruments but definitely cause errors.

(C) **Loading effects of Instruments**

• The errors committed by loading effects due to improper use of an instrument for measurement work.

• In measurement system, loading effects are identified and corrections should be made or more suitable instruments can be used.

• Example, a well calibrated voltmeter may give a misleading (may be false) voltage reading when connected across a high resistance circuit.

The same voltmeter, when connected across a low resistance circuit may give a more reliable reading (dependable or steady or true value).

In this example, voltmeter has a loading effect on the circuit, altering the actual circuit conditions by measurement process.

• So errors caused by loading effect of the meters can be avoided by using them intelligently.

(ii) Environmental Errors

Environmental error occurs due to external environmental conditions of the instrument, such as effects of temperature, pressure, humidity, dust, vibration or external magnetic or electrostatic fields.

Elimination or reduction methods of these undesirable errors are

- Arrangements should be made to keep the conditions as nearly as constant as possible. Example, temperature can be kept constant by keeping the instrument in the temperature-controlled region.
- The device which is used against these environmental effects.

Example, variations in resistance with temperature can be minimized by using very low resistance temperature co-efficient of resistive material.

- Employing techniques which eliminate the effects of these disturbances. For example, the effect of humidity dust etc., can be entirely eliminated by tightly sealing the equipment.
- The external or electrostatic effects can be eliminated by using magnetic or electrostatic shield on the instrument.
- Applying computed corrections: Efforts are normally made to avoid the use of application of computed corrections, but where these corrections are needed and are necessary, they are incorporated for the computations of the results.

(iii) Observational Errors

There are many sources of observational errors. As an example, the pointer of a voltmeter rests slightly above the surface of the scale. Thus an error on account of PARALLAX will be acquired unless the line of vision of the observer is exactly above the pointer. To minimize parallax errors, highly accurate meters are provided with mirrored scales as shown in figure 1.6.

Correct reading 250V

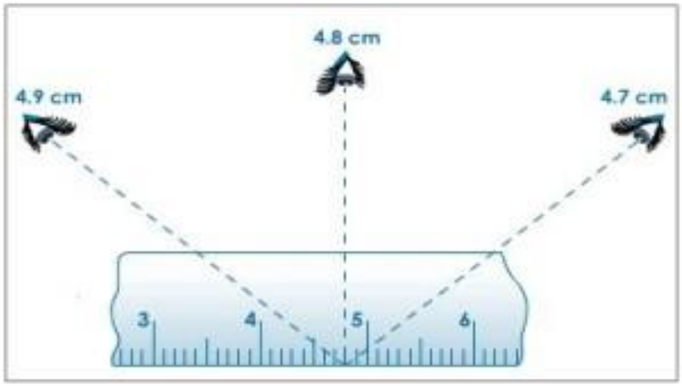


Figure 1.6: Errors due to parallax

When the pointer's image appears hidden by the pointer, observer's eye is directly in line with the pointer. Although a mirrored scale minimizes parallax error, an error is necessarily presented through it may be very small. So we can eliminate this parallax error by having the pointer and scale in the same plane as shown in figure 1.7

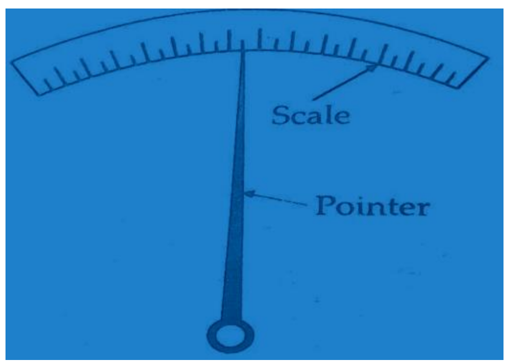


Figure: Arrangements showing scale and pointer in the same plane

The observational errors are also occurring due to involvement of human factors. For example, there are observational errors in measurements involving timing of an event Different observer may produce different results, especially when sound and light measurement are involved.

The complete elimination of this error can be achieved by using digital display of output.

3. Random Errors

• These errors are occurred due to unknown causes and are observed when the magnitude and polarity of a measurement fluctuate in changeable (random) manner.

• The quantity being measure is affected by many happenings or disturbances and ambient influence about which we are unaware are lumped together and called as Random or Residual. The errors caused by these disturbances are called Random Errors. Since the errors remain even after the systematic errors have been taken care, those errors are called as Residual (Random) Errors

• Random errors cannot normally be predicted or corrected, but they can be minimized by skilled observer and using a well-maintained quality instrument.

• These errors may be reduced by taking the average of a large number of readings.

Statistical Analysis:

Statistical Evaluation of measured data is obtained in two methods of tests as shown in below.

Multi Sample Test: In multi sample test, repeated measured data have been acquired by different instruments, different methods of measurement and different observers.

Single Sample Test: measured data have been acquired by identical conditions (same instrument, methods and observer) excepting time. In order to get the exact value of the quantity under measurement, tests should be done using many different procedures, techniques and experimenters.

Statistical Evaluation methods will give the most probable true value of measured quantity.

The mathematical background statistical evaluation methods are Arithmetic Mean, Deviation Average Deviation, Standard Deviation and variance.

1 Arithmetic Mean

• The most probable value of measured reading is the arithmetic mean of the number of reading taken.

• The best approximation is made when the number of readings of the same quantity is very large.

• Arithmetic mean or average of measured variables X is calculated by taking the sum of all readings and dividing by the number of reading.

• The Average is given by,

$$X = (x1 + x2 + x3 + \cdots + xn)/ n = \Sigma x /n$$

where, X= Arithmetic mean,

x1, x2....... xn = Readings or variable or samples and n= number of readings

2 Deviation (Deviation from the Average value)

• The Deviation is departure of the observed reading from the arithmetic mean of the group of reading.

• Let the deviation of reading x1 be d1 and that of x2 be d2 etc.,

d1= x1- X

d2= x2- X

.. .. ..

dn= xn- X

• The algebraic sum deviation is Zero

(d1+ d2+....+ dn= 0)

Algebraic sum of deviations= d1+d2+d3+… +dn

= (x1- X)+ (x2- X)+ ……..+ (xn- X)

= (x1+x2+..+xn)-nX=0

Where (x1+x2+..+xn)= nX

3.Average Deviation: Average deviation defined as the average of the modulus (without respect to its sign) of the individual deviations and is given by,

$D = |d_1| + |d_2| + |d_3| + \cdots + |d_n|\ n = \Sigma|d|\ n$

• Where, D= Average Deviation.

• The average deviation is used to identify precision of the instruments which is used in making measurements. Highly precise instruments will give a low average deviation between readings.

4 Standard Deviation :

• Standard deviation is used to analysis random errors occurred in measurement.

• The standard Deviation of an infinite number of data is defined as the square root of the sum of individual deviations squared, divided by the number of readings (n).

Standard deviation is $S.D = \sigma = \sqrt{\frac{{d_1}^2+{d_2}^2+{d_3}^2+\cdots+{d_n}^2}{n}} = \sqrt{\frac{\Sigma d^2}{n}}$; for n >20

Standard deviation is $S.D = s = \sqrt{\frac{{d_1}^2+{d_2}^2+{d_3}^2+\cdots+{d_n}^2}{n-1}} = \sqrt{\frac{\Sigma d^2}{n-1}}$; for n <20

5 Variance

The variance is the mean square deviation, which is the same as S.D except Square root. Variance is Just the squared standard deviation.

Variance V= (Standard deviation)^2

Variance $V=\sigma^2 = \frac{{d_1}^2+{d_2}^2+{d_3}^2+\cdots+{d_n}^2}{n} = \frac{\Sigma d^2}{n}$; for n >20

Variance $V=s^2 = \frac{{d_1}^2+{d_2}^2+{d_3}^2+\cdots+{d_n}^2}{n-1} = \frac{\Sigma d^2}{n-1}$; for n <20

6 Histogram (Frequency distribution Curve)

• When a number of Multisample observations are taken experimentally there is a scatter of the data about some central value.

• One graphical method to present test results is called histogram. A histogram is also called a frequency distribution curve.

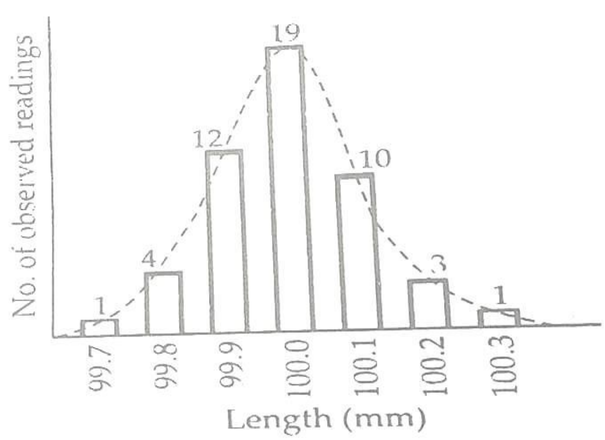
• This histogram indicates the number of occurrences of particular value.

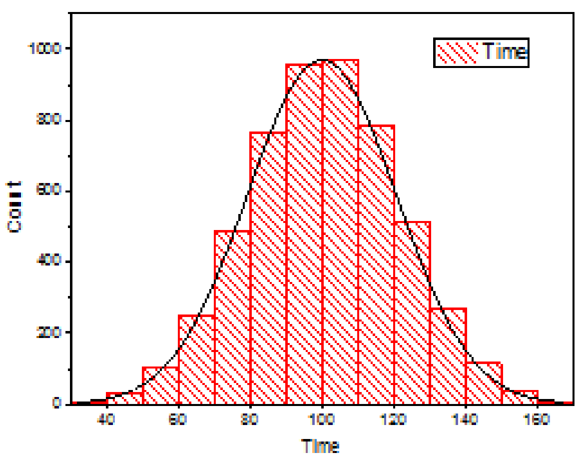
• The ordinate indicates the number of observed readings (frequency of occurrence) of a particular value.

• The steps have smaller increments and we get a smoother curve.

Length (mm)	Number of observed readings (frequency or occurrence)
99.7	1
99.8	4
99.9	12
100.0	19
100.1	10
100.2	3
100.3	1

Example: Table shows a set of 50 readings of length measurement. The most probable or central value of length is 100mm represented as shown in figure 1.8 Histogram.





7 Measure of Dispersion from the Mean

The property which denotes the extent to which the values are dispersed about the central value is termed as dispersion. The other name of dispersion is *spread or scatter*.

Measure of dispersion from central value is an indication of the degree of consistency (precision) and regularity of the data.

Example: Figure 1.9 shows the two sets of data and curve 1 vary from x1 to x2 and curve 2 vary from x3 to x4. Curve 1 is having smaller dispersion from central value than the curve 2. Therefore curve 1 is having greater precision than the curve 2.

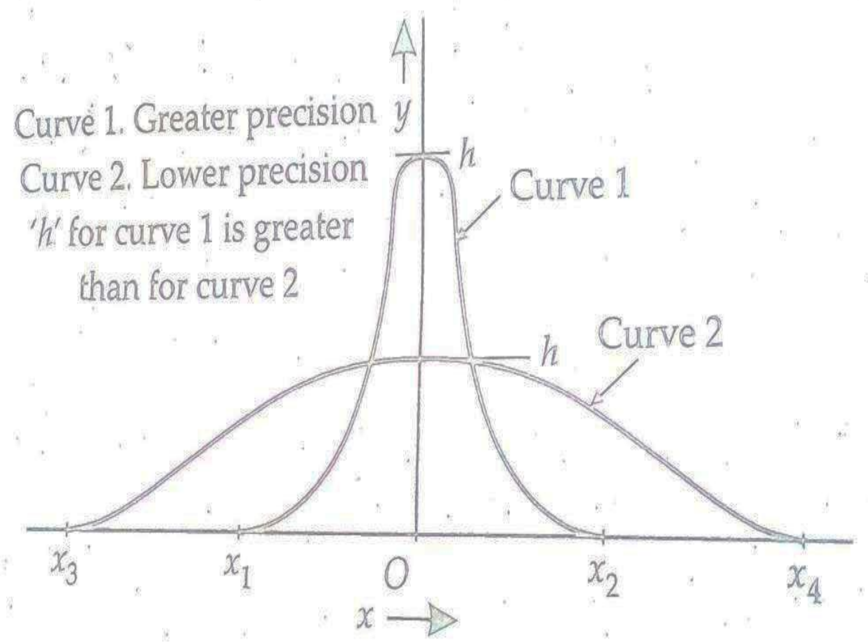


Figure 1.9: Curves showing different ranges and precision index

8 Probable error of finite number of readings

With a finite number of readings, the probable error is give by,

$$\boxed{e = 0.6745 \sqrt{\frac{\Sigma d^2}{n-1}}}$$

where $\quad d = $ deviation from mean

and $$\sigma = \sqrt{\frac{\Sigma d^2}{n-1}}$$

$\therefore \quad \boxed{e = 0.6745\, \sigma}$

This is probable error for one reading.

While the average reading has the probable error of,

$$\boxed{e_m = 0.6745 \frac{\sigma}{\sqrt{n-1}}}$$

9 Limiting error

• In most of the instruments the accuracy is guaranteed to be within a certain percentage of full scale reading.

• The manufacturer has to specify the deviations from the nominal value of a particular quantity.

• The limits of these deviations from the specified value are called as Limiting Errors or Guarantee Errors.

Thus the actual value with the limiting error can be expressed mathematically as,

$$\boxed{A_a = A_s \pm \delta A}$$

where A_a = Actual value

A_s = Specified or rated value

δA = Limiting error or tolerance

Another example is say a resistor is specified by the manufacturer as 4.7 kΩ with a tolerance of ± 5% then the actual value of the resistance is guaranteed to be within the limits.

$$R = 4.7\ k\Omega \pm (5\ \%\ \text{of}\ 4.7\ k\Omega) = 4.7\ k\Omega \pm 0.235\ k\Omega$$

$$= 4.935\ k\Omega \text{ and } 4.465\ k\Omega$$

10 Relative limiting error

• The relative limiting error is defined as the ratio of the error to the specified (nominal) magnitude of the quantity. This is also called fractional error.

Thus $\boxed{e = \frac{\delta A}{A_s}}$

where e = relative timing error

From the above equation, we can write,

$$\delta A = e \cdot A_s$$

and

$$A_a = A_s \pm \delta A$$

$$= A_s \pm e\, A_s$$

$$\therefore \quad \boxed{A_a = A_s [1 \pm e]}$$

The percentage relative limiting error is expressed as

$$\boxed{\%\, e = e \times 100}$$

The relative limiting error can be also be expressed as,

$$\boxed{e = \frac{\text{Actual value } (A_a) - \text{Specified value } (A_s)}{\text{Specified value } (A_s)}}$$

Example.1: The set of voltage measurement that were recorded by eight different students in the laboratory as follows: 532V, 548V, 543V, 535V, 546V, 531V, 543V and 536. Calculate the Arithmetic mean, Deviations from mean, average deviation, the standard deviation, variance and probable error on recorded voltage data.

No =	x	$d_i = x_i - X$	d_i^2
1	532	-7.25	52.56
2	548	8.75	76.56
3	543	3.75	14.06
4	535	-4.25	18.06
5	546	6.75	45.56
6	531	-8.25	68.06
7	543	3.75	14.06
8	536	-3.25	10.56
	$\sum x_i = 4314$	$\sum \lvert d_i \rvert = 46$	$\sum d_i^2 = 299.48$

- (i) Arithmetic mean,

$$X = (x1 + x2 + x3 + \cdots + xn)/\ n$$

$$= \Sigma x\ /n = 4314/8 = 539.25\ V$$

- (ii) Average Deviation,

$$D = (\lvert d1 \rvert + \lvert d2 \rvert + \lvert d3 \rvert + \cdots + \lvert dn \rvert)\ /n$$

$$= \Sigma \lvert d \rvert\ /n = 46/8 = 5.75\ V$$

(iii) Standard Deviation, $\sigma = \sqrt{\frac{\Sigma d_i^2}{n-1}}$

$$= \sqrt{\frac{299.48}{7}}$$

$$= 6.54V$$

• (IV) Variance $V =$ (Standard deviation)^2

$V = s^2$

V = 6.54*6.54

= 42.77 V

(V) Probable error of one reading = 0.6745 σ

= 0.6745 * 6.54

= 4.41 V

(VI) e_m = Probable error of mean = $\frac{0.6745\sigma}{\sqrt{n-1}}$

$= \frac{4.41}{\sqrt{8-1}}$

=1.66V

Example *The table given below lists a sample of experimental data;*

Value	3	4	5	6	7	8	9	10	11
Frequency of occurrence	1	2	3	6	7	6	4	2	1

Calculate : a) Mean b) Mean deviation c) Standard deviation d) Variance e) Probable error of one reading f) Probable error of mean.

Value x	Frequency f	$x \times f$	Deviation $d_i = x_i - \bar{x}$	$f \times d_i$	d_i^2	$f \times d_i^2$
3	1	3	−4.0625	−4.0625	16.503	16.503
4	2	8	−3.0625	−6.125	9.378	18.7578
5	3	15	−2.0625	−6.1875	4.2539	12.7617
6	6	36	−1.0625	−6.375	1.1289	6.7734
7	7	49	−0.0625	−0.4375	3.9×10^{-3}	0.0273
8	6	48	+0.9375	+5.625	0.8789	5.2734
9	4	36	+1.9375	+7.75	3.7539	15.0156
10	2	20	+2.9375	+5.875	8.6289	17.2578
11	1	11	+3.9375	+3.9375	15.503	15.5039
	n = 32	$\Sigma\ x \times f = 226$		$\Sigma \lvert f \times d_i \rvert = 46.375$		$\Sigma\ f d_i^2 = 107.875$

a) Mean, $\bar{x} = \frac{\Sigma x \times f}{n} = \frac{226}{32} = \mathbf{7.0625}$

(b) Mean Deviation = $\frac{\Sigma \lvert f \times d_i \rvert}{n} = \frac{46.375}{32} =$

= 1.45

c) Standard Deviation = $\sigma = \sqrt{\frac{\Sigma f d_i^2}{n}} = \sqrt{\frac{107.875}{32}} =$

=1.836

d) Variance, $\sigma^2 = (1.836)^2$

= 3.3708

e) e = Probable error of one reading

$= 0.6745 \times \sigma = 0.6745 \times 1.836$

= 1.238

f)Probable error of mean

$$e_m = \frac{0.6745\sigma}{\sqrt{n}}$$

$$= \frac{1.238}{\sqrt{32}} = 0.22$$

Calibration

Calibration is the process of checking the accuracy of instrument by comparing the instrument reading with a standard or against a similar meter of known accuracy. So using calibration is used to find the errors and accuracy of the measurement system or an instrument.

Calibration is an essential process to be undertaken for each instrument and measuring system regularly. The instruments which are actually used for measurement work must be calibrated against some reference instruments in which is having higher accuracy.

Reference instruments must be calibrated against instrument of still higher accuracy or against primary standard or against other standards of known accuracy.

The calibration is better carried out under the predetermined environmental conditions. All industrial grade instruments can be checked for accuracy in the laboratory by using the working standard.

Certification of an instrument manufactured by an industry is undertaken by National Physical Laboratory and other authorizes laboratories where the secondary standards and working standards are kept.

1 Process of Calibration

The procedure involved in calibration is called as process of calibration. Calibration procedure involves the comparison of particular instrument with either

- A primary standard,
- A secondary standard with higher accuracy than the instrument to be calibrated
- An instrument of known accuracy.

Procedure of calibration as follows.

- Study the construction of the instrument and identify and list all the possible inputs.
- Choose, as best as one can, which of the inputs will be significant in the application for which the instrument is to be calibrated.
- Standard and secure apparatus that will allow all significant inputs to vary over the ranges considered necessary.
- By holding some input constant, varying others and recording the output, develop the desired static input-output relations.

Theory and Principles of Calibration Methods

Calibration methods are classified into following two types,

1) Primary or Absolute method of calibration

2) Secondary or Comparison method of calibration

i. Direct comparison method of calibration

ii. Indirect comparison method of calibration

1) Primary or Absolute method of calibration

If the particular test instrument (the instrument to be calibrated) is calibrated against primary standard, then the calibration is called as primary or absolute calibration. After the primary calibration, the instrument can be used as a secondary calibration instrument.

Test Meter (The instrument to be calibrated) $\longleftrightarrow$ Primary standard meter

Figure: Representation of Primary Calibration

2) Secondary or Comparison calibration method

If the instrument is calibrated against secondary standard instrument, then the calibration is called as secondary calibration. This method is used for further calibration of other devices of lesser accuracy. Secondary calibration instruments are used in laboratory practice and also in the industries because they are practical calibration sources. Secondary standard meter or instrument

Test Meter (The instrument to be calibrated) $\longleftrightarrow$ Secondary standard meter

Figure : Representation of Secondary Calibration

Secondary calibration can be classified further two types,

i) Direct comparison method of Calibration

Direct comparison method of calibration with a known input source with same order of accuracy as primary calibration. So the instrument which is calibrated directly is also used as secondary calibration instruments.

Test Instrument (The voltmeter to be calibrated $\longleftrightarrow$ Standard instrument

Figure: Representation of Direct method of Calibration

ii) Indirect comparison method of Calibration

The procedure of indirect method of calibration is based on the equivalence of two different devices with same comparison concept.

Source Reading $\leftarrow$ Test Instrument (Device 1)

Source Reading $\longleftrightarrow$ Standard instrument (Device 2)

Figure: Representation of indirect method of Calibration

Standards of measurement:

• A standard is a physical representation of a unit of measurement. A known accurate measure of physical quantity is termed as standard. These standards are used to determine the accuracy of other physical quantities by the comparison method.

• Example, the fundamental unit of mass in the International System is the Kilogram and defined as the mass of a cubic decimetre of water at its temperature of maximum of density of 4oC.

• Different standards are developed for checking the other units of measurements and all these standards are preserved at the International Bureau of Weight and Measures at Serves, Paris.

Classification of Standards

• Based on the functions and applications, standards are classified into four categories

1)International standards

2) Primary standards

3) Secondary standards

4) Working standards

1)International standards

• International standards are defined and established upon internationally.

• They are maintained at the International Bureau of Weights and measures and are not

accessible to ordinary users for measurements and calibration.

• They are periodically evaluated and checked by absolute measurements in terms of fundamental units of physics.

• International Ohms: It is defined as the resistance offered by a column of mercury having a mass of 14.4521gms, uniform cross sectional area and length of 106.300cm, to the flow of constant current at the melting point of ice.

2)Primary Standards

• Primary standards are maintained by the National Standards Laboratories (NSL) in different parts of the world.

• The principle function of primary standards is the calibration and verification of secondary standards.

• They are not available outside the National Laboratory for calibration.

• These primary standards are absolute standards of high accuracy that can be used as ultimate reference standards.

3)Secondary Standards

• These standards are basic reference standards used by measurement and calibration laboratories in industries.

• These secondary standards are maintained by the particular industry to which they belong.

• Each industry has its own secondary standard.

• Each laboratory periodically sends its secondary standard to the National Standards Laboratory for calibration and comparison against the primary standards.

• After comparison and calibration, the National Standards Laboratory returns the secondary standards to the particular industrial laboratory with a certification of measuring accuracy in terms of primary standards.

4)Working Standards

• The working standards are used for day-to-day use in measurement laboratories. So this standard is the principle tools of a measurement laboratory.

• It is used to check and calibrate laboratory instruments for accuracy and performance. 28

• Example, manufacturers of electronic components such as capacitors, resistors etc , use a standard called working standard for checking the component values being manufactured, a standard resistor for checking of resistance value manufactured**.**

Steady state and dynamic state

- **Steady state means no change with respect to time**
- **Steady state = No change or the input is constant (for example, oven temperature is maintained constant)**
- **At steady state, differential equations are not needed**
- **Dynamic State means that some parameter is changing with time.**
- **Dynamic only relates to the period of time**
- **Dynamic state = oven temperature is changing with respect to time**
- **Differential equations are used to explain the behavior of something**
- **For example, when the oven was heating up, the oven temperature is changing with time**

Classification of Systems

A measuring system can be characterised by examining its behaviour to each of the three test inputs.

What has been found is that different systems can produce identical forms of response. For example, the response of the thermometer to the step change in temperature might have an identical pattern to a pressure sensor that is exposed to a step change in pressure.

Measurement systems can be classified based on their response into one of three groups

- Zero Order
- First Order
- Second Order

Each type of system has a different response to each of the three types of input we have mentioned.

We will next look at these three groups.

Systems of various orders

Zeros order systems

- Zeros order systems is represented by a differential equation of zero order as :

$$A_0\theta_0 = B_0\theta_i$$

$$OR \qquad \theta_0 = \frac{B_0}{A_0}\theta_i$$

$$\boxed{OR \quad \theta_0 = K\,\theta_i}$$

Where, K is the static sensitivity of the system and is the only parameters which characterized a zero order system.

First order system

- Such a system is represented by a first order differential equation

.

$$\boxed{A_1\frac{d\theta_0}{dt} + A_0\theta_0 = B_0\theta_i}$$

$$\frac{A_i}{A_0}\frac{d\theta_0}{dt} + \theta_0 = \frac{B_0}{A_0}\theta_i$$

$$\tau\frac{d\theta_0}{dt} + \theta_0 = K\theta_i$$

Is called time constant Where, $\boldsymbol{\tau} = \frac{A_i}{A_o}$

Is called static sensitivity Where, $\mathrm{K} = \frac{B_i}{A_o}$

SECOND ORDER SYSTEM

Modeling for dynamic performance

- For studying the dynamic response of an instrument it is to be represented by a mathematical model. That a relationship between input and output of the instrument is to be determined taking into account the physical parameters of its elements.

- A generalized relationship for a second order system can be expressed as:

$$A_2 \frac{d^2\theta_0}{dt^2} + A_1 \frac{d\theta_0}{dt} + A_0\theta_0 = B_0\theta_i$$

Where θ_i = input signal /information
θ_0 = output signal /information
A_2, A_1, A_0, B_0 are constants and represent system parameters , the significant of which shall be explained later

- ***The order of the system (instrument)*** is the order of the differential equation representing it. Above , differential equation contains second order derivative, so called a second order system.

Different Types of Input

The static characteristics refer to the results when a constant input is applied. What happens if the input is not constant but is changing? How does the instrument respond? That depends on the dynamic characteristics.

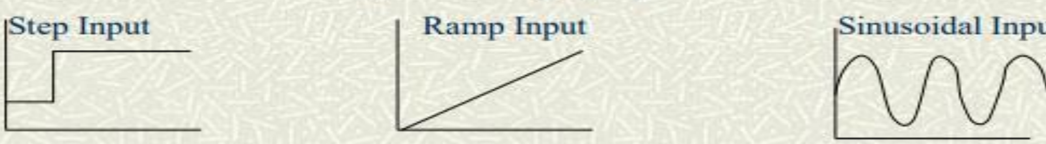
For example, a standard thermometer is suitable for measuring the temperature in this room. This changes slowly during the day and night, without sudden changes.

Compare this to the measurement of cylinder temperature in a combustion engine. This change extremely suddenly and by a large amount. The output from the standard thermometer to this type of input would be useless.

Different instruments handle changing inputs in different ways.

To compare instruments fairly, we should apply the same type of input to each and measure the result. An easily repeatable changing input is required.

There are three standard types of changing inputs



- **This is a measure of how well a system responds to a changing input.**

- The dynamic specification can be defined by applying one or all of three different inputs and examining the resultant output.
- The Step or Transient Response comes from the Step Input.
- The Ramp Response is given by the Ramp input and
- The Frequency Response is produced by the Sine Wave Input.

Step Input

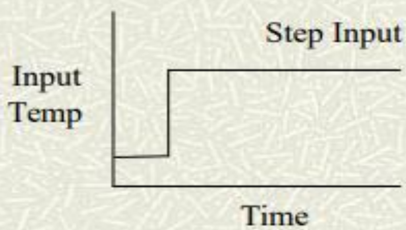
This is a an abrupt change from one steady input value to another. The response of the system to it is called the **transient response** and is a measure of how well the system can respond to sudden changes.

Think of the situation where a thermometer is suddenly moved from a beaker of ice and water into a bath of boiling water.

Is this a step change in the input?

Describe what happens to the reading on the thermometer.

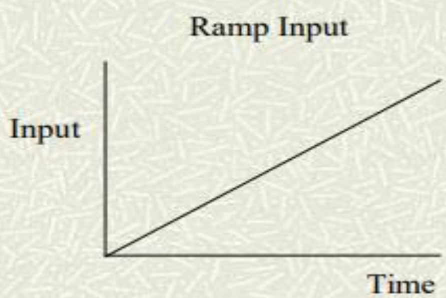
Does it take a long time to get to the new value?

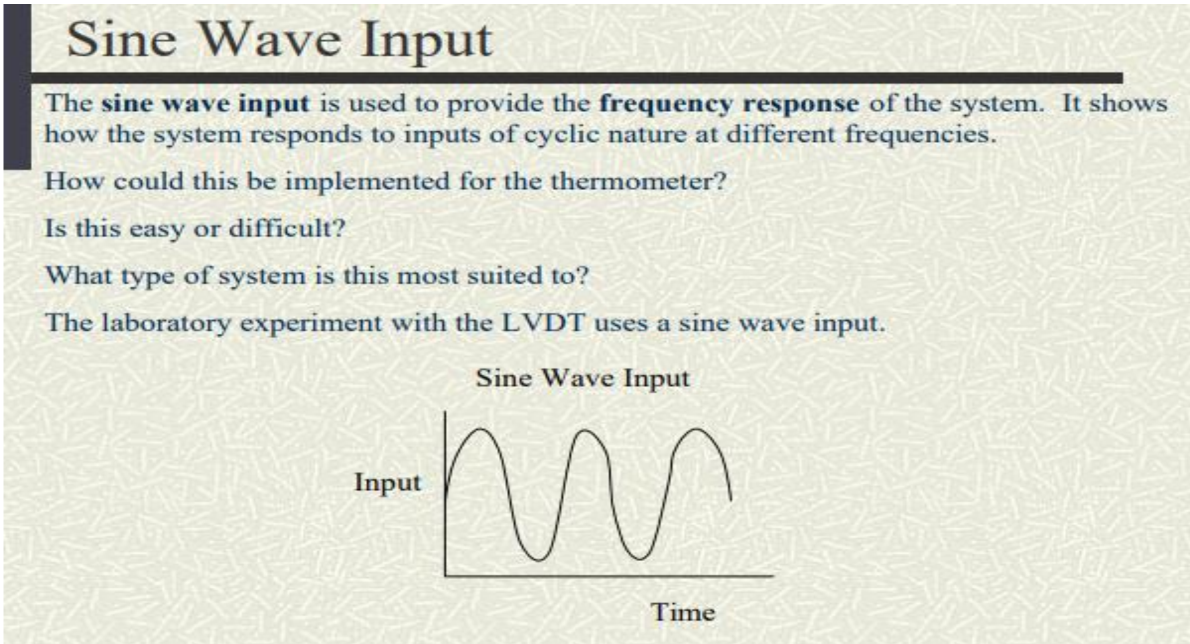


Ramp Input

The ramp input varies linearly with time and the **ramp response** of the system is observed to give the steady state error between the output and the input.

For example a thermometer is placed in a bath of water and ice and a constant heat is applied to the bath. The thermometer reading is recorded as the bath temperature is ramped from 0 to 100degC.





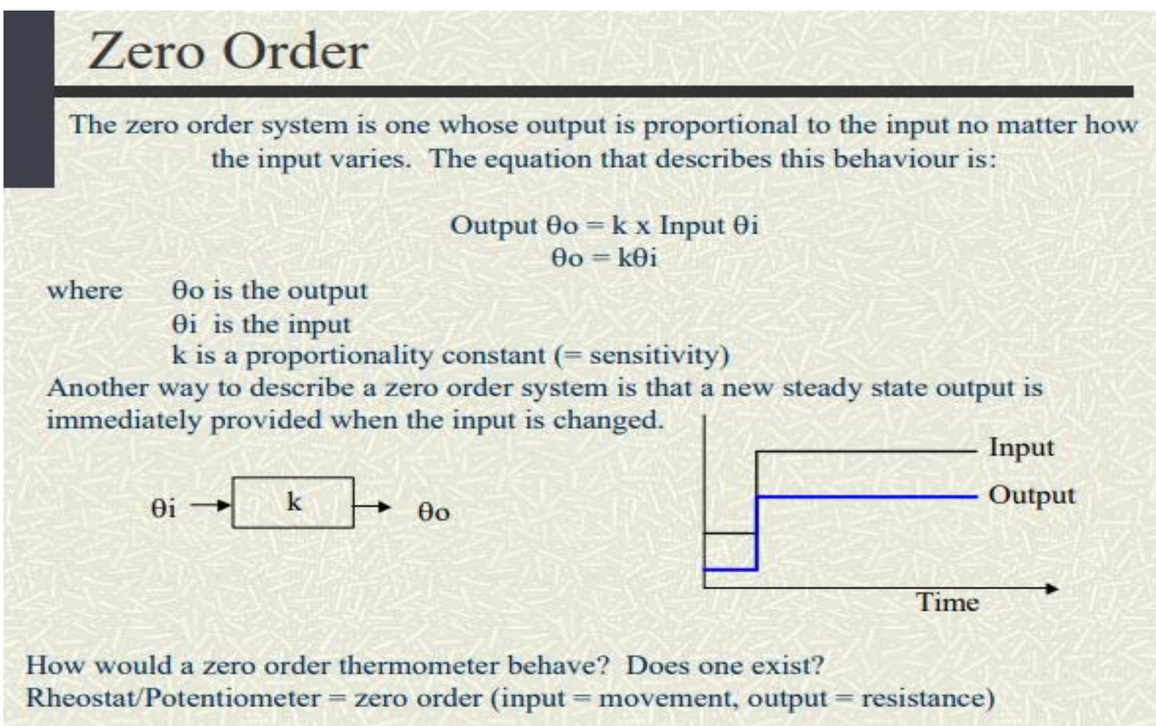
Zero Order Systems are defined as follows.

The output of a zero order system is proportional to the input.

At all times, the output is equal to the input multiplied by some constant of proportionality.

Example:–Rheostat, Potentiometer.

The voltage/resistance (output) instantly changes when the wiper is moved (input).



First Order Systems ultimately reach the same result as zero order systems except that they take some time to get there when a step input is applied.

The relationship between the output and the input is given by the following equation:

$$a\frac{d\theta_o}{dt} + b\theta_o = c\theta_i$$

where a, b and c are constants.

This equation is normally written as follows:

$$\tau\frac{d\theta_o}{dt} + \theta_o = K\theta_i$$

where t=a/b and is the time constant in seconds and K=c/b and is the static sensitivity (units depending on application)

The form of the step response is shown as follows:

The above curve is an exponential rise to a final value.

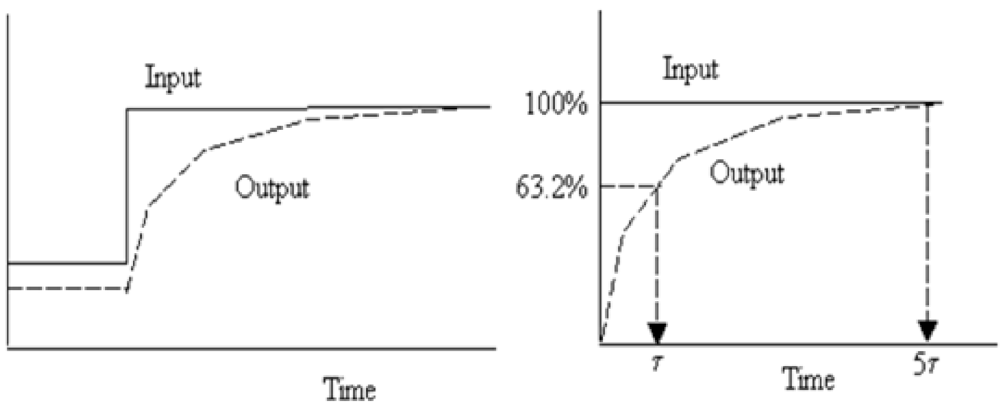
The equation that relates the output to time is as follows:

$$\theta_o = \theta_{initial} + (\theta_{final} - \theta_{initial})(1 - e^{-t/\tau})$$

where *θinitial* is the steady state value before the step input is applied and *θfinal* is the steady state value after the step input is applied, i.e. after the exponential rise.

The time constant, t, is the length of time for the output to reach 63.2% of its final value.

It takes almost five time constants for the output to reach its final value.



First Order

Many systems take time to reach a new steady state value. The definition of Steady State exists is that the output stops changing - Important definition!
If the behaviour when a step input is applied is such that the output responds quickly and then slackens as it reaches the new steady state value the system is first order.
The term first order is used because the relationship between the output and the input for these systems is described by first order differential equation:

$$a\frac{d\theta_o}{dt}+b\theta_o=c\theta_i$$

where a, b and c are constants.

This equation is normally written as follows:

$$\tau\frac{d\theta_o}{dt}+\theta_o=K\theta_i$$

where τ=a/b and is the time constant in seconds
K=c/b and is the static sensitivity (units depending on application)
We will solve this equation later in the course.

In General

The differential equation that describes the first order system is:

$$\tau\frac{d\theta_o}{dt}+\theta_o=K\theta_i$$

This equation is easily solved using Laplace transforms. The solution looks like this:

$$\theta_o=K\theta_i(1-e^{-t/\tau})$$

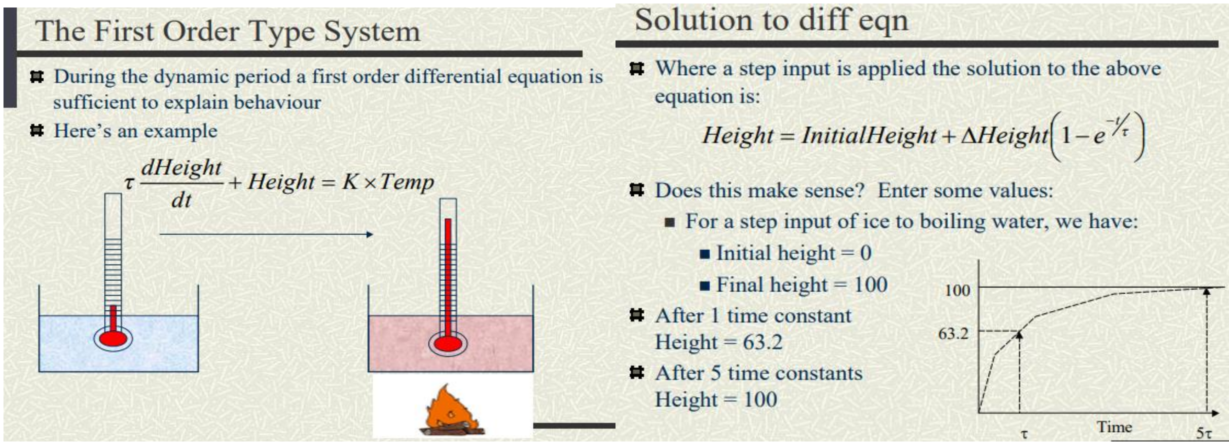
Expand this equation and then think about it for a minute:

$$\theta_o=K\theta_i-K\theta_i e^{-t/\tau}$$

This term varies with time, large initially, almost zero at t=5t

This term eventually dominates when the other dies away

Don't forget that τ is the time constant and has units of seconds.



The First Order System

Thermometer example

Example. A thermocouple housed in a protective sheath has an output voltage of q_{out} Volts and an input temperature of q_{in}°C. Determine the time constant and the static sensitivity for this system if its dynamic performance is given by the following equation:

$$30\frac{d\theta_o}{dt} + 3\theta_o = 1.5x10^{-5}\theta_i$$

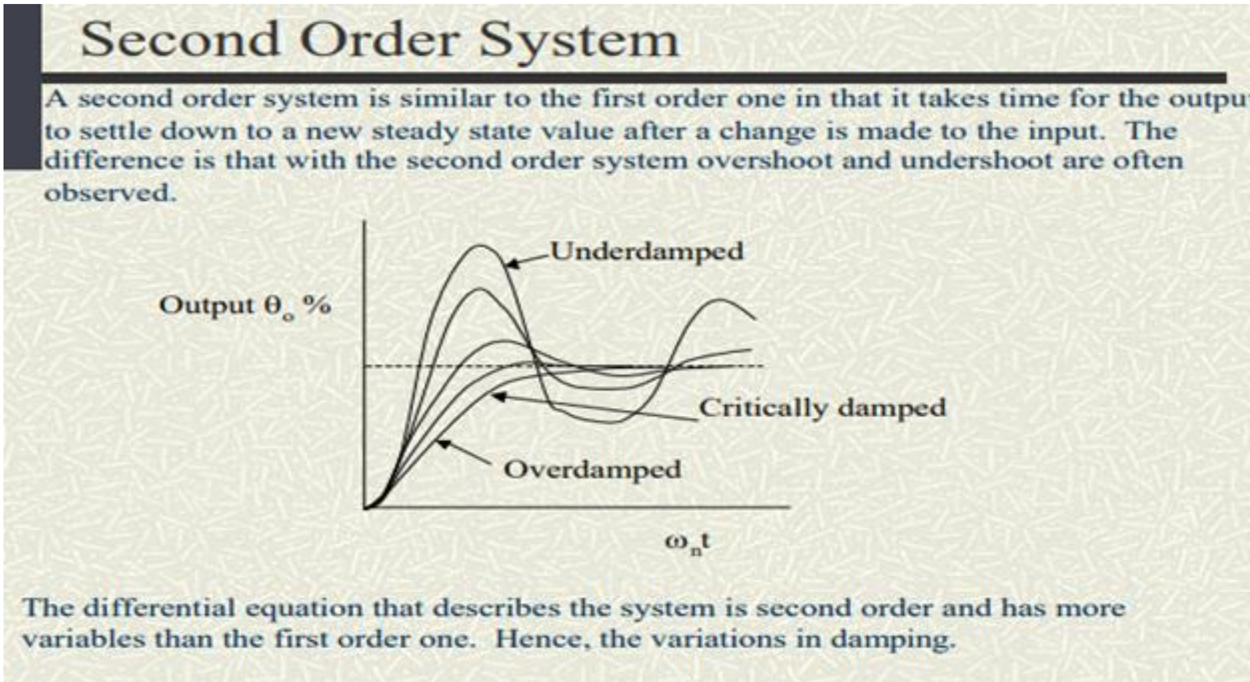
Solution. This equation is of the form given above. Rearranging slightly to give a unity coefficient for the *qout* term gives the following equation:

$$10\frac{d\theta_o}{dt} + \theta_o = 0.5x10^{-5}\theta_i$$

This is of the form:

$$\tau\frac{d\theta_o}{dt} + \theta_o = K\theta_i$$

Therefore, the time constant t=10 and the static sensitivity k=0.5x10-5.



SENSOR

DEFINITION OF SENSOR

A sensor is a device consists of optical component/system and a detector with electronic circuitry that will be **used to record the reflected and/or emitted energy from various objects**.

- We live in a World of Sensors. You can find different types of Sensors in our homes, offices, cars etc. working to make our lives easier by turning on the lights by detecting our presence, adjusting the room temperature, detect smoke or fire, make us delicious coffee, open garage doors as soon as our car is near the door and many other tasks.

What is a Sensor?

- **A Sensor is an input device which provides an output (signal) with respect to a specific physical quantity (input).** The term "input device" in the definition of a Sensor means that it is part of a bigger system which provides input to a main control system (like a Processor or a Microcontroller).
- Another unique definition of a Sensor is: **It is a device that converts signals from one energy domain to electrical domain**.
- In the broadest definition, a **Sensor is a device, module, machine, or subsystem whose purpose is to detect events or changes in its environment and send the information to other electronics, frequently a computer processor**. A **sensor** is always used with other electronics.

- A **sensor** is a device that detects the change in the environment and responds to some output on the other system. **A sensor converts a physical phenomenon into a measurable analog voltage (or sometimes a digital signal) converted into a human-readable display or transmitted for reading or further processing.**
- A **sensor** converts stimuli such as heat, light, sound and motion into electrical signals. These signals are passed through an interface that converts them into a binary code and passes this on to a computer to be processed
- **The simplest example of a sensor is an LDR or a Light Dependent Resistor. It is a device, whose resistance varies according to intensity of light it is subjected to. When the light falling on an LDR is more, its resistance becomes very less and when the light is less, well, the resistance of the LDR becomes very high**.
- We can connect this LDR in a voltage divider (along with other resistor) and check the voltage drop across the LDR. This voltage can be calibrated to the amount of light falling on the LDR. Hence, a Light Sensor.

Classification of Sensors

- ➢ In the first classification of the sensors, they are divided in to **Active and Passive.**
- ➢ The other type of classification is **based on the means of detection** used in the sensor. Some of the means of detection are Electric, Biological, Chemical, Radioactive etc.
- ➢ The next classification is **based on conversion phenomenon** i.e. the input and the output. Some of the common conversion phenomena are **Photoelectric, Thermoelectric, Electrochemical, Electromagnetic, Thermo-optic, etc.**
- ➢ The final classification of the sensors are **Analog and Digital Sensors**.

- ▪ **Active sensors**: Require an external source of power (excitation voltage) that provides the majority of the output power of the signal
- ▪ **Active Sensors** are those which require an external excitation signal or a power signal.
- ▪ **Passive Sensors**, on the other hand, do not require any external power signal and directly generates output response.
- ▪ **Passive sensors**: The output power is almost entirely provided by the measured signal without an excitation voltage
- ▪ **Passive sensors** detect reflected electromagnetic radiation from a source such as the sun. The camera on your phone is a **passive sensor**, receiving the reflected spectrum from the sun as it reflects off your body and clothes, thus capturing your likeness in a photo

Analog vs. Digital Sensors

- ▪ **Analog Sensors** produce an analog output i.e. **a continuous output signal with respect to the quantity being measured**.
- ▪ **Analog sensors**: The signal produced by the sensor is continuous and proportional to the measurand.

- **Digital Sensors**, in contrast to Analog Sensors, **work with discrete or digital data**.
- The data in digital sensors, which is used for conversion and transmission, is digital in nature.
- **Digital sensors**: The signal produced or reflected by the sensor is binary

Null and Deflection Methods

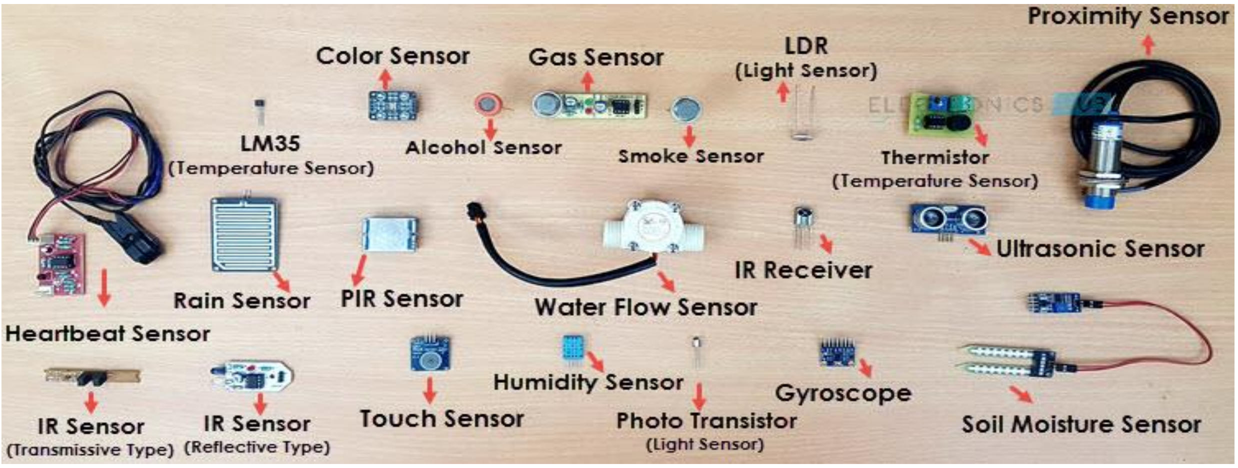
- **Deflection**: The signal produces some physical (deflection) effect closely related to the measured quantity and transduced to be observable.
- **Null**: The signal produced by the sensor is counteracted to minimize the deflection. That opposing effect necessary to maintain a zero deflection should be proportional to the signal of the measurand.

Input-Output Configuration

- 1) Method of inherent insensitivity: Use whenever possible
- 2) Method of high gain feedback:
- 3) Method of calculated output corrections
- 4) Method of signal filtering
- 5) Method of opposing inputs

Different Types of Sensors

- The following is a list of different types of sensors that are commonly used in various applications. All these sensors are used for measuring one of the physical properties like Temperature, Resistance, Capacitance, Conduction, Heat Transfer etc.
- Temperature Sensor, Proximity Sensor, Accelerometer, IR Sensor (Infrared Sensor), Pressure Sensor, Light Sensor, Ultrasonic Sensor, Smoke, Gas and Alcohol Sensor, Touch Sensor, Color Sensor, Humidity Sensor, Tilt Sensor and Flow and Level Sensor, etc.
- All types of sensors can be basically classified into analog sensors and digital sensors.
- But, there are a few types of sensors such as **temperature sensors**, IR sensors, **ultrasonic sensors**, **pressure sensors**, **proximity sensors**, and touch sensors are frequently used in most electronics applications.
- Vision and Imaging Sensors, Temperature Sensors, Radiation Sensors
- Proximity Sensors, Pressure Sensors, Position Sensors
- Photoelectric Sensors, Particle Sensors, Motion Sensors
- Metal Sensors, Level Sensors, Leak Sensors, Humidity Sensors
- Gas and Chemical Sensors, Force Sensors, Flow Sensors, Flaw Sensors
- Flame Sensors, Electrical Sensors, Contact Sensors, Non-Contact Sensors



What is a Transducer

- A **device** which **converts a physical quantity into the proportional electrical signal** is called a **transducer**.
- The **electrical signal** produced may be a **voltage, current or frequency**.
- A transducer uses many effects to produce such conversion.
- **The process of transforming signal from one form to other is called transduction.**
- A transducer is also called **pick up**. The transduction element transforms the output of the sensor to an electrical output, as shown in the Fig.
- Any electrical/ electronic/ electro-mechanical device that converts one form of energy to another is called a Transducer.
- Some examples include Loudspeakers, Microphones, Antenna, Thermometers, Pressure Sensors and Position Sensors.
- Although not considered as transducers in true sense, LEDs, photocells and common light bulbs also work as transducers.
- Efficiency is very important for any transducer. It is defined as the ratio between the desired output power to the total input power.

Mathematically, if we were to represent “P” as total input power and “Q” as required form of output power, then efficiency “E” is given by

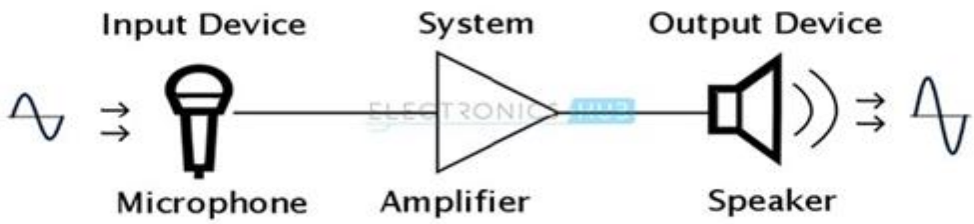
$$E = \frac{Q}{P}$$

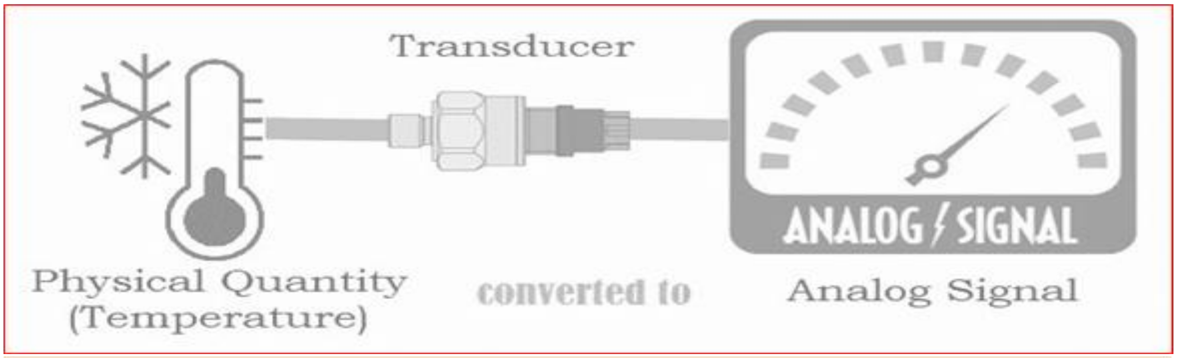
If E% is the percentage of efficiency then,

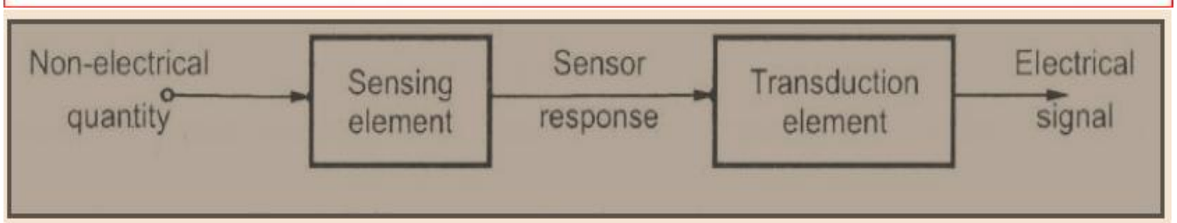
$$E\% = \frac{100Q}{P}$$

- However, it is important to note that 100% efficiency cannot be achieved by any transducer. The energy conversion process always takes away some energy. This loss is generally manifested in the form of heat.

Principle of Transducer



- 



ELEMENTS OF TRANSDUCERS

- A transducer will have basically two main components: Sensors that work as monitoring systems and actuators that work by imposing certain conditions on a system. These are considered to be the most comprehensive groups of transducers. It implies that at any given moment, transducers are functioning either as an actuator or a sensor.
- Few transducers function both as sensors and actuators, but, not simultaneously. Such transducers are considered as reversible. For instance, a loudspeaker (actuator) can be used to detect motions of the speaker's diaphragm. An accelerometer is another example of reversible transducers that can be used to sense vibrations and also perform as a shaker.

They are

1. Sensing Element : The physical quantity or its rate of change is **sensed and responded to by this part of the transistor**.

2. Transduction Element : The output of the sensing element is passed on to the transduction element. This element is responsible for converting the non-electrical signal into its **proportional electrical signal.**

- There may be cases when the transduction element performs the action of both transduction and sensing. The best example of such a transducer is a **thermocouple**. **A thermocouple**

is used to generate a voltage corresponding to the heat that is generated at the junction of two dissimilar metals.

Characteristics of Transducers: Some specifications on which the transducers are rated: –

1. Dynamic Range

- It is defined as the ratio between the largest and smallest amplitude signals that can be translated by a transducer. Larger the Dynamic Range implies more sensitive and precise transducers will be.

2. Repeatability

- A transducer's ability to produce identical output upon stimulation by the same input is termed as repeatability.

3. Noise

- All transducers have some random noise in their output. Small signals are largely affected by noise in comparison to larger signals.

4. Hysteresis

- This is property wherein a transducer's output is dependent not only on the present input, but, also on the previous inputs.

Factors that Influence the Choice of a Transducer

- The choice of a transducer used for measuring different quantities depends on many factors such as:

1. Operating Principle

- The selection of transducers may be made based on its different operating principles like inductive, resistive, capacitive, piezoelectric, optoelectronic etc.

2. Operating Range

- A transducer having a wide range of operation is an ideal choice because it does not break during an operation.

3. Sensitivity

- It is necessary for producing the correct, detectable output.

4. Cross Sensitivity

- The measure of a transducer can vary across different planes due to sensitivity. Hence, cross sensitivity is essential for accurate results.

5. Accuracy

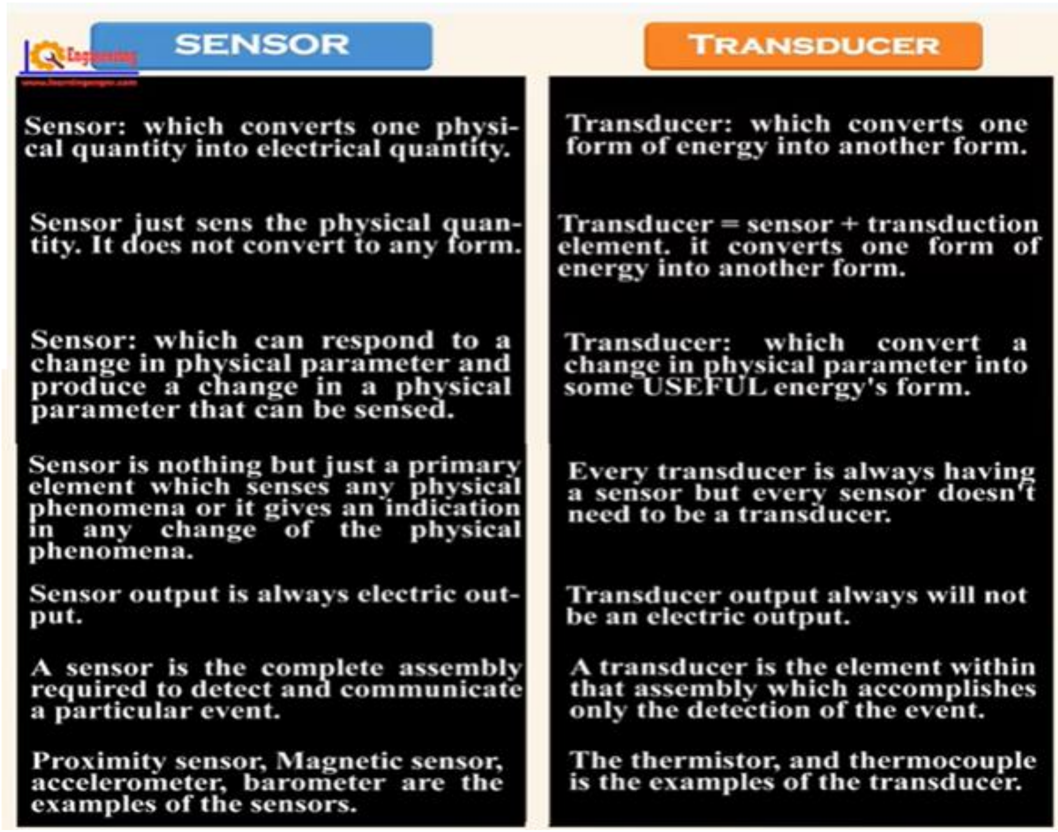
- Generally, transducers produce accurate values after calibration. A small gap for variability from desired value is permissible and is necessary for industrial applications.

6. Environmental Compatibility

➢ A transducer must be able to perform in any environment. It must work well with shocks and high pressure.

7. Reliability and Stability

➢ Transducers must have great stability for sustained operations. They must also be reliable in order to avoid failures or errors.



SENSOR	TRANSDUCER
Sensor: which converts one physical quantity into electrical quantity.	Transducer: which converts one form of energy into another form.
Sensor just sens the physical quantity. It does not convert to any form.	Transducer = sensor + transduction element. it converts one form of energy into another form.
Sensor: which can respond to a change in physical parameter and produce a change in a physical parameter that can be sensed.	Transducer: which convert a change in physical parameter into some USEFUL energy's form.
Sensor is nothing but just a primary element which senses any physical phenomena or it gives an indication in any change of the physical phenomena.	Every transducer is always having a sensor but every sensor doesn't need to be a transducer.
Sensor output is always electric output.	Transducer output always will not be an electric output.
A sensor is the complete assembly required to detect and communicate a particular event.	A transducer is the element within that assembly which accomplishes only the detection of the event.
Proximity sensor, Magnetic sensor, accelerometer, barometer are the examples of the sensors.	The thermistor, and thermocouple is the examples of the transducer.

Classification of Transducers

1. Based on the physical phenomenon

- Primary transducer
- Secondary transducer

2. Based on the power type Classification

- Active transducer
- Passive transducer

3. Based on the type of output the classification of transducers are made

- Analog transducer
- Digital transducer

4. Based on the electrical phenomenon is a best Classification of Transducer

- Resistive transducer
- Capacitive transducer
- Inductive transducer
- Photoelectric transducer
- Photovoltaic transducer

5. Based on the non-electrical phenomenon Classification of transducer

- Linear displacement
- Rotary displacement

6. Based on the transduction phenomenon

- Transducer
- Inverse transducer.

The Classification of Transducers are based on their

- ➢ Area of application,
- ➢ Method of energy conversion,
- ➢ Nature of output signal,
- ➢ According to Electrical principles involved,
- ➢ Electrical parameter used,
- ➢ Principle of operation & Typical applications.

The transducers can be classified broadly

1. As primary and secondary transducers
2. On the basis of transduction form used
3. As active and passive transducers
4. As transducers and inverse transducers.

Primary Transducers and Secondary Transducers

Bourdon tube acting as a primary detector senses the pressure and converts the pressure into a displacement of its free end. The displacement of the free end moves the core of a linear variable differential transformer(LVDT) which produces an output voltage.

Analog Transducers:-

These transducers convert the input quantity into an analog output which is a continuous function of time.

◦ Strain Gauge ◦ LVDT ◦ Thermocouple ◦ Thermistor

Digital Transducers:-

These transducers convert the input quantity into an electrical output which is in the form of pulses.

◦ Glass Scale can be read optically by means of a light source, an optical system and photocells .

Transducers and Inverse Transducers:

A Transducer can be broadly defined as a device which converts a non-electrical quantity into an electrical quantity.

Ex:-Resistive, inductive and capacitive transducers

An inverse transducer is defined as a device which converts an electrical quantity into a non-electrical quantity. Ex:-Piezoelectric crystals

Source of energy considerations they are classified as

(I) Active & (II) Passive transducers.

Active transducers

Active transducer is a device which converts the given non-electrical energy into electrical energy by itself. Thermocouple, Photovoltaic cell and more are the best examples of the transducers.

- Active transducers are those which do not require an auxiliary power source to produce their output.
- They are also known as self generating type since they produce their own voltage or current output.

Passive transducers

Passive transducer is a device which converts the given non-electrical energy into electrical energy by external force. Resistance strain gauge, Differential Transformer are the examples for the Passive transducers.

- A component whose output energy is supplied entirely by its input signal (physical quantity under measurement) is commonly called a "passive transducer".
- In other words the passive transducers derive the power required for transduction from an auxiliary source.
- Some of the passive transducers (lectrical transducers), their electrical parameter (resistance, capacitance, etc), principle of operation and applications are listed below.

Classification based on Source of Energy

Transducers are also classified based on the source of energy.

Under this category, there usually two types of transducers:

- Active Transducers
- Passive Transducers

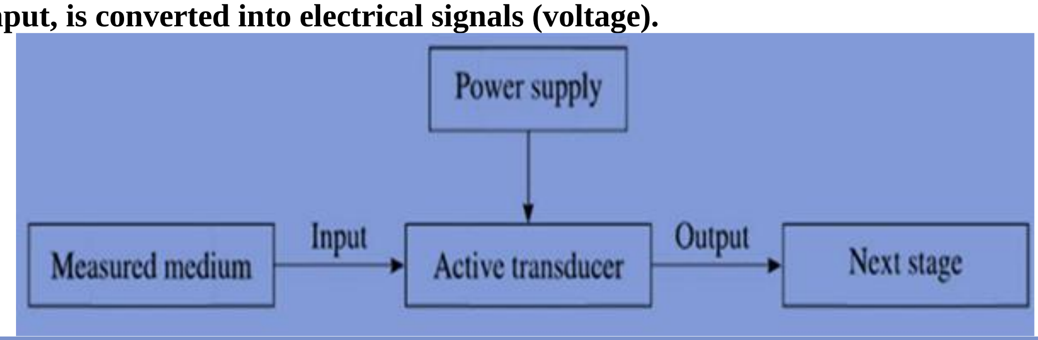
Active Transducers

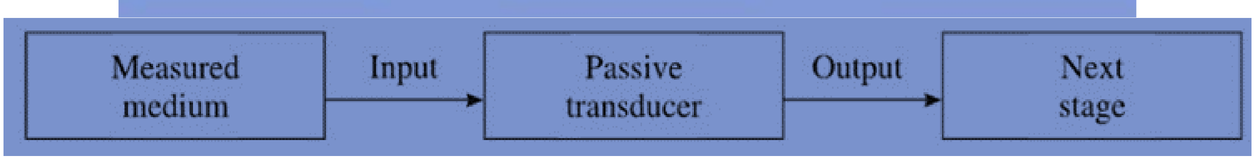
In Active Transducers, the **energy from the input is used as a control signal in the process of transferring energy from power supply to proportional output.**

For example, a **Strain Gauge is an Active Transducer, in which the strain is converted into resistance**. But since the energy from the strained element is very small, **the energy for the output is provided by an external power supply.**

Passive Transducers

In Passive Transducers, **the energy from the input is directly converted into the output**. For example, a **Thermocouple is a passive transducer, where the heat energy, which is absorbed from input, is converted into electrical signals (voltage).**





Comparison	Active Transducer	Passive Transducer
What is	The transducer which generate the output in the form of voltage or current, without any external energy source is known as active transducer.	The passive transducer means the transducer whose internal parameters like capacitance, resistance & inductance changes because of the input signal.
Additional Energy Source	Not Require	Require
Working Principle	Draw energy from the measurand source.	Take power from the external source which changes the physical properties of transducer.
Design	Simple	Complicated
Resolution	Low	High
Output signal	Produces from the signal to be measured.	Output obtains by receiving the signal from the external power source.
Examples	Tachogenerator, Thermocouple, Photovoltaic cell etc.	Thermistor, Differential transformer, Photomultiplier tube, Photovoltaic cell.

Self-Generating Transducers (No External Power) – Active Transducers

They do not require an external power, and produce an analog voltage or current when stimulated by some physical form of energy.

1.Thermocouple and thermopile Principle of operation: An emf is generated across the junction of two dissimilar metals or semiconductors when that junction is heated.

Applications: Temperature, heat flow, radiation.

2. Moving-coil generator: Principle of operation: Motion of a coil in a magnetic field generates a voltage.

Applications: Velocity. Vibration

3. Piezoelectric pickup: An emf is generated when an external force is applied to certain crystalline materials, such as quartz Sound, vibration. acceleration, pressure changes

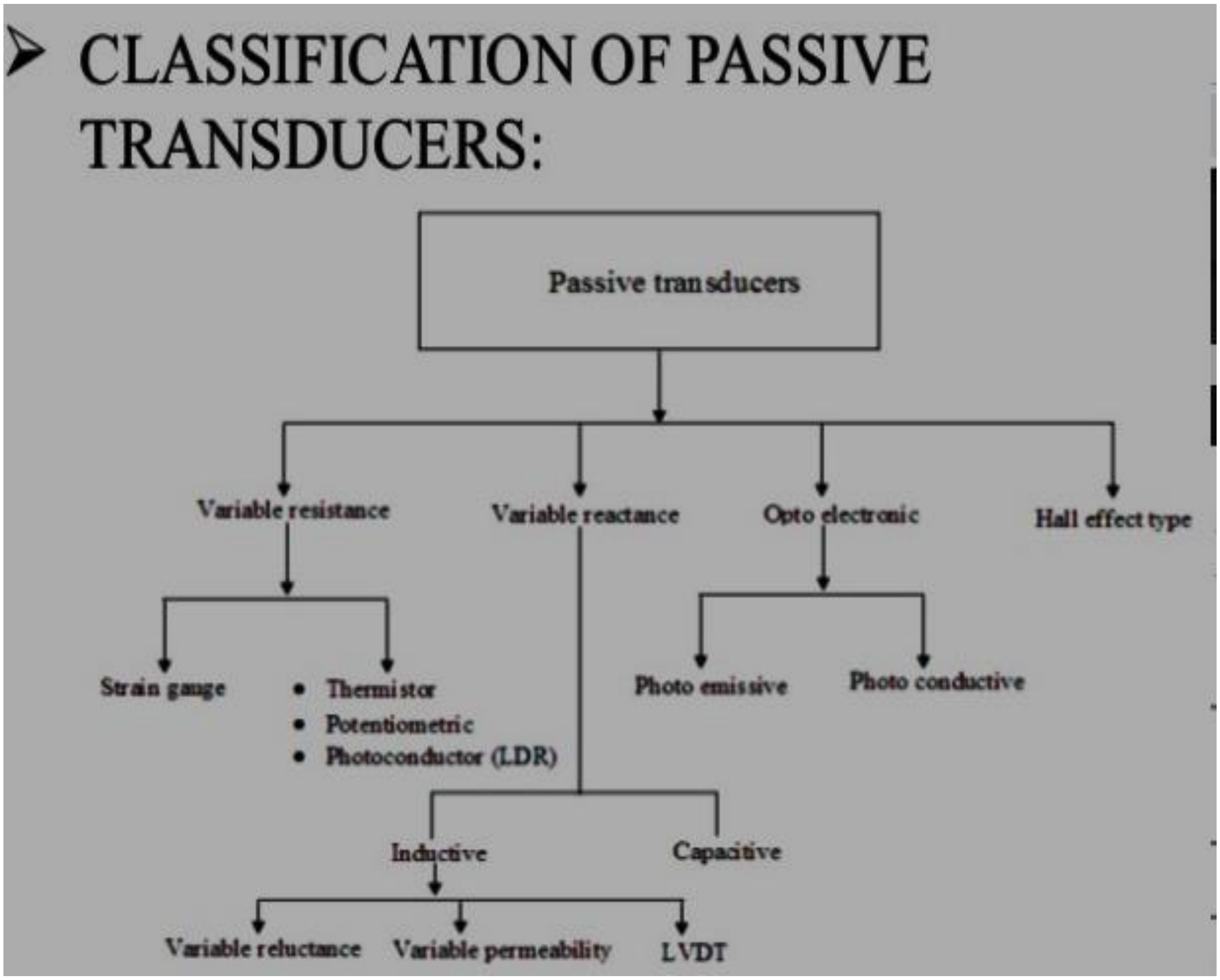
4. **Photovoltaic cell Principle of operation:** A voltage is generated in a semi-conductor junction device when radiant energy stimulates the cell

Applications: Light meter, solar cell

Passive transducer

- **Passive transducer** is a transducer, which produces the variation in passive element.
- We will consider the passive elements like resistor, inductor and capacitor.
- Three types of passive transducers depending on the passive element that are

- Resistive Transducer
- Inductive Transducer
- Capacitive Transducer



Resistive Transducers

1. Resistance Strain Gauge

The change in value of resistance of metal semi-conductor due to elongation or Compression is known by the measurement of torque, displacement or force.

2. Resistance Thermometer

The change in resistance of metal wire due to the change in temperature known by the measurement of temperature.

3**. Resistance Hygrometer**

The change in the resistance of conductive strip due to the change of moisture content is known by the value of its corresponding humidity.

4. Hot Wire Meter

The change in resistance of a heating element due to convection cooling of a flow of gas is known by its corresponding gas flow or pressure.

5. Photoconductive Cell

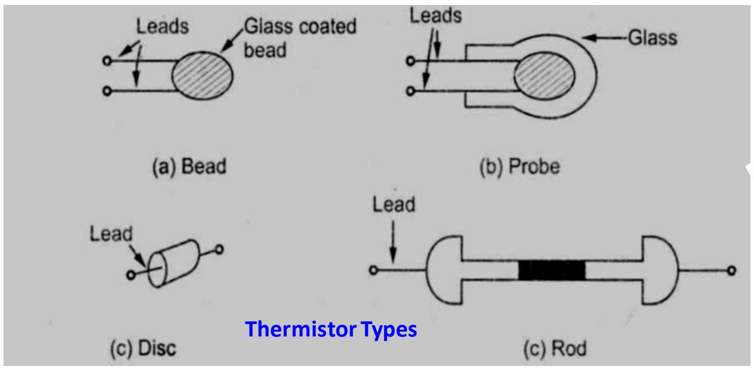
The change in resistance of a cell due to a corresponding change in light flux is known by its corresponding light intensity.

6. Thermistor

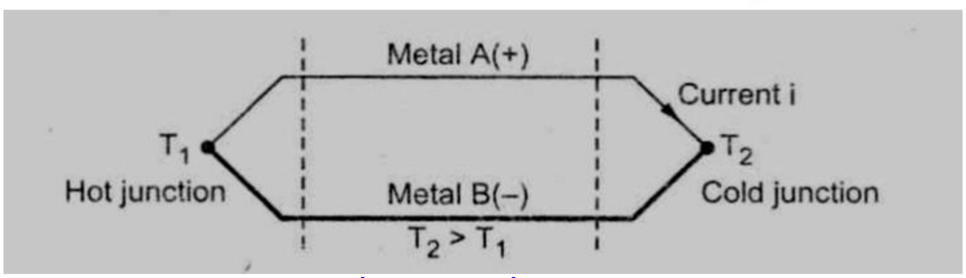
The change in resistance of a semi-conductor that has a negative co-efficient of resistance is known by its corresponding measure of temperature.

7. Potentiometer Type

The change in resistance of a potentiometer reading due to the movement of the slider as a part of an external force applied is known by its corresponding pressure or displacement.



Thermistor Types



Thermocouple

A passive transducer is said to be a **resistive transducer**, when it produces the variation (change) in resistance value.

The following formula is for **resistance**, R of a metal conductor.

$$\mathbf{R=\rho l/A}$$
$$\mathbf{R=\rho lA}$$

where, ρ is the resistivity of conductor

l is the length of conductor

A is the cross sectional area of the conductor

The resistance value depends on the three parameters ρ, l & A.

So, we can make the **resistive transducers** based on the variation in one of the three parameters ρ, l & A.

The variation in any one of those three parameters changes the resistance value.

- Resistance, **R** is directly proportional to the **resistivity** of conductor, **ρ**.
- So, as resistivity of conductor, ρ increases the value of resistance, R also increases.
- Similarly, as resistivity of conductor, ρ decreases the value of resistance, R also decreases.

- Resistance, R is directly proportional to the **length** of conductor, l.
- So, as length of conductor, l increases the value of resistance, R also increases.
- Similarly, as length of conductor, l decreases the value of resistance, R also decreases.
- Resistance, R is inversely proportional to the **cross sectional area** of the conductor, A.
- So, as cross sectional area of the conductor, A increases the value of resistance, R decreases.
- Similarly, as cross sectional area of the conductor, A decreases the value of resistance, R increases.

Inductive Transducer

A passive transducer is said to be an **inductive transducer**, when it produces the variation (change) in inductance value. the following formula for **inductance**, L of an inductor.

$L= N^2/S$ Equation 1

Where,

N is the number of turns of coil, S is the number of turns of coil

the following formula is for **reluctance**, S of coil.

$S = l/\mu A$ Equation 2

Where,

l is the length of magnetic circuit

μ is the permeability of core

A is the area of magnetic circuit through which flux flows

Substitute, Equation 2 in Equation 1.

$L=N^2/(l/\mu A)$

$\Rightarrow L=N^2\mu A/l$ Equation 3

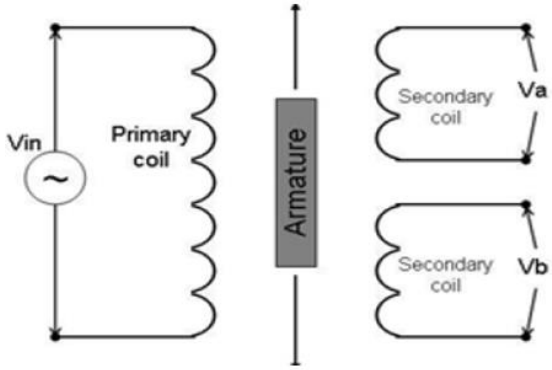
From Equation 1 & Equation 3, we can conclude that the inductance value depends on the three parameters N,S & μ.

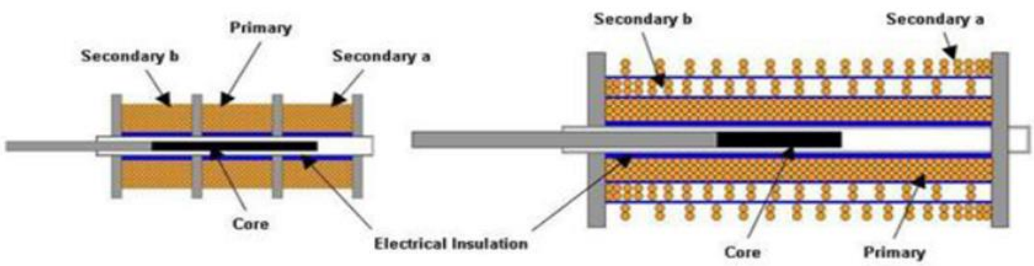
So, we can make the **inductive transducers** based on the variation in one of the three parameters N,S & μ. Because, the variation in any one of those three parameters changes the inductance value.

Inductance, L is directly proportional to square of the **number of turns of coil**. So, as number of turns of coil, N increases the value of inductance, L also increases. Similarly, as number of turns of coil, N decreases the value of inductance, L also decreases.

Inductance, L is inversely proportional to **reluctance of coil**, S. So, as reluctance of coil, S increases the value of inductance, L decreases. Similarly, as reluctance of coil, S decreases the value of inductance, L increases.

Inductance, L is directly proportional to **permeability of core**, μ. So, as permeability of core, μ increases the value of inductance, L also increases. Similarly, as permeability of core, μ decreases the value of inductance, L also decreases.





The LVDT: construction and principle of operation

Inductive Transducer

1. Magnetic circuit transducer
   Principle of operation: Self inductance or mutual inductance of ac-excited coil is varied by changes in the magnetic circuit.
   Applications: Pressure, displacement

2. Reluctance pickup
   Principle of operation: Reluctance of the magnetic circuit is varied by changing the position of the iron core of a coil.
   Applications: Pressure, displacement, vibration, position

3. Differential transformer
   Principle of operation: The differential voltage of two secondary windings of a transformer is varied by positioning the magnetic core through an externally applied force. Applications:
   Applications: Pressure, force, displacement, position

4. Eddy current gage
   Principle of operation: Inductance of a coil is varied by the proximity of an eddy current plate.
   Applications: Displacement, thickness

5. Magnetostriction gauge
   Principle of operation: Magnetic properties are varied by pressure and stress.
   Applications: Force, pressure, sound

Capacitive Transducer

A passive transducer is said to be a **capacitive transducer**, when it produces the variation (change) in capacitance value, the following formula for **capacitance**, **C** of a parallel plate capacitor.

$$\mathbf{C = \varepsilon\ A\ d}$$

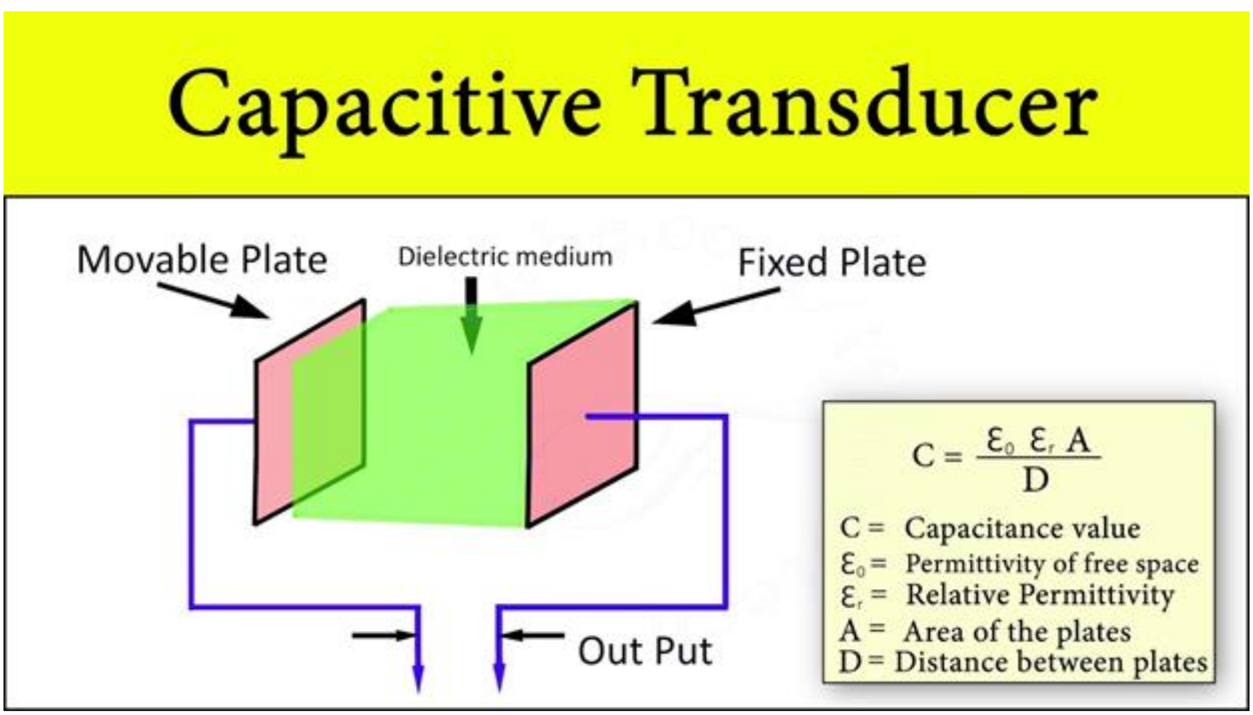
where, **ε** is the **permittivity or the dielectric constant**, **A** is the **effective area of two plates**, **d** is the **effective area of two plates**

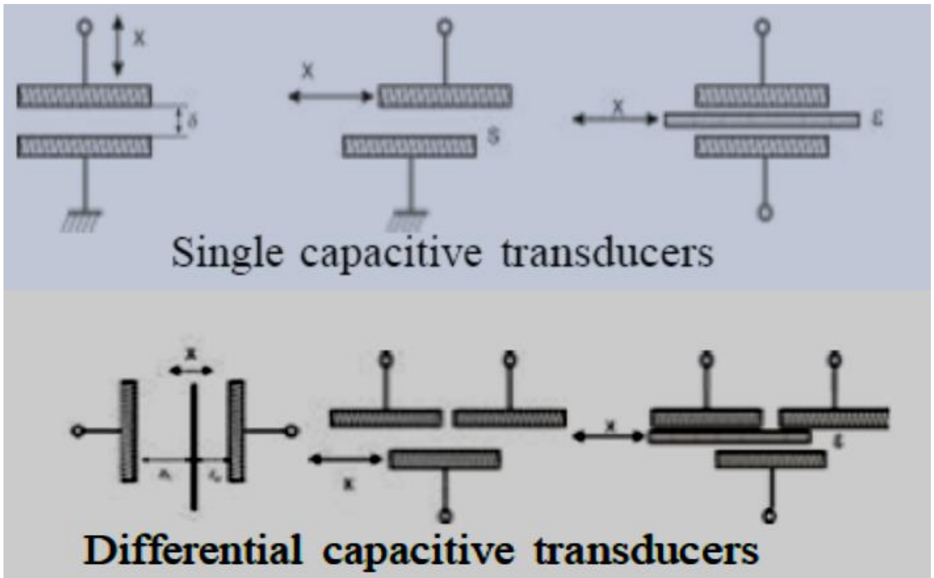
The capacitance value depends on the three parameters **ε, A & d**.

So, we can make the **capacitive transducers** based on the variation in one of the three parameters **ε, A & d**.

Because, the variation in any one of those three parameters changes the capacitance value.

- Capacitance, **C** is directly proportional to **permittivity**, **ε**.
- So, as permittivity, ε increases the value of capacitance, **C** also increases. Similarly, as permittivity, **ε** decreases the value of capacitance, **C** also decreases.
- Capacitance, **C** is directly proportional to the **effective area of two plates**, **A**.
- So, as effective area of two plates, **A** increases the value of capacitance, **C** also increases.
- Similarly, as effective area of two plates, **A** decreases the value of capacitance, **C** also decreases.
- Capacitance, **C** is inversely proportional to the **distance between two plates**, **d**.
- So, as distance between two plates, **d** increases the value of capacitance, **C** decreases.
- Similarly, as distance between two plates, **d** decreases the value of capacitance, **C** increases.
- Capacitive transducers are capacitors that change their capacity under the influence of the input magnitude, which can be linear or angular movement.





1. Variable capacitance pressure gage -

   Principle of operation: Distance between two parallel plates is varied by an externally applied force

   Applications: Measurement of Displacement, pressure

2. Capacitor microphone

   Principle of operation: Sound pressure varies the capacitance between a fixed plate and a movable diaphragm.

   Applications: Speech, music, noise

3. Dielectric gauge

   Principle of operation: Variation in capacitance by changes in the dielectric.

   Applications: Liquid level, thickness

Voltage and current Transducers

1. Hall effect pickup
   Principle of operation: A potential difference is generated across a semiconductor plate (germanium) when magnetic flux interacts with an applied current. Applications: Magnetic flux, current
2. Ionization chamber
   Principle of operation: Electron flow induced by ionization of gas due to radioactive radiation. Applications: Particle counting, radiation
3. Photoemissive cell
   Principle of operation: Electron emission due to incident radiation on photoemissive surface. Applications: Light and radiation
4. Photomultiplier tube
   Principle of operation: Secondary electron emission due to incident radiation on photosensitive cathode. Applications: Light and radiation, photo-sensitive relays

Model Questions

1. Explain Generalized Measurement System with neat diagram.
2. Draw and explain the Generalized Measurement System and various elements of the Bourdon Tube Pressure Gauge
3. Explain the Static and Dynamic performance characteristics of measurement system.
4. Explain various types of Errors in Measurements with suitable examples
5. Differentiate between static and dynamic characteristics of measuring instruments.
6. Explain the Calibration procedure and its importance in measurement system.
7. Explain various Standards used in measurement system with examples
8. Explain the performance characteristics of Zero Order, First Order and Second Order Systems
9. Classify Sensors and Transducers with their applications
10. Explain the working principles of resistive type transducers with governing equations.
11. Explain the general working principles of capacitive type transducers with governing equations.
12. Explain the working principles of inductive type transducers with governing equations.
13. Compare active and passive sensors with examples
14. Explain Static characteristics, Systematic errors and Random errors in detail
15. Explain various types of transducers with neat sketches

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHATRONICS ENGINEERING

UNIT II - Measurement of Non Electrical Parameters - 1- SMR1302

SMR1302 SENSORS AND INSTRUMENTATION

UNIT II - MEASUREMENT OF NON ELECTRICAL PARAMETERS - 1

TOPICS:

Linear and angular displacement: Resistive, capacitive, inductive types and Optics (encoders), proximity sensors, Velocity measurement: Tachometers, tacho-generators and resolvers, Temperature measurement: Contact type: Bimetallic, RTD, Thermocouple and Thermistor, Non - Contact type: Radiation Pyrometer – Optical Pyrometer, Humidity: Capacitive and resistive and hot and wet bulbs. Other sensors: Fire, smoke and metal detectors.

Linear and angular displacement: -

Displacement and Position sensors

- Displacement sensors are basically used for the measurement of movement of an object.
- Position sensors are employed to determine the position of an object in relation to some reference point.

➢ Proximity sensors are a type of position sensor and are used to trace when an object has moved with in particular critical distance of a transducer.

Resistive displacement sensors

Resistive displacement sensors are commonly **termed as Potentiometers or "POTS**." A pot is an **electromechanical device** containing an **electrically conductive** ***wiper*** that slides against a **fixed** ***resistive element*** according to the position or angle of an external shaft (Figure 1.). Electrically, the resistive element is "divided" at the point of wiper contact. To measure displacement, a pot is typically wired in a "voltage divider" configuration, as shown in Figure 2. The circuit's output, a function of the wiper's position, is **an analog voltage** available for **direct use or digitization**. Calibration maps the output voltage to units of displacement. Versatile, inexpensive, and easy- to-use, pots are a popular choice for precision measurement. Precision pots are available in *rotary*, *linear-motion*, and *string pot* forms. **String pots — also called** ***Cable pots***, ***Yo-yo pots***, ***Cable extension transducers***, and ***Draw wire transducers***- measure the extended length of a spring-loaded cable. **Rotary pots** are available with **single or multiturn** abilities: commonly 3, 5, or 10 turns. **Linear-motion pots** are available with maximum strokes ranging from **roughly 5 mm to over 4 m**. **String pots** are available with **maximum extensions exceeding 50 m**. Pot manufacturers usually specify a pot's type, dimensions, resistive element composition, electrical and mechanical parameters, and mounting method.

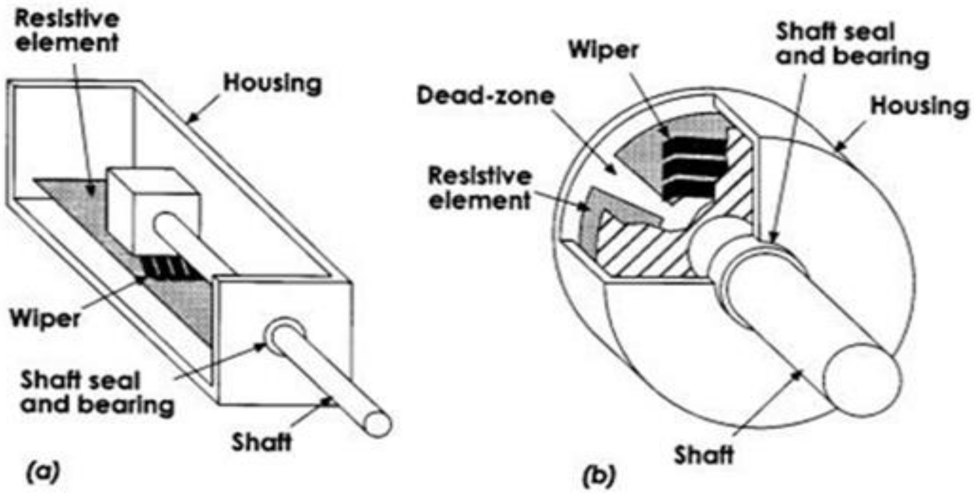


FIGURE 1 Representative cutaways of linear-motion (*a*) and rotary (*b*) potentiometers.

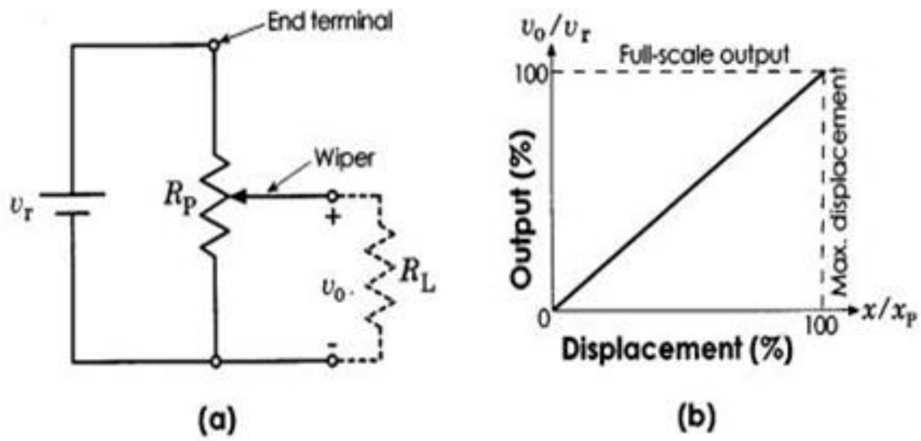


FIGURE 2 (*a*) Schematic diagrams depict a potentiometer as a resistor with an arrow representing the wiper. This schematic shows a pot used as a variable voltage divider — the preferred configuration for precision measurement. R_P is the total resistance of the pot, R_L is the load resistance, v_r is the reference or supply voltage, and v_o is the output voltage. (*b*) shows an ideal linear output function where *x* represents the wiper position, and x_P is its maximum position.

Potentiometer Elements:

Resistive Element: Broadly, a pot's resistive element can be **classified as either *wirewound*, or *nonwirewound***.

Wirewound elements contain **tight coils of resistive wire** that quantize measurement in **step-like increments**. In contrast, **nonwirewound** elements present a **continuous sheet of resistive material capable** of essentially unlimited measurement resolution.

Wirewound elements **offer excellent temperature stability** and **high power dissipation abilities**.

The coils quantize measurement according to **wire size and spacing**. Providing the resolution limits are acceptable, wirewound elements can be a satisfactory choice for precision measurement; however, conductive plastic or hybrid elements will usually perform better and for considerably more cycles.

Conductive plastic elements feature a smooth film with unlimited resolution, low friction, low noise, and long operational life.

They are **sensitive to temperature and other environmental factors** and their **power dissipation abilities** are **low**; however, they are an excellent choice for **most precision measurement applications**.

Hybrid elements feature a **wirewound core** with a **conductive plastic coating**, combining wirewound and conductive plastic technologies to realize some of the more desirable attributes of both.

The plastic limits power dissipation abilities in exchange for low noise, long life, and unlimited resolution. Like wirewounds, hybrids offer excellent temperature stability. They make an excellent choice for precision measurement.

Cermet elements, made from a **ceramic-metal alloy**, offer **unlimited resolution and reasonable noise levels**. Their advantages include **high power dissipation abilities** and **excellent stability in adverse conditions**. Cermet elements are rarely applied to precision measurement because conductive plastic elements offer lower noise, lower friction, and longer life.

Carbon composition elements, molded under pressure from a carbon–plastic mixture, **are inexpensive** and very popular for general use, but **not for precision measurement**. They offer **unlimited resolution and low noise**, but are **sensitive to environmental stresses** (e.g., temperature, humidity) and are **subject to wear**.

Displacement sensors

1. Potentiometer Sensors

Figure 1 shows the construction of a rotary type potentiometer sensor employed to measure the linear displacement. The potentiometer can be of linear or angular type. It works on the principle of conversion of mechanical displacement into an electrical signal.

The sensor has a resistive element and a sliding contact (wiper). The slider moves along this conductive body, acting as a movable electric contact. The object of whose displacement is to be measured is connected to the slider by using

• a rotating shaft (for angular displacement)

• a moving rod (for linear displacement)

• a cable that is kept stretched during operation

The resistive element is a wire wound track or conductive plastic. The track comprises of large number of closely packed turns of a resistive wire. Conductive plastic is made up of plastic resin embedded with the carbon powder. Wire wound track has a resolution of the order of ±

0.01 % while the conductive plastic may have the resolution of about 0.1 μm. During the sensing operation, a voltage *Vs* is applied across the resistive element. A voltage divider circuit is formed when slider comes into contact with the wire.

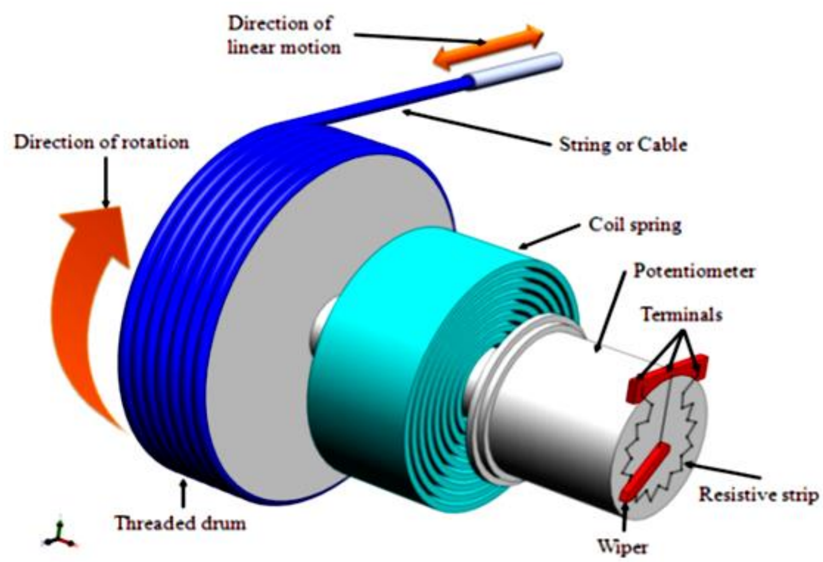


Figure 1 Schematic of a potentiometer sensor for measurement of linear displacement

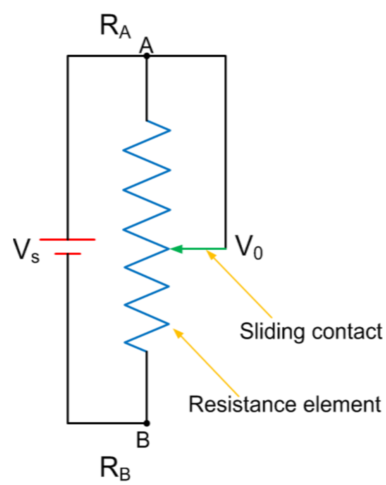


Figure 2 Potentiometer: electric circuit

The output voltage (*VA*) is measured as shown in the figure 2. The output voltage is proportional to the displacement of the slider over the wire. Then the output parameter displacement is calibrated against the output voltage *VA.*

$$VA = I\ RA \qquad (1)$$

$$\text{But } I = VS / (RA + RB) \qquad (2)$$

$$\text{Therefore } VA = VS\ RA / (RA + RB) \qquad (3)$$

As we know that $R = \rho\ L / A$,

where ρ is electrical resistivity, L is length of resistor and A is area of cross section

$$VA = VS\ LA / (LA + LB) \qquad (4)$$

Applications of potentiometer

- These sensors are primarily used in the **control systems with a feedback loop** to ensure that the moving member or component reaches its commanded position.
- These are typically used on **machine-tool controls, elevators, liquid-level assemblies, forklift trucks, automobile throttle controls.**
- In manufacturing, these are used in **control of injection molding machines, woodworking machinery, printing, spraying, robotics,** etc.
- These are also used in **computer-controlled monitoring of sports equipment.**

Strain Gauges

The strain in an element is a ratio of change in length in the direction of applied load to the original length of an element. The strain changes the resistance *R* of the element. Therefore, we can say,

$$\Delta R/R \ \alpha \ \varepsilon;$$

$$\Delta R/R = G\ \varepsilon \quad (1)$$

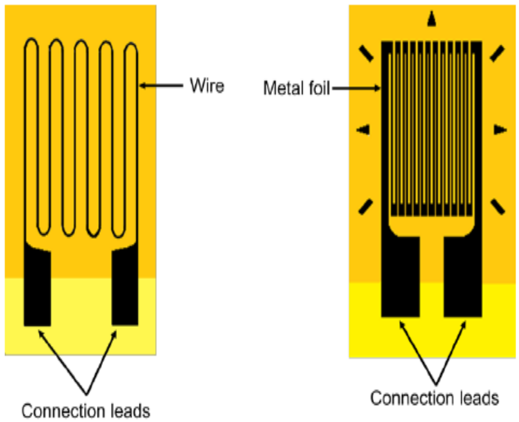
where **G** is the constant of proportionality and is called as **gauge factor.**

In general, the value of G is considered in between 2 to 4 and the resistances are taken of the order of 100 Ω. Resistance strain gauge follows the principle of change in resistance as per the equation 1. It comprises of a pattern of resistive foil arranged as shown in Figure. These foils are made of Constantan alloy (copper-nickel 55-45% alloy) and are **bonded to a backing material plastic (ployimide), epoxy or glass fiber reinforced epoxy**. The strain gauges are secured to the work piece by using epoxy or Cyanoacrylate cement Eastman 910 SL. As the work piece undergoes change in its shape due to external loading, the resistance of strain gauge element changes. This change in resistance can be detected by a using a Wheatstone's resistance bridge as shown in Figure. In the balanced bridge we can have a relation,

$$R2 / R1 = Rx / R3 \qquad (6)$$

where *Rx* is resistance of strain gauge element, R2 is balancing/adjustable resistor, *R1* and *R3* are known constant value resistors.

The measured deformation or displacement by the stain gauge is calibrated against change in resistance of adjustable resistor *R2* which makes the voltage across nodes A and B equal to zero.



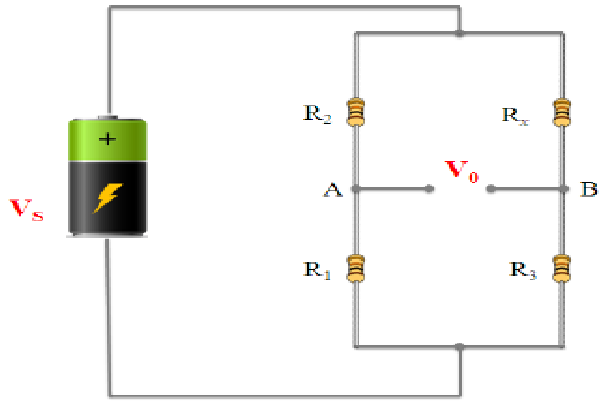


Figure 1: A pattern of resistive foils **Figure 2: Wheatstone's bridge**

Applications of strain gauges

Strain gauges are widely used in **experimental stress analysis** and **diagnosis on machines and failure analysis.**

They are basically used for **multi-axial stress fatigue testing**, **proof testing**, **residual stress and vibration measurement**, **torque measurement**, **bending and deflection measurement**, **compression and tension measurement** and **strain measurement.**

Strain gauges are primarily used as sensors for machine tools and safety in automotive.

In particular, they are employed for force measurement in machine tools, hydraulic or pneumatic press and as **impact sensors in aerospace vehicles**.

Linear variable differential transformer (LVDT)

Linear variable differential transformer (LVDT) is a **primary transducer used for measurement of linear displacement with an input range of about ± 2 to ± 400 mm in general**. It has non-linearity error ± 0.25% of full range.

It has three coils symmetrically spaced along an insulated tube. The central coil is primary coil and the other two are secondary coils. Secondary coils are connected in series in such a way that their outputs oppose each other.

A magnetic core attached to the element of which displacement is to be monitored is placed inside the insulated tube. Due to an alternating voltage input to the primary coil, alternating electro-magnetic forces (emfs) are generated in secondary coils. When the magnetic core is centrally placed with its half portion in each of the secondary coil regions then the resultant voltage is zero. If the core is displaced from the central position as shown in Figure, say, more in secondary coil 1 than in coil 2, then more emf is generated in one coil i.e. coil 1 than the other, and there is a resultant voltage from the coils. If the magnetic core is further displaced, then the value of resultant voltage increases in proportion with the displacement. With the help of signal processing devices such as low pass filters and demodulators, precise displacement can be measured by using LVDT sensors. LVDT exhibits good repeatability and reproducibility.

It is generally used as an absolute position sensor. Since there is no contact or sliding between the constituent elements of the sensor, it is highly reliable. These sensors are completely sealed and are widely used in Servomechanisms, automated measurement in machine tools. A rotary variable differential transformer (RVDT) can be used for the measurement of rotation. Readers are suggested to prepare a report on principle of working and construction of RVDT sensor.

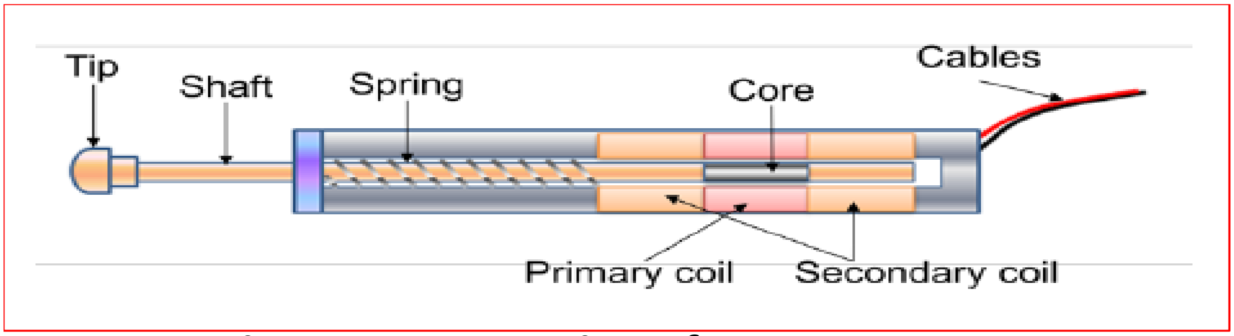


Figure: Construction of a LVDT sensor

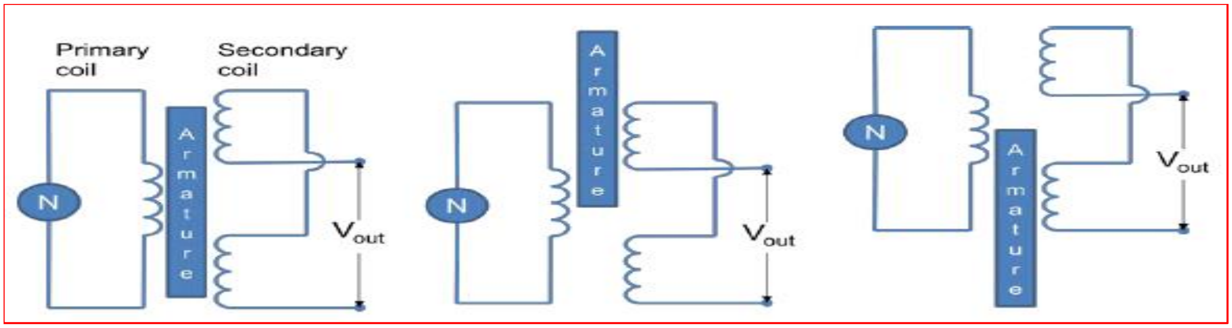


Figure: Working of LVDT sensor

Applications of LVDT sensors

- Measurement of spool position in a wide range of servo valve applications
- To provide displacement feedback for hydraulic cylinders
- To control weight and thickness of medicinal products viz. tablets or pills
- For automatic inspection of final dimensions of products being packed for dispatch
- To measure distance between the approaching metals during Friction welding process
- To continuously **monitor fluid level as part of leak detection system**
- To **detect the number of currency bills dispensed by an ATM**

Pneumatic sensors

Pneumatic sensors are used to measure the displacement as well as to sense the proximity of an object close to it. The displacement and proximity are transformed into change in air pressure.

Figure shows a schematic of construction and working of such a sensor. It comprises of three ports. Low pressure air is allowed to escape through port A. In the absence of any obstacle / object, this low pressure air escapes and in doing so, reduces the pressure in the port B. However when an object obstructs the low pressure air (Port A), there is rise in pressure in output port B. This rise in pressure is calibrated to measure the displacement or to trigger a switch. **These sensors are used in robotics, pneumatics and for tooling in CNC machine tools.**

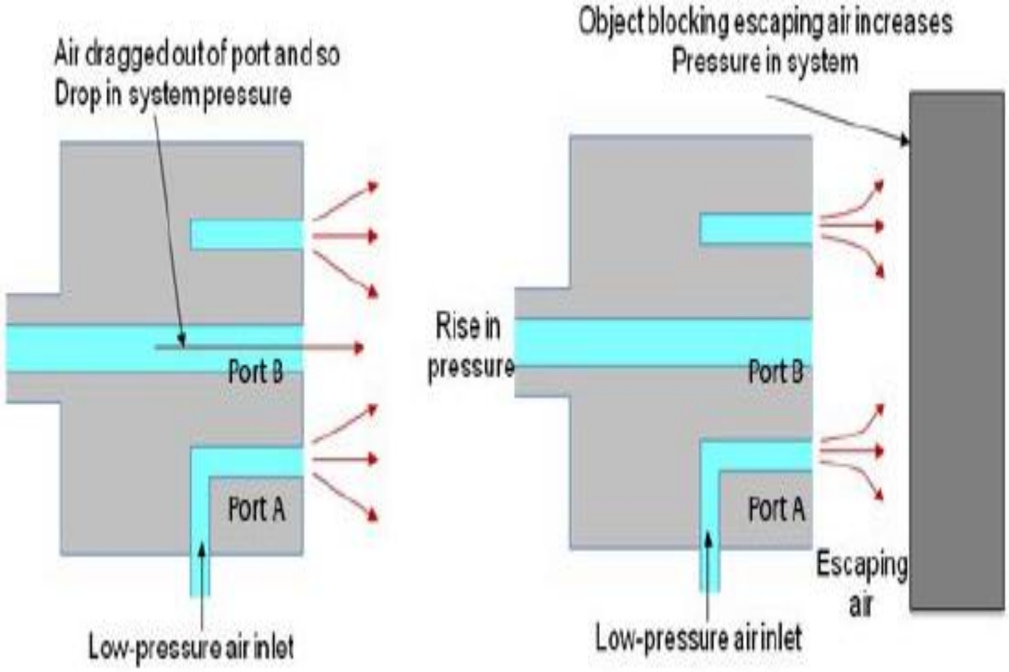


Figure: Working of Pneumatic Sensors

Proximity Switches

Figure shows a number of configurations of contact-type proximity switch being used in manufacturing automation. These are small electrical switches which require physical contact and a small operating force to close the contacts. They are basically employed on conveyor systems to detect the presence of an item on the conveyor belt. Magnet based Reed switches are used as proximity switches. When a magnet attached to an object brought close to the switch, the magnetic reeds attract to each other and close the switch contacts. A schematic is shown in Figure. Photo emitting devices such as Light emitting diodes (LEDs) and photosensitive devices such as **photo diodes and photo transistors** are used in combination to work as proximity sensing devices. Figure shows two typical arrangements of LEDs and photo diodes to detect the objects breaking the beam and reflecting light.

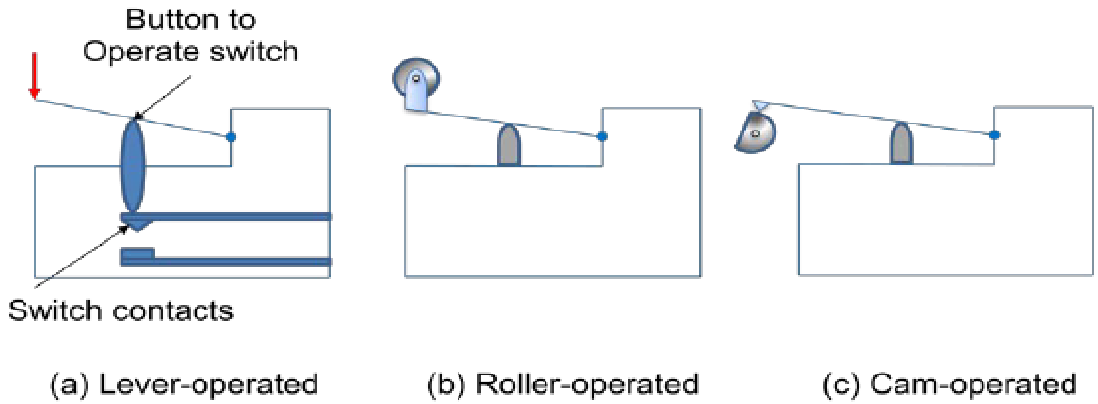


Figure 1 : Configurations of contact type proximity switch

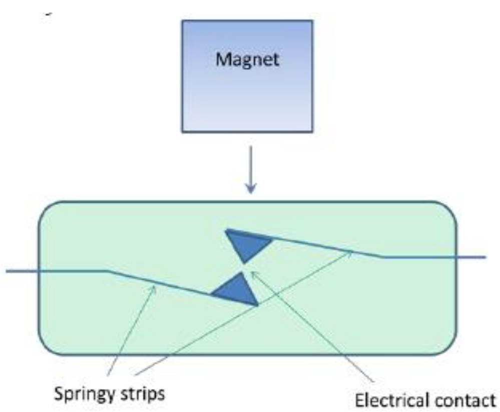


Figure 2 : Reed Switch

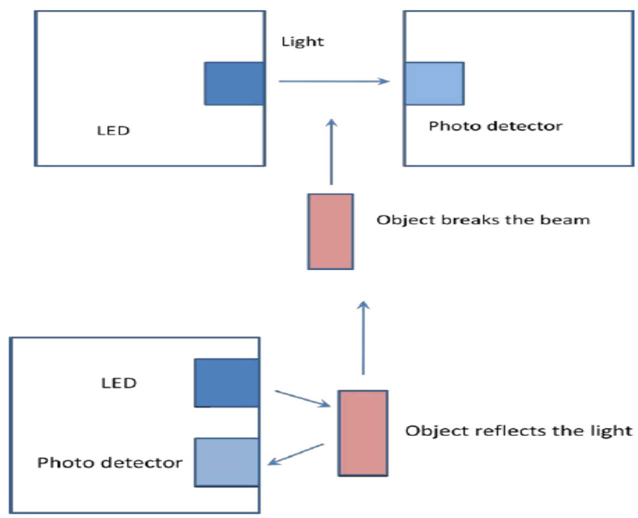


Figure 3: LED based proximity sensors

Hall effect sensors

Hall effect sensors work on the principle that when a beam of charge particles passes through a magnetic field, forces act on the particles and the current beam is deflected from its straight line path. Thus one side of the disc will become negatively charged and the other side will be of positive charge. This charge separation generates a potential difference which is the measure of distance of magnetic field from the disc carrying current. The typical application of Hall effect sensor is the measurement of fluid level in a container. The container comprises of a float with a permanent magnet attached at its top. An electric circuit with a current carrying disc is mounted in the casing. When the fluid level increases, the magnet will come close to the disc and a potential difference generates. This voltage triggers a switch to stop the fluid to come inside the container. These sensors are used for the measurement of displacement and the detection of position of an object. Hall effect sensors need necessary signal conditioning circuitry. They can be operated at 100 kHz. Their non-contact nature of operation, good immunity to environment contaminants and ability to sustain in severe conditions make them quite popular in industrial automation.

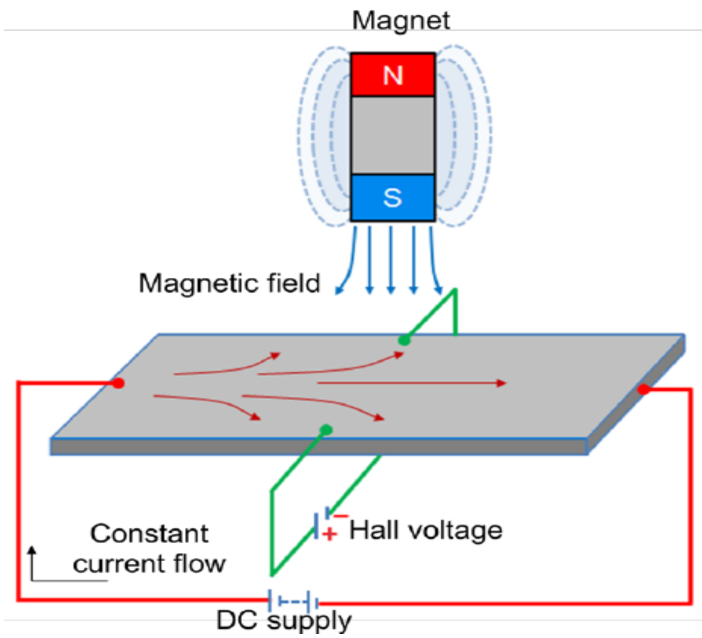


Figure :The principle of working of Hall effect sensor

Proximity sensors

Proximity sensors detect the presence or absence of objects using electromagnetic fields, light, and sound. There are many types, each suited to specific applications and environments.

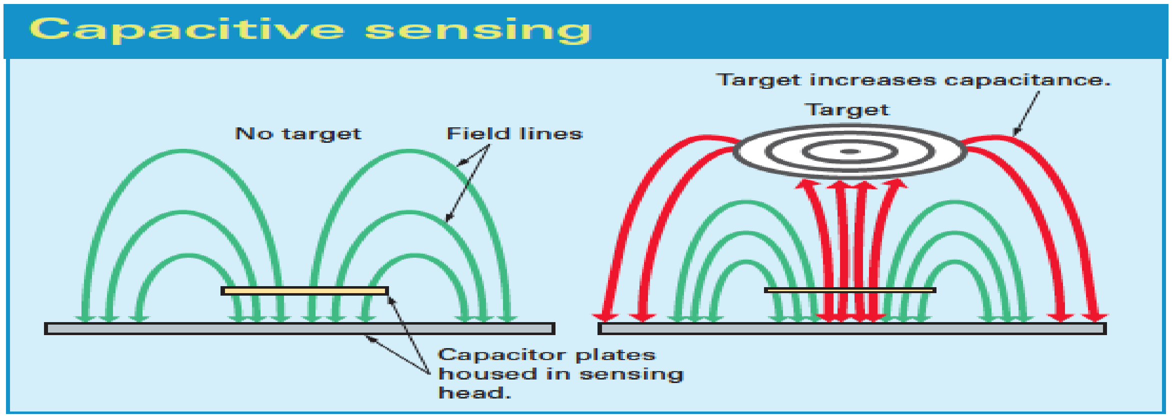
Types of Proximity Sensor:

- Inductive **Proximity Sensor**.
- Optical **Proximity Sensor**.
- Capacitive **Proximity Sensor**.
- Magnetic **Proximity Sensor**.
- Ultrasonic **proximity Sensor**

Capacitive sensors

Capacitive proximity sensors can detect both metallic and non-metallic targets in powder, granulate, liquid, and solid form.

This, along with their ability to sense through nonferrous materials, makes them ideal for sight glass monitoring, tank liquid level detection, and hopper powder level recognition.



As a ferrous or nonferrous target enters the sensing zone, capacitance increases; circuit natural frequency shifts towards the oscillation frequency, causing amplitude gain.

In capacitive sensors, the two conduction plates (at different potentials) are housed in the sensing head and positioned to operate like an open capacitor.

Air acts as an insulator; at rest there is little capacitance between the two plates. Like inductive sensors, these plates are linked to an oscillator, a Schmitt trigger, and an output amplifier. As a target enters the sensing zone the capacitance of the two plates increases, causing oscillator amplitude change, in turn changing the Schmitt trigger state, and creating an output signal.

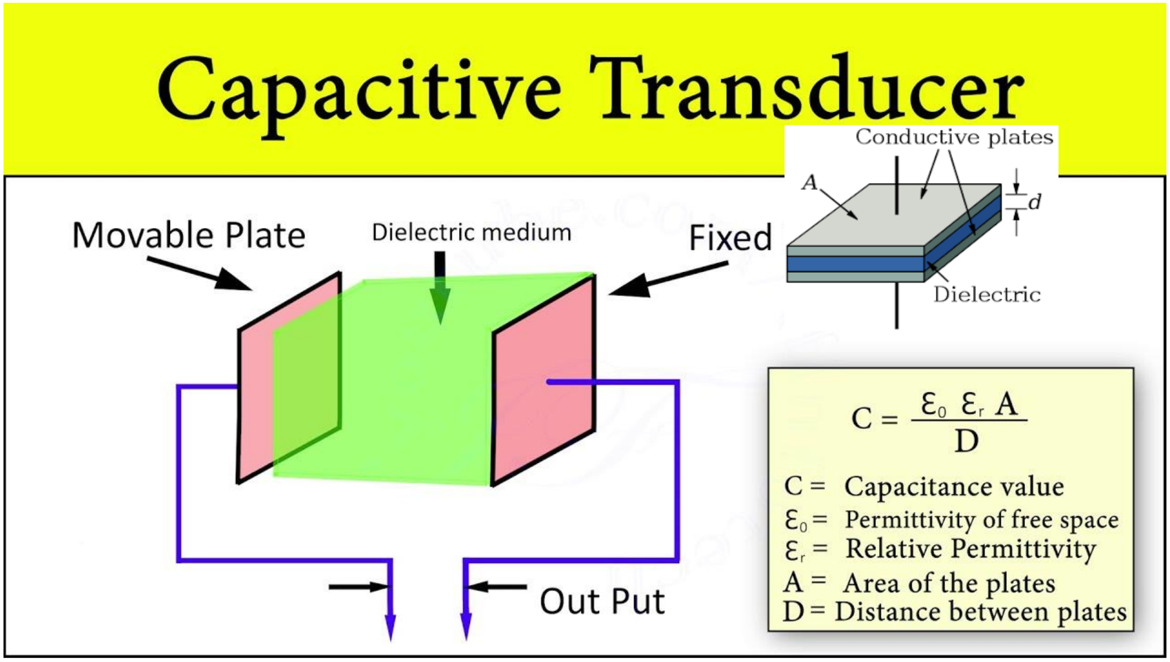
Note the difference between the inductive and capacitive sensors: inductive sensors oscillate until the target is present and capacitive sensors oscillate when the target is present. Because capacitive sensing involves charging plates, it is somewhat slower than inductive sensing ... ranging from 10 to 50 Hz, with a sensing scope from 3 to 60 mm.

Many housing styles are available; common diameters range from 12 to 60 mm in shielded and unshielded mounting versions. Housing (usually metal or PBT plastic) is rugged to allow mounting very close to the monitored process.

If the sensor has normally-open and normally-closed options, it is said to have a complimentary output.

- Due to their ability to detect most types of materials, capacitive sensors must be kept away from non-target materials to avoid false triggering.
- For this reason, if the intended target contains a ferrous material, an inductive sensor is a more reliable option.

- Capacitive sensor is of non-contact type sensor and is primarily used to measure the linear displacements from few millimeters to hundreds of millimeters.
- It comprises of three plates, with the upper pair forming one capacitor and the lower pair another.



The linear displacement might take in two forms:

a. one of the plates is moved by the displacement so that the plate separation changes

b. area of overlap changes due to the displacement.

Figure 2.2.5 shows the schematic of three-plate capacitive element sensor and displacement measurement of a mechanical element connected to the plate 2.

The capacitance C of a parallel plate capacitor is given by,

$$C = \varepsilon r\ \varepsilon o\ A / d \qquad (1)$$

where *εr* is the relative permittivity of the dielectric between the plates, *εo* permittivity of free space, *A* area of overlap between two plates and *d* the plate separation. As the central plate moves near to top plate or bottom one due to the movement of the element/workpiece of which displacement is to be measured, separation in between the plate changes. This can be given as,

$$C1 = (\varepsilon r\ \varepsilon o\ A) / (d + x) \qquad (2)$$

$$C2 = (\varepsilon r\ \varepsilon o\ A) / (d - x) \qquad (3)$$

When C1 and C2 are connected to a Wheatsone’s bridge, then the resulting out-of-balance voltage would be in proportional to displacement x.

Capacitive elements can also be used as proximity sensor. The approach of the object towards the sensor plate is used for induction of change in plate separation. This changes the capacitance which is used to detect the object.

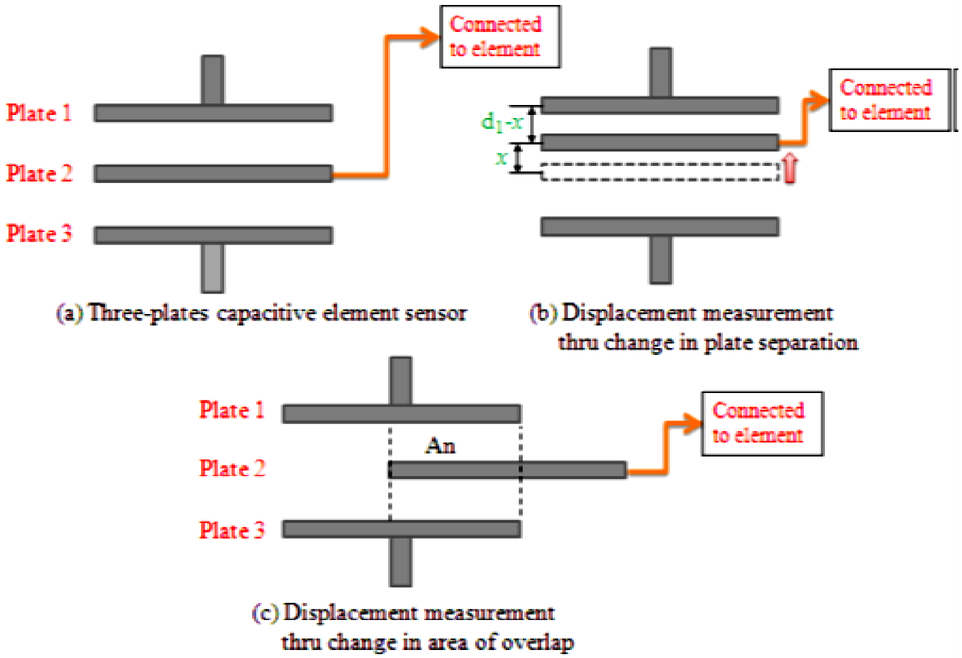


Figure. Displacement measurement using capacitive element sensor

Applications of capacitive element sensors

- Feed hopper level monitoring
- Small vessel pump control
- Grease level monitoring
- Level control of liquids
- Metrology applications

➢ to measure shape errors in the part being produced

➢ to analyze and optimize the rotation of spindles in various machine tools such as surface grinders, lathes, milling machines, and air bearing spindles by measuring errors in the machine tools themselves

➢ Assembly line testing

❖ to test assembled parts for uniformity, thickness or other design features

❖ to detect the presence or absence of a certain component, such as glue etc

Inductive sensors

Inductive sensors are widely used in industry in many diverse applications.

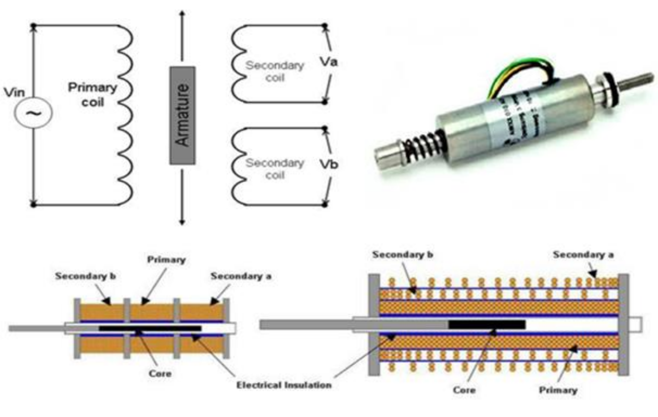
They are robust and compact, and are less affected by environmental factors (e.g., humidity, dust) in comparison to their capacitive counterparts. Inductive sensors are primarily based on the principles of magnetic circuits.

They can be classified as self-generating or passive. The **self-generating types** utilize an **electrical generator principle**; that is, when there is a relative motion between a conductor and a magnetic field, a voltage is induced in the conductor.

Or, a **varying magnetic field linking a stationary conductor produces** voltage in the conductor.

In instrumentation applications, the magnetic field may be varying with some frequency and the conductor may also be moving at the same time.

In inductive sensors, the relative motion between field and conductor is supplied by **changes in the measurand**, usually by means of some mechanical motion. On the other hand, the passive transducer requires an external source of power. In this case, the action of the transducer is simply the **modulation of the excitation signal.**



The LVDT: construction and principle of operation

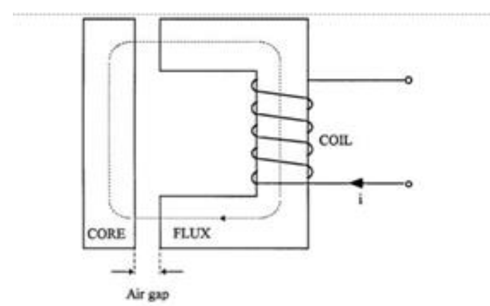


FIGURE 6.7 A basic inductive sensor consists of a magnetic circuit made from a ferromagnetic core with a coil wound on it. The coil acts as a source of magnetomotive force (mmf) that drives the flux through the magnetic circuit and the air gap. The presence of the air gap causes a large increase in circuit reluctance and a corresponding decrease in the flux. Hence, a small variation in the air gap results in a measurable change in inductance.

For the explanation of the basic principles of inductive sensors, a simple magnetic circuit is shown in Figure. The magnetic circuit consists of a core, made from a ferromagnetic materia,l with a coil of *n* number of turns wound on it. The coil acts as a source of magnetomotive force (mmf) which drives the flux Φ through the magnetic circuit.

If one assumes that the air gap is zero, the equation for the magnetic circuit can be expressed as:

- such that the reluctance limits the flux in a magnetic circuit just as resistance limits the current in an electric circuit. By writing the mmf in terms of current, the magnetic flux may be expressed as:

- In Figure the flux linking a single turn is by Equation 3; but the total flux linking by the entire *n* number of the turns of the coil is

$$\text{mmf} = \text{Flux} \times \text{Reluctance} = \Phi \times A - \text{turns} \quad (1)$$

$$\Phi = ni \text{ weber} \quad (2)$$

$$\Psi = n\Phi = n2i \text{ weber} \quad (3)$$

$$L = \Psi\, I = n2 \quad (4)$$

Equation 4 leads to self inductance *L* of the coil, which is described as the total flux (Ψ weber) per unit current for that particular coil; that is

This indicates that the self inductance of an inductive element can be calculated by magnetic circuit properties. Exprssing in terms of dimensions as:

$$= l\ \mu\mu 0\ A \quad (5)$$

where l e= the total length of the flux path

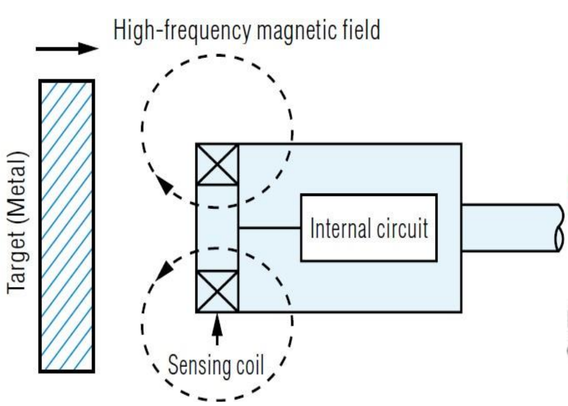
μ = the relative permeability of the magnetic circuit material

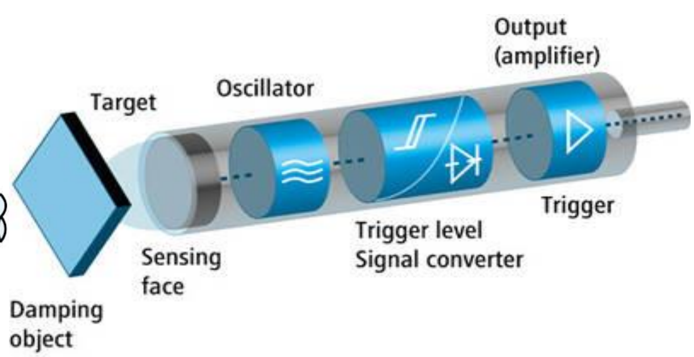
= the permeability of free space

$\mu 0$ (= $4\pi \times 10{-}7$ H/m)

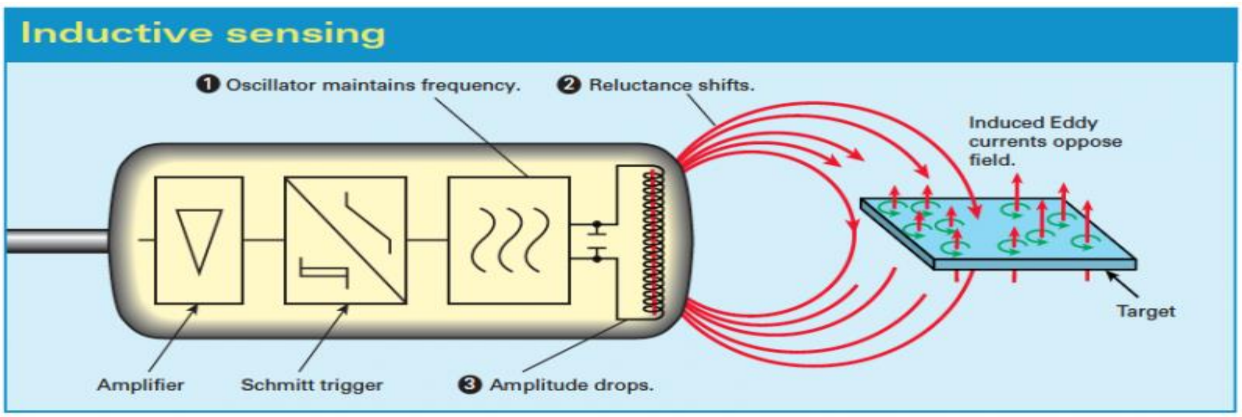
A = the cross-sectional area of the flux path

- An **inductive proximity sensor** is a non-contact electronic **proximity sensor**.
- It is used for positioning and detection of metal objects.
- The sensing range of an **inductive** switch is dependent on the type of metal being detected.
- The **sensor** consists of an induction loop or detector coil.





- These non-contact proximity sensors detect ferrous targets, ideally mild steel thicker than one millimeter.
- They consist of four major components: a *ferrite core* with *coils*, an *oscillator*, a *Schmitt trigger*, and an *output amplifier*.
- The oscillator creates a symmetrical, oscillating magnetic field that radiates from the ferrite core and coil array at the sensing face.
- When a ferrous target enters this magnetic field, small independent electrical currents called eddy currents are **induced** on the metal's surface.
- This changes the reluctance (natural frequency) of the magnetic circuit, which in turn reduces the oscillation amplitude. As more metal enters the sensing field the oscillation amplitude shrinks, and eventually collapses.
- (This is the "Eddy Current Killed Oscillator" or ECKO principle.)



Ferrous targets change the reluctance of the magnetic circuit; system oscillation frequency, which gets left behind when the natural frequency shifts, then loses amplitude.

- The Schmitt trigger responds to these amplitude changes, and adjusts sensor output.
- When the target finally moves from the sensor's range, the circuit begins to oscillate again, and the Schmitt trigger returns the sensor to its previous output.
- If the sensor has a **normally open** configuration, its output is an **on** signal when the target enters the sensing zone. With *normally closed*, its output is an *off* signal with the target present.
- Output is then read by an external control unit (e.g. PLC, motion controller, smart drive) that converts the sensor on and off states into useable information. Inductive sensors are typically rated by frequency, or on/off cycles per second.
- Their speeds range from 10 to 20 Hz in ac, or 500 Hz to 5 kHz in dc. Because of magnetic field limitations, inductive sensors have a relatively narrow sensing range — from fractions of millimeters to 60 mm on average — though longer-range specialty products are available.

- To accommodate close ranges in the tight confines of industrial machinery, geometric and mounting styles available include shielded (flush), unshielded (non-flush), tubular, and rectangular “flat-pack”.
- Tubular sensors, by far the most popular, are available with diameters from 3 to 40 mm.
- But what inductive sensors lack in range, they make up in environment adaptability and metal-sensing versatility.
- With no moving parts to wear, proper setup guarantees long life.
- Special designs with IP ratings of 67 and higher are capable of withstanding the buildup of contaminants such as cutting fluids, grease, and non-metallic dust, both in the air and on the sensor itself.
- It should be noted that metallic contaminants (e.g. filings from cutting applications) sometimes affect the sensor’s performance.
- Inductive sensor housing is typically nickel-plated brass, stainless steel, or PBT plastic.

1. Eddy current proximity sensors

- Eddy current proximity sensors are used to detect non-magnetic but conductive materials.
- They comprise of a coil, an oscillator, a detector and a triggering circuit. When an alternating current is passed thru this coil, an alternative magnetic field is generated.

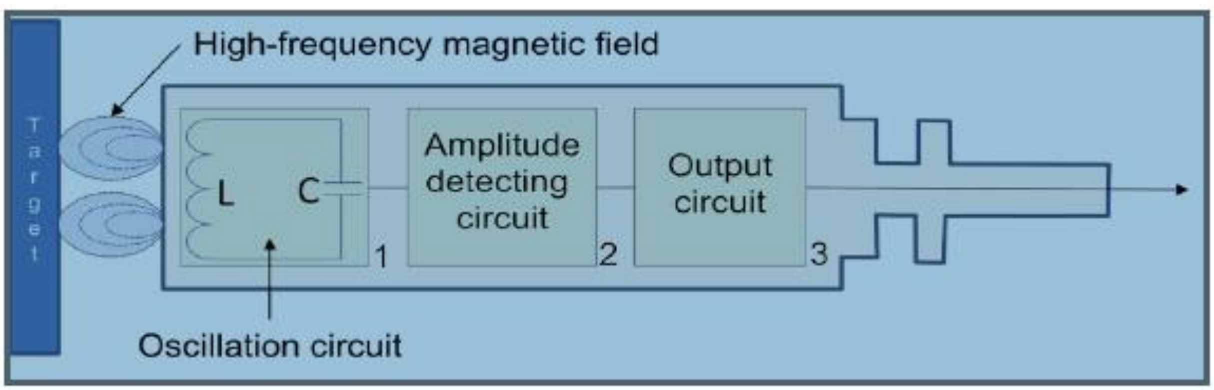


Figure shows the construction of eddy current proximity switch

- If a metal object comes in the close proximity of the coil, then eddy currents are induced in the object due to the magnetic field.
- These eddy currents create their own magnetic field which distorts the magnetic field responsible for their generation. As a result, impedance of the coil changes and so the amplitude of alternating current.
- This can be used to trigger a switch at some pre-determined level of change in current.

- Eddy current sensors are relatively inexpensive, available in small in size, highly reliable and have high sensitivity for small displacements.

Applications of eddy current proximity sensors

Automation requiring precise location

- Machine tool monitoring
- Final assembly of precision equipment such as disk drives
- Measuring the dynamics of a continuously moving target, such as a vibrating element,
- Drive shaft monitoring
- Vibration measurements

Inductive proximity switches

- Inductive proximity switches are basically used for detection of metallic objects.
- Figure shows the construction of inductive proximity switch.
- An inductive proximity sensor has four components; the coil, oscillator, detection circuit and output circuit.
- An alternating current is supplied to the coil which generates a magnetic field.
- When, a metal object comes closer to the end of the coil, inductance of the coil changes.
- This is continuously monitored by a circuit which triggers a switch when a preset value of inductance change is occurred.

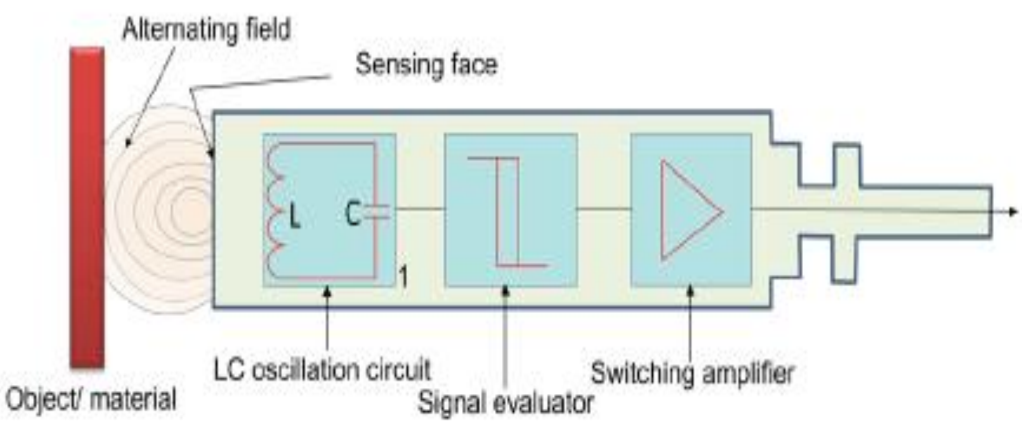
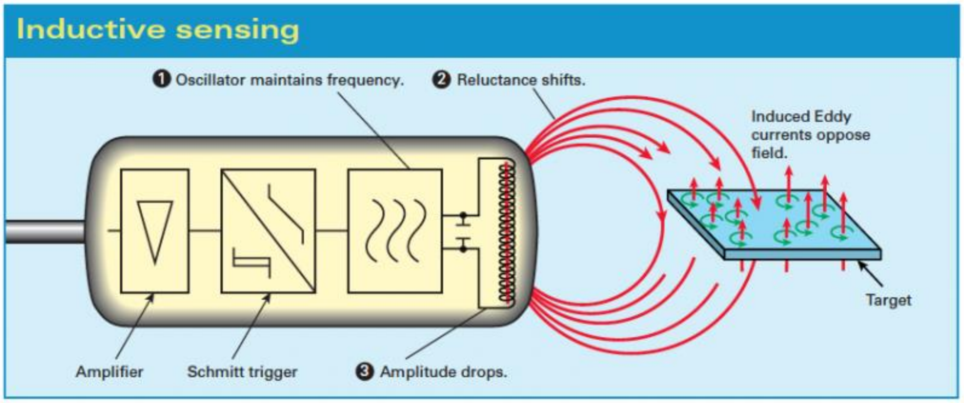


Figure . Schematic of Inductive Proximity Switch



Ferrous targets change the reluctance of the magnetic circuit; system oscillation frequency, which gets left behind when the natural frequency shifts, then loses amplitude.

Applications of inductive proximity switches

- Industrial automation: counting of products during production or transfer
- Security, • detection of metal objects, arms, land mines

Optical encoders

- Optical encoders provide digital output as a result of linear / angular displacement.
- These are widely used in the Servo motors to measure the rotation of shafts.
- Figure shows the construction of an optical encoder.

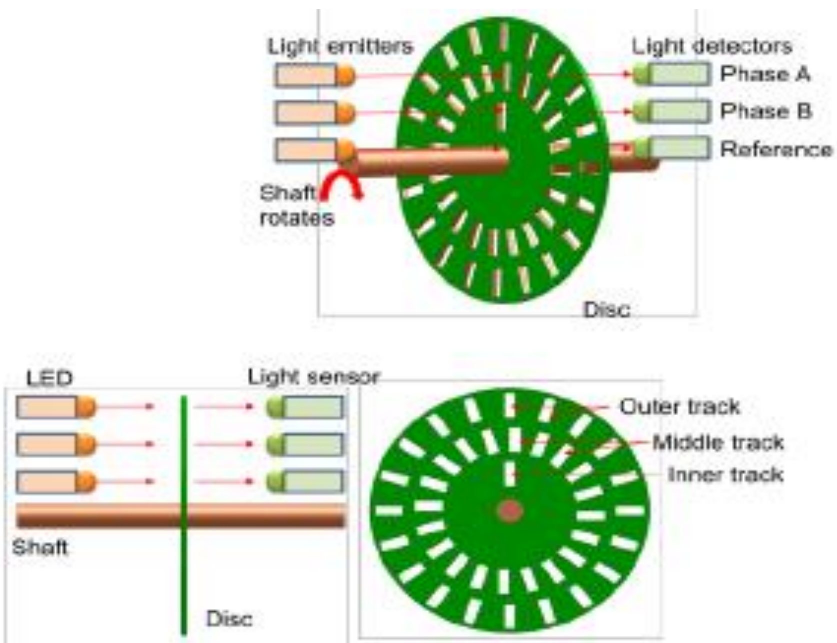


Figure Construction and working of optical encoder

It comprises of a disc with three concentric tracks of equally spaced holes. Three light sensors are employed to detect the light passing thru the holes. These sensors produce electric pulses which give the angular displacement of the mechanical element e.g. shaft on which the Optical encoder is mounted.

The inner track has just one hole which is used locate the 'home' position of the disc. The holes on the middle track offset from the holes of the outer track by one-half of the width of the hole.

This arrangement provides the direction of rotation to be determined. When the disc rotates in clockwise direction, the pulses in the outer track lead those in the inner; in counter clockwise direction they lag behind.

The resolution can be determined by the number of holes on disc. With 100 holes in one revolution, the resolution would be,

$$\mathbf{360^o/100 = 3.6^o.}$$

Velocity measurement

Tachometer

Introduction

Speed is a rate variable defined as a time-rate of motion. Common form and units of speed measurement include: linear speed expressed as m/s or km/h and angular speed of a rotating component usually expressed as revolution per minute or rad/s. Measurement of rotational speed has acquired prominence over the linear speed. Continuous measurement of linear speed is usually made in terms of angular speed and then converted in to linear speed of a reciprocating part. RPM measurement is important when controlling or monitoring the speed of motors, conveyors, turbines, etc.

Several methods for the measurement of rotational speed are available. Angular measurements are made with a device called tachometer. The word "tachometer" is derived from the Greek words *tachos*, meaning "speed," and *metron*, meaning "to measure." Tachometer may be broadly classified in to two categories: mechanical tachometer and electrical tachometer.

Mechanical Tachometer

Mechanical tachometer employs only mechanical parts and mechanical movements for the measurement of speed. Most common type of mechanical tachometers are hand tachometer and the revolution counter.

Hand-held tachometer

The hand-held tachometer is shown in Fig. 1. It consists of a worm gear attached to spindle. The worm gear meshes with a spur gear that in turn moves a pointer on calibrated dial to indicate revolutions. Generally two dials are placed in position. In one dial each division represents one revolution of the spindle while on the other on division represents the one revolution of the former. A stop watch is attached to the revolution. For measuring the speed the tachometer is manually pressed at the contact point at the rotating shaft whose speed is to be measured. The spindle starts rotating and provides motion to the pointer through the worm gear indicating the total revolution of the shaft in a given period of time noted with the help of a stop watch. The average speed is then calculated.

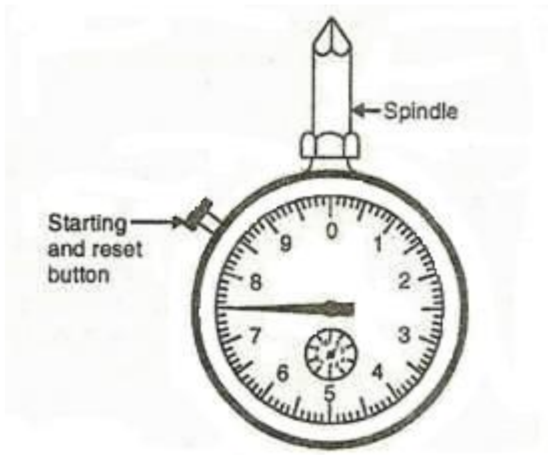


Fig.1 Hand-held tachometer

In another arrangement an automatic timer is used to indicate the speed directly in rpm on the calibrated dial. The spindle operates when brought in contact with the shaft. The counter however does not function until the start button pressed to start the watch and engage the automatic clutch. Depressing the starting knob also serves to wind the timer watch. The revolution counter automatically gets disengaged after a short period of time. These tachometers can measure up to a speed of 30000 rpm with an accuracy of 1%. The revolution counter is used with a timing device to determine the number of revolutions in a measured length of time. Thus it measures an average rotational speed over a short interval of time rather than instantaneous rotational speed.

Digital tachometers have become more common as they give numerical readings instead of using dials and needles.

Centrifugal tachometer

The principle of operation of centrifugal tachometer is that the centrifugal force is proportional to the speed of rotation. The schematic diagram of a centrifugal tachometer is shown in Fig. 2. Two small weights in the form of balls are attached to the spindle and rotate along with the spindle. As the spindle rotates the centrifugal force is developed by these balls. This centrifugal force compresses the spring and a grooved collar or sleeve attached to its free end slides on the spindle and its position can be calibrated with the spindle speed. Through a series of linkages, motion of the sleeve is amplified and communicated to the pointer of the instrument to indicate speed. Certain attachments are provided with the spindle to indicate the linear speed. These types of instrument can be used up to 40000 rpm. They are also used in the speed governors to break circuit for speed control. These tachometers have a distinct advantage over revolution counter in that they indicate whether or not the speed remains substantially constant.

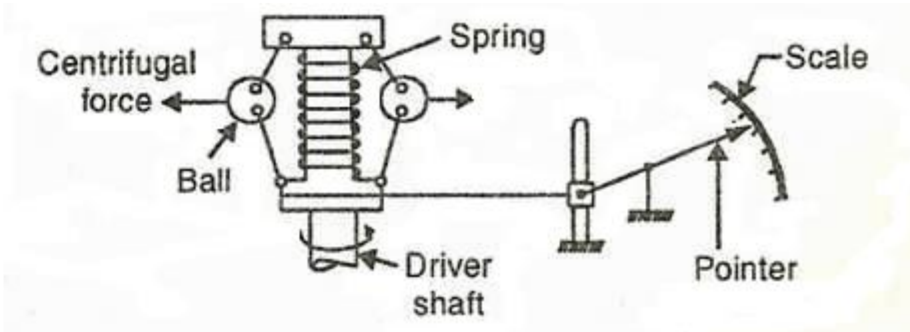


Fig.2 Centrifugal tachometer

Electrical Tachometer

Electrical tachometers provide the advantages of electrical transducers and in view of this they are preferred over mechanical tachometer. They depend for its indication upon an electrical signal generated in proportion to the rotational speed of the shaft. Depending upon the type of transducer, electrical tachometers have been constructed in the variety of designs. For example *commutated capacitor tachometer* based on alternately charging and discharging capacitor controlled by speed of rotating member. In *eddy current type tachometer* the rotating shaft rotates a permanent magnet and this induces eddy currents in a disc. The eddy current produces a torque that rotates the disc against the torque of a spring. The disc turns in the direction of rotating magnetic field until the torque developed equals that of spring. A pointer attached to the disc indicated the rotational speed on a calibrated scale. The *tachometer generator* has been developed on the principle that the e.m.f. generated depends upon the magnetic field and the speed. If for the field the permanent magnetic pole pieces are used then the generated voltage only depends upon the speed. The tachogenerator may be AC or DC type of tachometer depending upon the taking out means of e.m.f. generated. Hence the speed can be calculated by measuring the e.m.f. generated.

Photoelectric Tachometer

The photoelectric tachometer utilizes a rotating shaft to intercept a beam of light falling on a photo conductive cell. The shaft has an intermittent reflecting (white) and non reflecting (black) surfaces. When a beam of light hits the reflecting surface on the rotating shaft, light pulses are obtained and the reflected light is focused on to the photoelectric cell. The frequency of light pulses is proportional to the shaft speed and so will be the frequency of electric output pulses from the photo electric cell.

Another similar method consists of an opaque disc mounted on the rotating shaft as shown in Fig. 3. The disc has a number of evenly spaced peripheral holes. A light source is placed on one side of the disc and a light sensor on the other side of the disc inline with it.

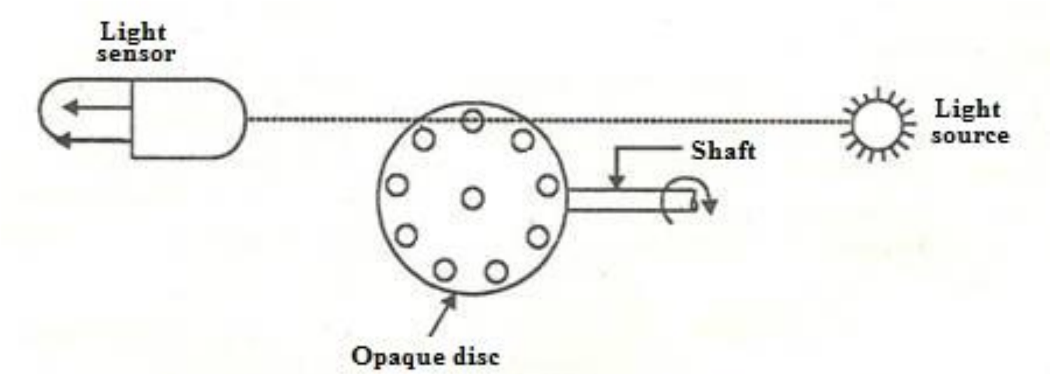


Fig. 3 Photoelectric tachometer

When the opaque portion is between the light source and the light sensor, no light falls on the light sensor and there is no output. At the time when a hole appears between the two, the light illuminates the sensor and a pulse of voltage is produced. The frequency of pulse generation is determined by the number of holes in the disc and its speed of rotation. Since the number of holes is fixed in the disc the frequency of the output is calibrated to measure the rotational speed of the rotating shaft. Photoelectric tachometer is a digital instrument. It however requires replacing the light source periodically.

Tachogenerator

- Tachogenerator works on the **principle of variable reluctance.** It consists of an assembly of **a toothed wheel and a magnetic circuit** as shown in figure
- Toothed wheel is mounted on the shaft or the element of which angular motion is to be measured.
- **Magnetic circuit comprising of a coil wound on a ferromagnetic material core.**
- As the wheel rotates, the air gap between wheel tooth and magnetic core changes which results in cyclic change in flux linked with the coil.
- The **alternating emf generated** is the measure of angular motion.
- A pulse shaping signal conditioner is used to transform the output into a number of pulses which can be counted by a counter.

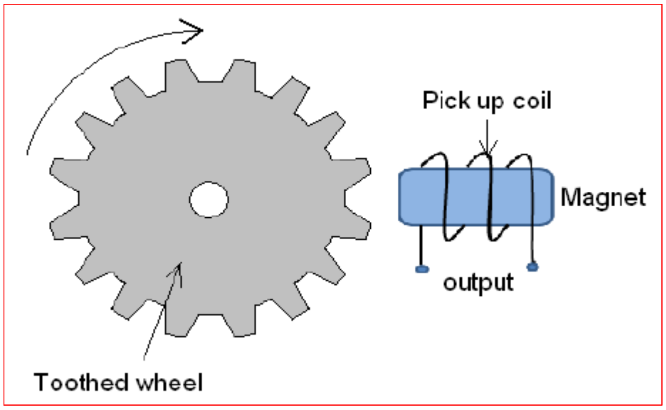


Figure: Principle of working of Techogenerator

AC generator

- An alternating current (AC) generator can also be used as a techognerator.
- It comprises of **rotor coil** which rotates with the shaft.
- The rotor rotates in **the magnetic field** produced by a stationary permanent magnet or electromagnet.
- During this process, an alternating emf is produced which is the measure of the angular velocity of the rotor.
- In general, these sensors exhibit **nonlinearity error of** about ± **0.15%** and are employed for the rotations up to about **10000 rev/min**.

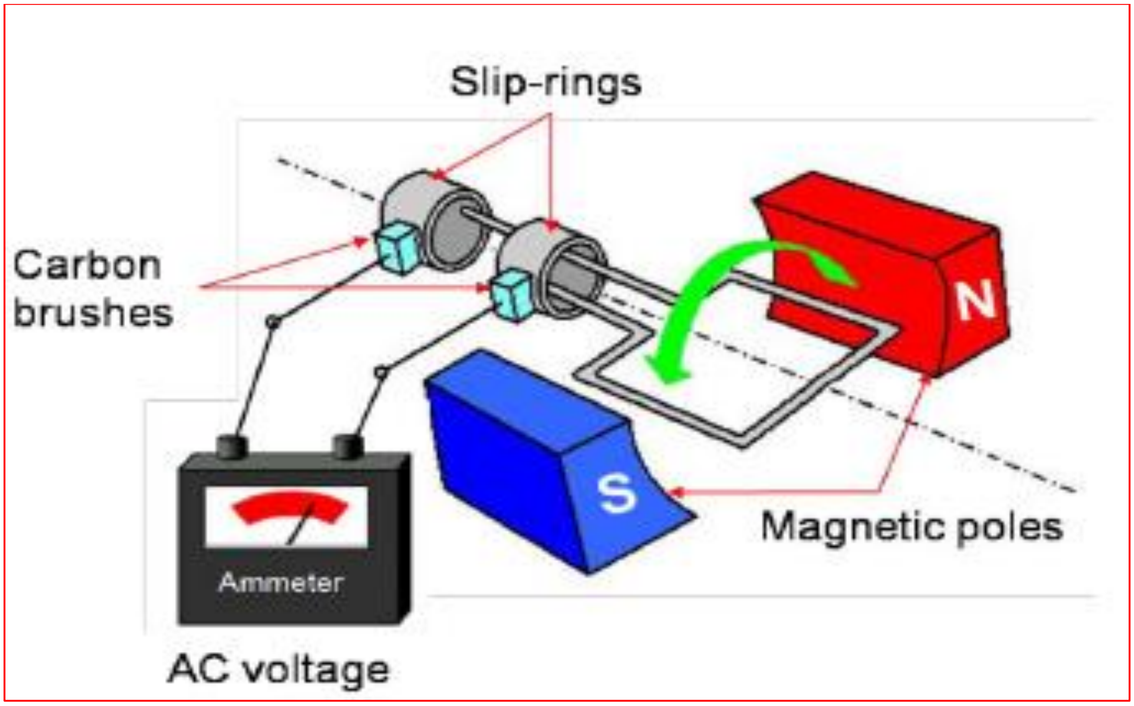


Figure : Construction and working of AC generator

Pyroelectric sensors

- These sensors work on the principle of *pyroelectricity*, which states that a crystal material such as Lithium tantalite generates charge in response to heat flow.
- In presence of an electric field, when such a crystal material heats up, its electrical dipoles line up as shown in figure. This is called as polarization.
- On cooling, the material **retains its polarization**. In absence of electric field, when this polarized material is subjected to **infra red irradiation**, its polarization reduces.
- This phenomenon is the measure of detection of movement of an object. Pyroelectric sensor comprises of a thick element of polarized material coated with thin film electrodes on opposite faces as shown in figure 2.4.4.
- Initially the electrodes are in electrical equilibrium with the **polarized material.** On incident of infra red, the material heats up and reduces its polarization.
- This leads to charge imbalance at the interface of crystal and electrodes.
- To balance this disequilibrium, measurement circuit supplies the charge, which is calibrated against the detection of an object or its movement.

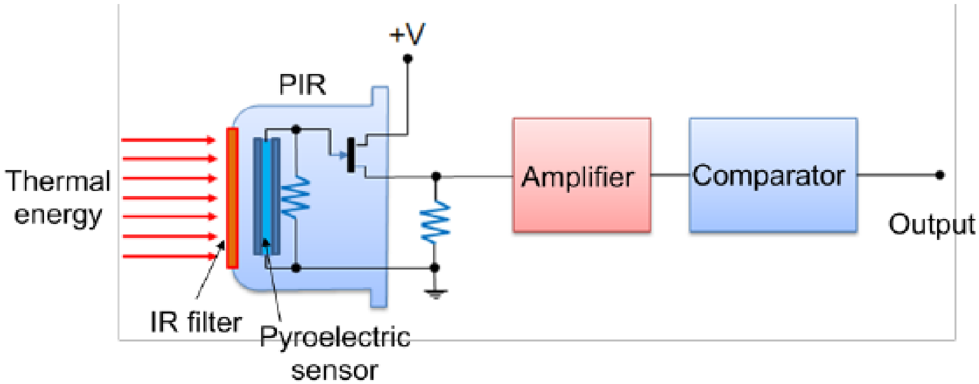


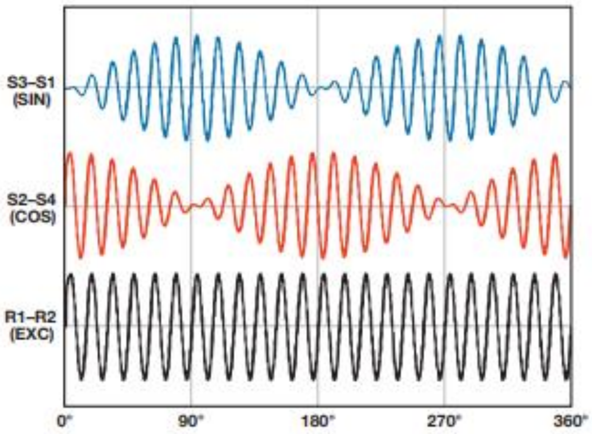
Figure: Construction and working a Pyroelectric sensor

Applications of Pyroelectric sensors

- Intrusion detector • Optothermal detector • Pollution detector • Position sensor
- Solar cell studies • Engine analysis

RESOLVERS

- A resolver is an **electromagnetic transducer** that can be used in a wide variety of **position and velocity feedback applications** which includes light duty/servo, light industrial or heavy duty applications.
- Resolvers, known as motor resolvers, are commonly used in servo motor feedback applications due to their good performance in high temperature environments.
- Because the resolver is an analog device and the electrical outputs are continuous through one complete mechanical revolution, the theoretical resolution of a single speed resolver is infinite.
- Because of its simple transformer design and lack of any on board electronics, the resolver is a much more rugged device than most any other feedback device and is the best choice for those applications where **reliable performance is required in those high temperature**, high shock and vibration, radiation and contamination environments which makes the resolver the sensible design alternative for **shaft angle encoding.**



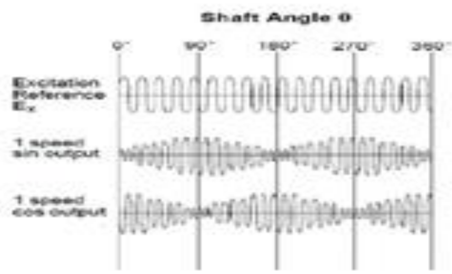


Figure 2. Resolver electrical signal representation.

- A resolver outputs signal by energizing the input phase of the resolver with an AC voltage (VAC) to induce voltage into each of the output windings. The resolver amplitude modulates the VAC input in proportion to the Sine and the Cosine of the angle of mechanical rotation.
- The resolver is sometimes known as an Analog Trigonometric Function Generator or a Control Transmitter. The function of the resolver is to resolve a vector into its components (Sine and Cosine).
- Electrical Zero (EZ) is defined as the position of the rotor with respect to the stator at which there is minimum voltage amplitude across the Sine winding and the maximum voltage amplitude across the Cosine winding when the input winding is excited with the rated voltage.
- The rotor position or angle is simply the Arc tan of the voltage output of the Sine winding divided by the output of the Cosine winding.
- This ratio metric format provides an inherent noise reduction feature for any injected noise whose magnitude is approximately equivalent on both windings and also results in a large degree of temperature compensation

The 7 functional operating parameters which define the resolver operation are:

1. Accuracy
2. Input Excitation Voltage
3. Input Excitation Frequency
4. Input Current Maximum
5. Transformation Ratio of Output Voltage to the Input Voltage
6. Phase shift of the Output Voltage from the Input Voltage
7. Null Voltage

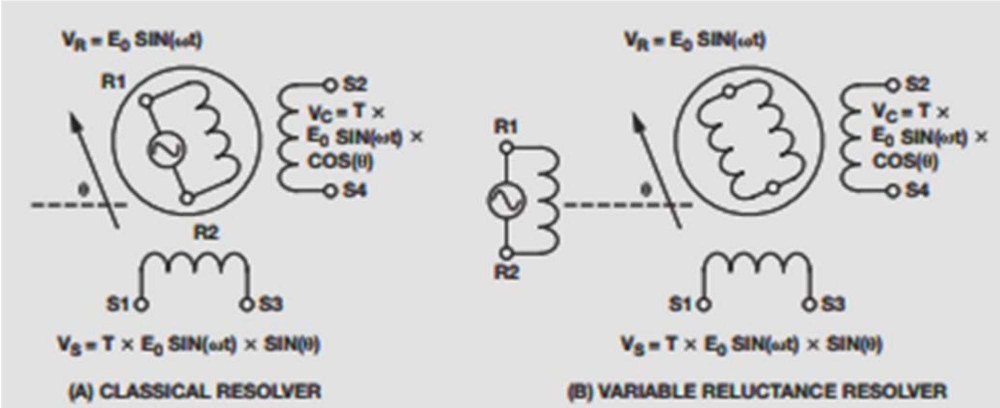


Figure 1. Classical resolver vs. variable reluctance resolver.

Resolvers, electromechanical sensors that measure **precise angular position**, operate as **variable coupling transformers**, with the amount of magnetic coupling between the primary winding and two secondary windings varying according to the position of the rotating element (rotor), which is typically mounted on the motor shaft.

Employed in **industrial motor controls, servos, robotics, power-train units in hybrid- and full-electric vehicles**, and many other applications that **require precise shaft rotation, resolvers can withstand severe** conditions for a very long time, making them the perfect choice for military systems **in harsh environments**.

Standard resolvers have a primary winding on the rotor and two secondary windings on the stator. Variable reluctance resolvers, on the other hand, have no windings on the rotor.

Their **primary and secondary windings** are all on the stator, but the saliency (exposed poles) of the rotor couples the sinusoidal variation in the secondary with the angular position.

When the primary winding, R1–R2, is excited with a sinusoidal signal as expressed in Equation 1, a signal is induced in the secondary windings.

The amount of coupling onto the secondary dialogue windings is a function of the position of the rotor relative to that of the stator, and an attenuation factor known as the **resolver transformation ratio**.

- Because the secondary windings are displaced mechanically by 90,° the two output sinusoidal signals are phase shifted by 90° with respect to each other. The relationships between the resolver input and output voltages are shown in Equation 2 and Eq 3.
- Equation 2 is the sine signal; Eq 3 is the cosine signal.

$$R1-R2 = E_0 \sin \omega t \qquad (1)$$

$$S3-S1 = T \times E_0 \sin \omega t \times \sin \theta \qquad (2)$$

$$S2-S4 = T \times E_0 \sin \omega t \times \cos \theta \qquad (3)$$

where: θ is the shaft angle, ω is the excitation signal frequency, E0 is the excitation signal amplitude, and T is the resolver transformation ratio.

- The **two output signals** are modulated by the **sine and cosine of the shaft angle**.
- A graphical representation of the excitation signal and the sine and cosine output signals is shown in Figure 2. The sine signal has maximum amplitude at 90° and 270° and the cosine signal has maximum amplitude at 0° and 180.°
- A resolver sensor has a unique set of parameters that should be considered during the design phase.
- The most critical electrical parameters and the respective typical specifications are summarized in Table 1.

Table 1. Resolver Key Parameters

Electrical Parameter	Typical Range	Unit	Description
Input Voltage	3–7	V rms	Recommended excitation signal amplitude to be applied to resolver primary winding R1–R2
Input Frequency	50–20,000	Hz	Recommended excitation signal frequency to be applied to resolver primary winding R1–R2
Transformation Ratio	0.2–1.0	V/V	Ratio between the primary and secondary windings signal amplitude
Input Impedance	100–500	Ω	Input impedance of resolver
Phase Shift	±25	degrees	Phase shift between excitation signal applied to primary winding (R1–R2) and sine/cosine signals on secondary windings (S3–S1, S2–S4)
Pole Pairs	1–3		Number of electrical rotations per mechanical rotation

RESOLVER APPLICATIONS

- The simplicity of the resolver design makes them reliable in **many harsh environment and extreme applications**.
- **Common applications of resolvers include:**
- Servo motor feedback
- Speed and position feedback in steel and paper mills
- Oil and gas production
- Jet engine fuel systems
- Aircraft flight surface actuators
- Communication position systems
- Control systems in land based military vehicles

RESOLVERS VS ENCODERS

- With no onboard electronics, resolvers can survive extreme temperatures and tolerate shock and vibration, making resolvers suitable in applications where encoders would fail.
- As feedback devices, resolvers can be used as alternatives to both incremental encoders and absolute encoders.
- However, resolvers output an analog signal and require a separate analog-to-digital converter where encoders output digital signals.
- For applications where radiation is present, resolves can be rad hardened to be used in these environments.
- Their lack of onboard electronics also provides an advantage in radiated environments.
- Compared to absolute encoders, single-speed resolvers provide absolute position and can be used as absolute devices, making them alternatives when environment conditions do not allow for the use of absolute encoders.

Temperature sensors

- Temperature conveys the state of a mechanical system in terms of expansion or contraction of solids, liquids or gases, change in electrical resistance of conductors, semiconductors and thermoelectric emfs.
- Temperature sensors such as bimetallic strips, thermocouples, thermistors are widely used in monitoring of manufacturing processes such as casting, molding, metal cutting etc.
- The construction details and principle of working of some of the temperature sensors are discussed in following sections.

1. **Contact type:**
   - **Bimetallic,**
   - **RTD,**
   - **Thermocouple and**
   - **Thermistor**

2. **Non - Contact type Temperature sensors:**
   - **Radiation Pyrometer**
   - **Optical Pyrometer**

Bimetallic strips

- **Bimetallic strips are used as thermal switch** in controlling the temperature or heat in a manufacturing process or system.
- It contains two different metal strips bonded together. The metals have different coefficients of expansion.
- On heating the strips bend into curved strips with the metal with higher coefficient of expansion on the outside of the curve.
- Figure 2.5.1 shows a typical arrangement of a bimetallic strip used with a setting-up magnet.
- As the strips bend, the soft iron comes in closer proximity of the small magnet and further touches.
- Then the electric circuit completes and generates an alarm. In this way bimetallic strips help to protect the desired application from heating above the pre-set value of temperature.

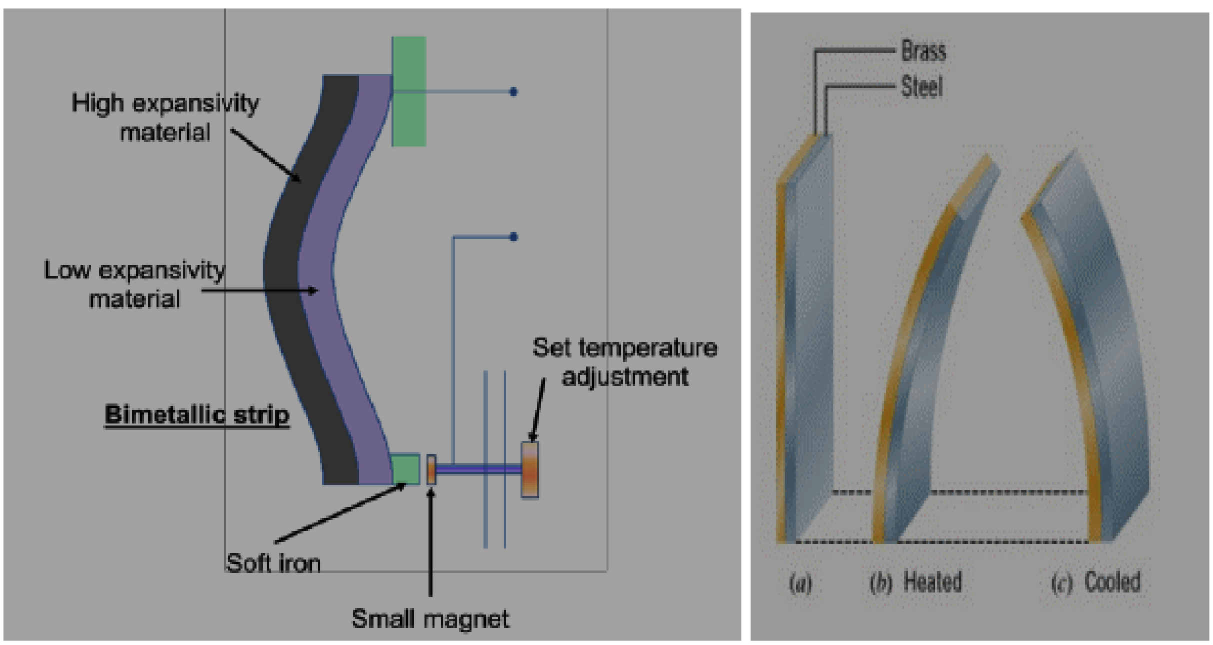


Figure Construction and working of Bi-metallic strip

Every metal and alloy has its won coefficient of expansion. That means they are expanded in their size differently for same temperature increase. If we couple two strips made of two different metals or alloys, then due to dissimilarity in coefficient of expansion they will be expanded or contracted differently during temperature change and consequently the whole bimetallic strip assembly will bend or be deformed. As this deformation of shape of a specific bimetallic strip is due to temperature rise or fall, this deformation can also be measured in the scale of temperature. From this principle, the concept of **Bimetallic Strip Thermometer** came

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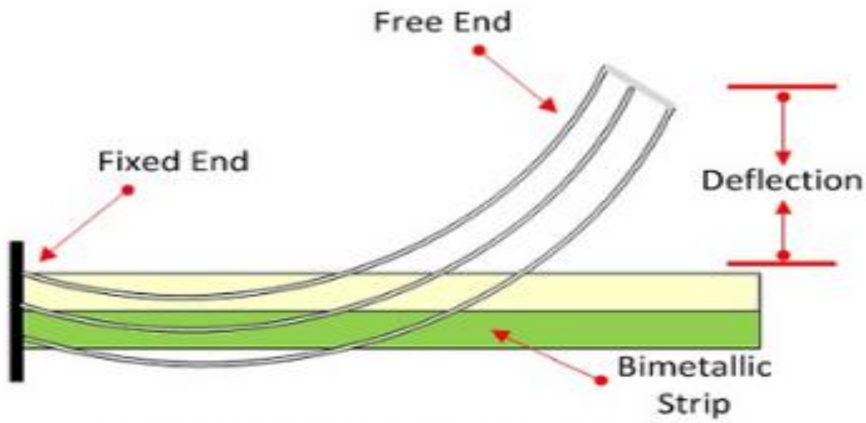


Bimetallic Strip fixed at one end

.

Bimetallic strip mainly used in industries in temperature control devices. It is assembled with temperature controller system. When temperature reaches to a preset value, the bimetallic strip is so bent it closes an NO contact which initiates the cooling system to decrease the temperature of the system. Bimetallic strip thermometer is also widely used in industries because of their simplicity and robustness.

There are mainly two types of **bimetallic strip thermometer** are available in the market. Both are same in working but differ in construction.

Spiral Strip Bimetallic Thermometer

Here the bimetallic strip used is in spiral shaped. When temperature rises, due to bimetallic property, the spring twists more. Due to this mechanical deformation of the spring, a pointer attached to the dial moves and indicates the temperature, as the dial of this **bimetallic strip thermometer** is calibrated in temperature scale.

Cantilever Strip Bimetallic Thermometer

Here a straight bimetallic strip is attached as a cantilever. When temperature rises or falls, the strip bends either sides and the movement of the front end of the strip is transferred to a pointer dial system via gear – lever system, to take reading of temperature.

Advantages and Disadvantages of Bimetallic Strip Thermometer

There are mainly three major advantages of this instrument. One they are robust two they are simple and three they are fully mechanical devices no need of power source.

Main disadvantages are they are not very accurate and they are not suitable for measuring lower temperature as the metals and metallic alloys show nearly same expansion or contraction in lower range of temperature.

Resistance temperature detectors (RTDs)

RTDs work on the principle that the **electric resistance of a metal changes due to change in its temperature**. On heating up metals, their resistance increases and follows a linear relationship as shown in Figure. The correlation is

$$Rt = R0\,(1 + \alpha T) \qquad (1)$$

where Rt is the resistance at temperature T (ºC) and $R0$ is the resistance at temperature at 0ºC and α is the constant for the metal termed as **temperature coefficient of resistance.**

The sensor is usually made to have a resistance of 100 Ω at 0 °C

Figure 2.5.3 shows the construction of a RTD. It has a resistor element connected to a Wheatstone bridge. The element and the connection leads are insulated and protected by a sheath. A small amount of current is continuously passing though the coil.

As the temperature changes the resistance of the coil changes which is detected at the Wheatstone bridge.RTDs are used in the form **of thin films**, **wire wound or coil.** They are generally made of metals such as platinum, nickel or nickel-copper alloys. Platinum wire held by a high-temperature glass adhesive in a ceramic tube is used to measure the temperature in a metal furnace.

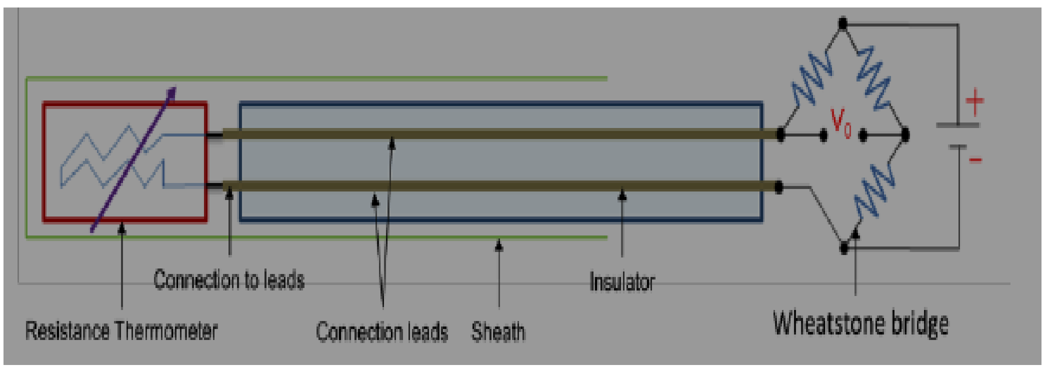


Figure Construction of a Resistance temperature detector (RTD)

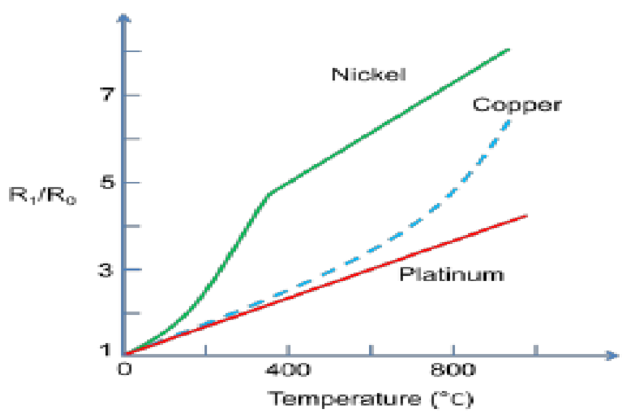


Figure Behavior of RTD materials

Other applications are:

- Air conditioning and refrigeration servicing ,
- Food Processing ,
- Stoves and grills ,
- Textile production
- Plastics processing ,
- Petrochemical processing,
- Micro electronics ,
- Air, gas and liquid temperature measurement in pipes and tanks ,
- Exhaust gas temperature measurement
-

Thermistors follow the principle of decrease in resistance with increasing temperature. The material used in thermistor is generally a semiconductor material such as a sintered metal oxide (mixtures of metal oxides, chromium, cobalt, iron, manganese and nickel) or doped polycrystalline ceramic containing barium titanate ($BaTiO_3$) and other compounds. As the temperature of semiconductor material increases the number of electrons able to move about increases which results in more current in the material and reduced resistance. Thermistors are rugged and small in dimensions. They exhibit nonlinear response characteristics. Thermistors are available in the form of a bead (pressed disc), probe or chip. It has a small bead of dimension from 0.5 mm to 5 mm coated with ceramic or glass material. The bead is connected to an electric circuit through two leads. To protect from the environment, the leads are contained in a stainless steel tube. Figure 2.5.4 shows the construction of a bead type thermistor.

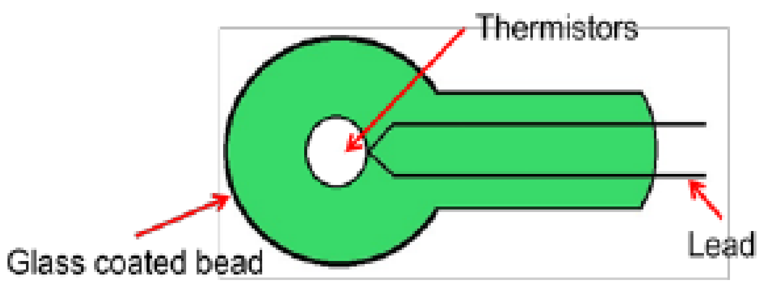


Figure Schematic of a thermistor

Applications of Thermistors

- To monitor the coolant temperature and/or oil temperature inside the engine
- To monitor the temperature of an incubator
- Thermistors are used in modern digital thermostats
- To monitor the temperature of battery packs while charging
- To monitor temperature of hot ends of 3D printers
- To maintain correct temperature in the food handling and processing industry equipments
- To control the operations of consumer appliances such as toasters, coffee makers, refrigerators, freezers, hair dryers, etc.

Thermocouple

Thermocouple works on the fact that when a junction of dissimilar metals heated, it produces **an electric potential** related to temperature. As per Thomas Seebeck (1821), when two wires composed of dissimilar metals are joined at both ends and one of the ends is heated, then there is a continuous current which flows in the thermoelectric circuit. Figure 2.5.5 shows the schematic of thermocouple circuit.

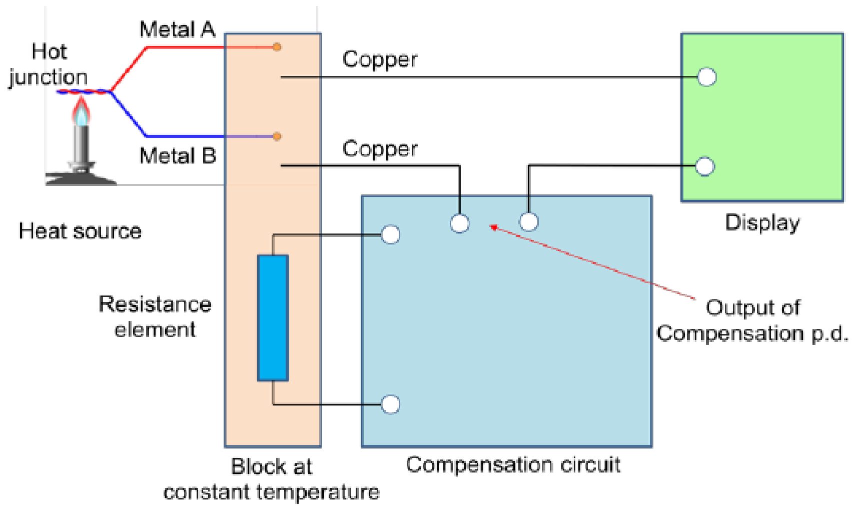


Figure Schematic of thermocouple circuit

The net open circuit voltage (the Seebeck voltage) is a function of junction temperature and composition of two metals. It is given by,

$$\Delta VAB = \alpha \, \Delta T \qquad (1)$$

where α, the Seebeck coefficient, is the constant of proportionality.
Generally, **Chromel (**90% nickel and 10% chromium)–**Alumel** (95% nickel, 2% manganese, 2% aluminium and 1% silicon) are used in the manufacture of a thermocouple.
Table The various other materials, their combinations and application temperature ranges

Table Thermocouple materials and temperature ranges [1]

Materials	Range (°C)	(μV/°C)
Platinum 30% rhodium/platinum 6% rhodium	0 to 1800	3
Chromel/constantan	-200 to 1000	63
Iron/constantan	-200 to 900	53
Chromel/alumel	-200 to 1300	41
Nirosil/nisil	-200 to 1300	28
Platinum/platinum 13% rhodium	0 to 1400	6
Platinum/platinum 10% rhodium	0 to 1400	6
Copper/constantan	-200 to 400	43

Applications of Thermocouples

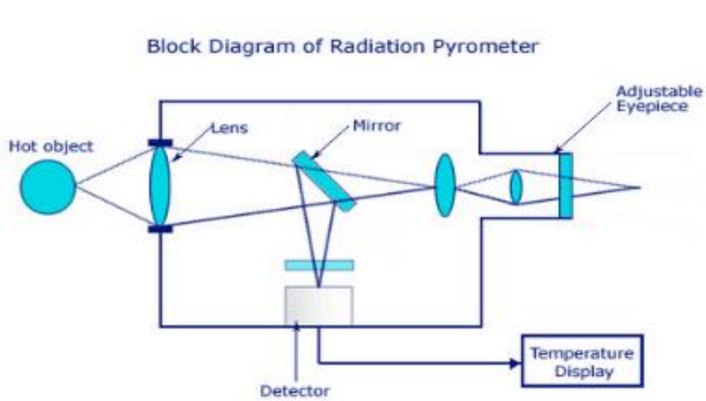
- To monitor temperatures and chemistry throughout the steel making process
- Testing temperatures associated with process plants e.g. chemical production and petroleum refineries
- Testing of heating appliance safety
- Temperature profiling in ovens, furnaces and kilns
- Temperature measurement of gas turbine and engine exhausts
- Monitoring of temperatures throughout the production and smelting process in the steel, iron and aluminum industry

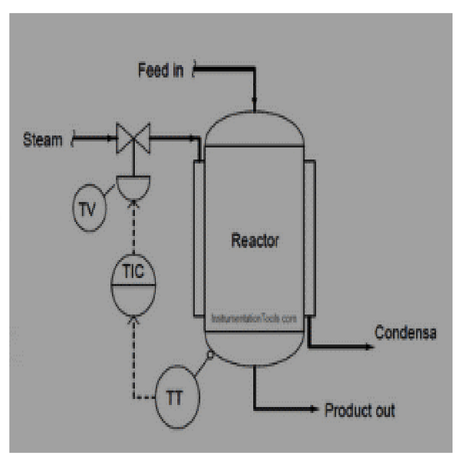
Radiation Pyrometer

- For measuring any temperature above 1200^{o}C a **radiation pyrometer** type thermometer is generally used. The main reason behind that, this type of temperature sensors or thermometer is not required to be brought in touch with the object whose temperature to be measured.
- For very high temperature, conventional thermometer is not at all suitable to touch with the hot object as there may be always a chance severe damage of the thermometer
- Not only that, some time the hot object is located in so narrow passage of system, it is impossible to bring a thermometer near to that. In this situation too, radiation pyrometer is successfully used for temperature measurement.
- The main working principle of this type of instruments is that, it senses the **heat radiation from a targeted hot body** and reads and records its temperature, depending upon the intensity of radiation.
- There are mainly two **types of radiation pyrometers** one is

1. Fixed focus type another is

2. Variable focus type.





Fixed Focus Type Radiation Pyrometer

It mainly consists of a long tube, a concave mirror is placed at the end of the tube as shown. A sensitive thermocouple is placed in front of the concave mirror in such a suitable distance, that the heat radiation which enters the tube through narrow aperture at the front end of tube, reflected by the concave mirror and focused on the hot junction of the thermocouple.

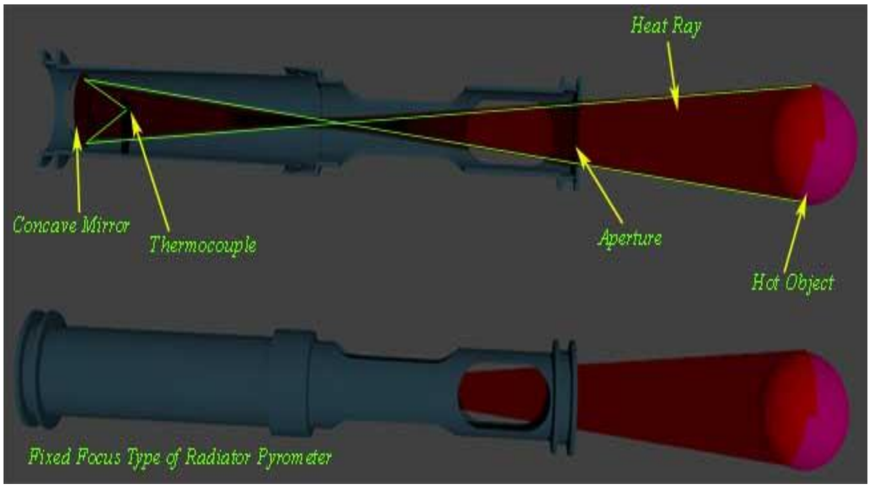
Due to this fixed concave mirror the radiation is always focused on the thermocouple irrespective of the distance between hot object and this instrument. This is reason for which this instrument is called fixed focus type **radiation pyrometer**.

The emf generated in the thermocouple is then measured with a help of a galvanometer or millivoltmeter and this can be directly calibrated with temperature to get temperature reading readily.

- They are suitable for measuring temperature above 600oC as because in lower temperature the temperature of the pyrometer itself can not be ignored compared to the temperature of the hot body.

Application of Radiation Pyrometer

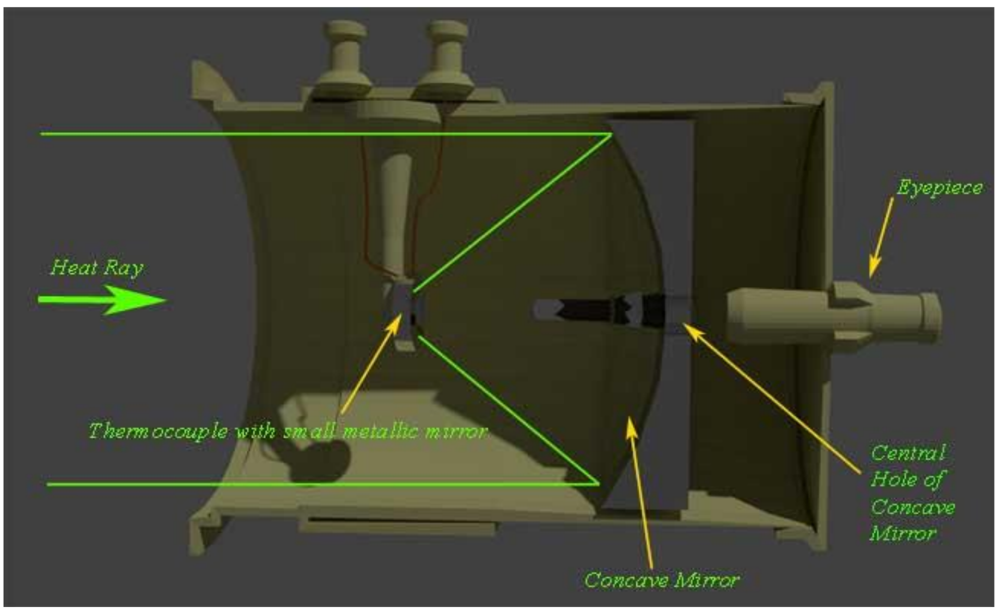
- The radiation pyrometer type temperature sensor are mainly used for measuring temperature of furnaces.
- But the terminals of the thermocouple which creates the cold junction must be protected against the heat from the hot body.



Variable Focus Type Radiation Pyrometer

- The figure below shows a basic construction of adjustable focus type of instrument.
- Unlike, fixed focus radiator pyrometer, here the position of the concave mirror can be adjusted by adjusting knob attached to the instrument.

- Due to this adjustable concave mirror, the instrument is known as variable focus radiation pyrometer. The concave mirror made of highly polished steel.
- The heat rays form the targeted hot object are first received by the concave mirror then are reflected on to the blackened thermo junction consisting of a very small copper or silver disc to which the wires forming the junction are soldered.
- The visible image of the hot body can be seen on the small metallic disc attached to thermo-couple junction, through the eyepiece and the central hole of the main concave mirror.
- The position of main concave mirror is adjusted until the focus coincides with the smaller metallic disc attached to the thermocouple junction.
- The heating of the thermo junction due to this thermal image on the small metal disc produces an electro-motive force.
- The temperature of the object can be measured by measuring this thermally generated emf by an sesative galvanometer or millivoltymeter.



The **working principle and construction of an Optical Pyrometer** are quite simple. We have drawn an experimental model of this type of temperature sensors. It is a measuring instrument that measures temperature of a hot glowing object.

The instrument has an illuminated reference, with which the brightness of that of the hot body is matched by controlling the input electric current of the reference. When, the glow of the reference matches with the hot object through an eye piece, that electric current is measured to calibrate the temperature of the hot body.

Construction of Optical Pyrometer

It is quite simple. Consider it as a cylinder, which has a lens in one end and in the other end there is an eye piece. In between there is a lamp. In front of the eye piece there is a colored glass (usually red), to make lights monochromatic. The lamp is connected to a battery source through an ammeter and a rheostat

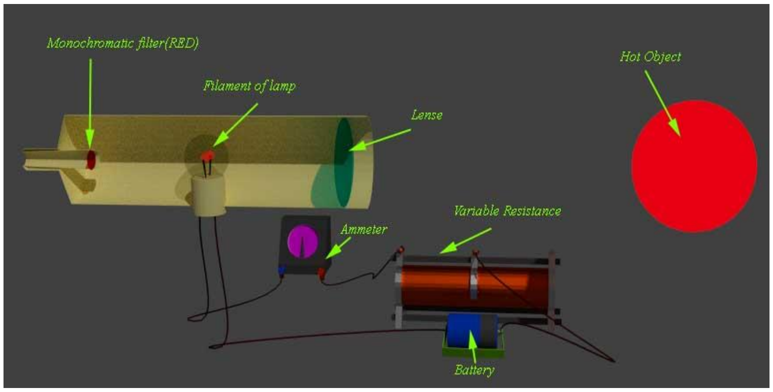
The **optical pyrometer** works in a certain simple process. The process is, the brightness of the filament of the lamp, that we are using through a battery source can be controlled by the rheostat. Now by controlling the incoming current, the brightness of the filament is increased or decreased.

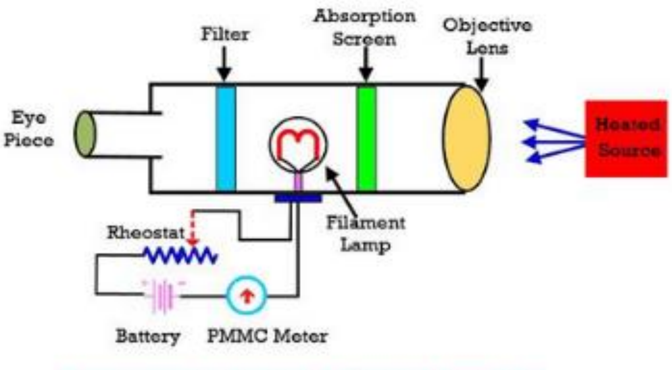
Going through this process there will be a certain point, when the filament of the lamp will not be visible from the eye piece. That very moment the brightness of the filament matches with the brightness of the hot body as seen through the monochromatic glass. From the reading of the ammeter of that particular condition we can get the temperature of the hot body, as the ammeter is previously calibrated in temperature scale.

Limitations of Optical Pyrometer

There are some limitations of this pyrometer. Such as:–

1. This type of pyrometer can measure the temperature of only those objects which are emitting light that means glowing objects.
2. The **optical pyrometer** has a range of measuring temperature of 1400°C to 3500°C.





Disappearing Filament Type Optical Pyrometer

Humidity Sensors

- **Capacitive Type**
- **Resistive Type**
- **Hot and Wet Bulbs.**

Capacitive Type :

Capacitive sensors are the most popular amongst all the existing humidity sensors. The capacitive humidity sensor works on the principle of change in the dielectric of the capacitor due to the absorption of water in the atmosphere. The dielectric material is a hygroscopic material that responds to the humidity after meeting the water content. The speed of a capacitive humidity sensor can be changed by using a **more humidity-sensitive material** or by a **change in the shape/geometry of the sensor film.**

The conventional parallel plate-structured sensors have only one side of the sensing layer exposed to the moisture. The newly developed cylindrical sensor has polyimide columns of a very small diameter available, which allows extreme adsorption of the humidity. Polyimide is used as the **hygroscopic material**, and it is deposited on a polysilicon material, which acts as a heater. The heater prevents condensation, which is the key factor in the recovery period of the sensor. The sensor shows high speed because of the application of the moisture around the circumference of the sensor film. This shows a response time of 1.0 second for a polyimide diameter of 5µm. Further speed enhancement can be achieved by using polyimide film columns with lesser diameters.

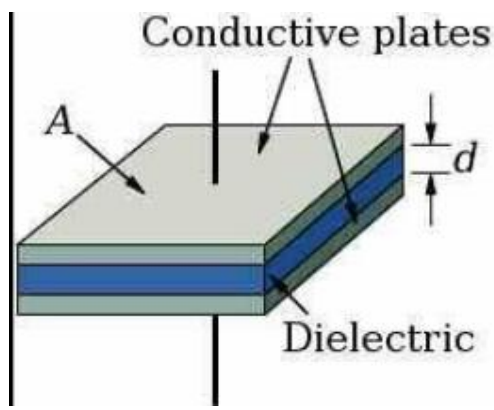


Fig. 3 Setup for capacitive type humidity sensor.

Resistive Type

The sensor material used is sensitive to humidity (hygroscopic), and its resistance varies with the change for moisture present. From the open literature written in the last 25 years, those materials are acetates, fluorides, chlorides, iodides, nitrates, sulphate, carbonates, phosphates, and oxides, as well as polymeric materials.

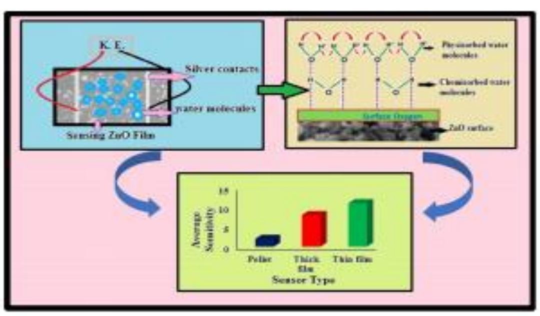
These materials can also be used to design a capacitive humidity sensor. This type of humidity sensors show the variation in electrical resistance of a humid medium for example a conductive polymer, salt, or dried substrate. Fig.1 show the typical characteristic of resistive humidity sensor. **The variation in resistance is normally an inverse exponential connection to the humidity.**

Resistive type sensors usually hold noble metal electrodes either placed on a substrate by photoresist system or wire-wound electrodes on a plastic or glass hose. The sensor material used is sensitive to humidity (hygroscopic), and its resistance varies with the change for moisture present. From the open literature written in the last 25 years, those materials are acetates, fluorides, chlorides, iodides, nitrates, sulphate, carbonates, phosphates, and oxides, as well as polymeric materials. These materials can also be used to design a capacitive humidity sensor. This type of humidity sensors show the variation in electrical resistance of a humid medium for example a conductive polymer, salt, or dried substrate.

Fig.1 show the typical characteristic of resistive humidity sensor. The variation in resistance is normally an inverse exponential connection to the humidity.

Resistive type sensors usually hold noble metal electrodes either placed on a substrate by photoresist system or wire-wound electrodes on a plastic or glass hose. The substrate is encrusted with a salt or conductive polymer. On the other hand, the substrate may be treated by activating elements such as acid. The sensor adsorbs the water vapour, and ionic functional groups are dissociated, resulting in an increase in electrical conductivity. Mostly, resistive type humidity sensing devices consume regular AC excitation voltage with no DC bias to avoid polarization of the sensor. The resulting current is rehabilitated and rectified to a DC voltage signal for the other scaling or strengthening.

The substrate is encrusted with a salt or conductive polymer. On the other hand, the substrate may be treated by activating elements such as acid. The sensor adsorbs the water vapour, and ionic functional groups are dissociated, resulting in an increase in electrical conductivity. Mostly, resistive type humidity sensing devices consume regular AC excitation voltage with no DC bias to avoid polarization of the sensor. The resulting current is rehabilitated and rectified to a DC voltage signal for the other scaling or strengthening.



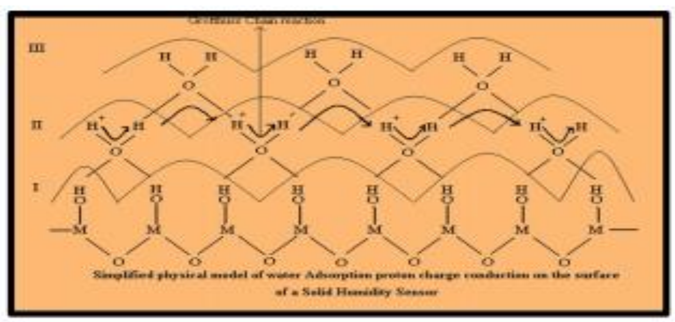


Fig.1 Resistive type humidity sensor Fig. 2 Humidity sensing mechanism for resistive type humidity sensor

resistive type humidity sensors are based on the variation in conductivity/resistivity of materials with the amount of water adsorbed by them. This principle is employed for the measurement of humidity for all such type of humidity sensors. Although this type of sensor can be subdivided into two parts depending upon their conduction mechanism;

(i) Ionic-type humidity sensor (ii) Electronic-type humidity sensor.

1) Ionic Type: This type of sensor uses the change of ionic conductivity resulting from water adsorption and desorption. The humidity sensitive characteristics depend on the intrinsic conductivity of the materials used and microstructure of specimen.

Ionic category oxides are associated equally to the chemisorption and physisorption of the water molecules on the oxide surface along with capillary condensation in the micro pores of ceramics. These sensors mostly work at low temperatures.

W. J. Fleminghas shown that the physical mechanism operating for ionic type humidity sensors is the same for both the capacitive and resistive types.

a) Identification of the Charge Carriers: Experimental studies have shown that humidity enhanced conduction on nonconducting surfaces is entirely due to electrical charges residing on the external surfaces. The simultaneous measurement of surface charge and conduction charge by means of Kelvin probe and an integrating ammeter, has proved that humidity enhanced conduction must be the result of an ionic charge flow on the external surface of the solid.

b) Adsorption and Dissociation Mechanism of Water Molecules: Since water is a polar molecule, the negatively charged oxygen of the water molecule is electrostatically attracted to the positively charged cationic side of the metal oxide surface. If the charge density of the cationic side is low then water remains physically adsorbed at the surface by weak electrostatic field. When the cationic charge density is high, as in the case of alkali salts, the electrostatic force is high enough to form a chemical bond between hydrogen and oxygen of water molecule, which in turn break the bond between oxygen and one of the hydrogen atoms. Mostly the force is high enough to break the bond in the initially adsorbed water vapour layer. Therefore, the initial monolayer in generally chemisorbed. This chemisorbed layer can be removed thermally by increasing the ambient temperature. The irreversible reaction of the first layer can be given as: The complete water adsorption is schematically depicted in the following Figure. The subsequent water layer is physically adsorbed (shown as layer II in Fig. 2) on the first chemisorbed layer. This physisorbed water layer is bound by weak electrostatic force (known as hydrogen bonding) on the underlying chemisorbed layer and can be reversibly removed by decreasing humidity. Therefore, this layer is mostly contributed for the humidity sensitive conduction of ceramic materials. The chemisorbed water molecule exerts electrostatic field, which not only attract water molecule. It was concluded that the weakening action of the surface electrostatic field promotes the dissociation of physisorbed water molecule in the following manner:

2) Electronic Type: In the electronic type of humidity sensor, the major charge carriers are electrons whose concentrations and mobility are influenced by adsorbed water. In the above-mentioned mechanism of ionic based humidity sensor, the physisorbed layer present is always in equilibrium with the atmospheric humidity as the rate of adsorption is equal to the rate of desorption. Since the ambient temperature increases, the thickness of the physisorbed water layer decreases because of the rate of desorption increases. The sensors now work as a semiconductor gas sensor, where electronic conductivity changes with ambient gas concentration. Operating temperatures of this type of sensor is usually greater than 100°C. The observed change in this type of sensor is based on the chemisorption of the water molecule on the semiconducting oxide. The resistivity increases or decreases according to the type of semiconducting oxide. i.e. p or n-type. This indicates that electrons are apparently transferred from water molecule to oxide. The surface of the semiconductor is adsorbed with oxygen ions in the air, which reduces the conductivity of the base material. The reaction of reducing gas with this adsorbed oxygen removes the oxygen ion and the conductivity again increases.

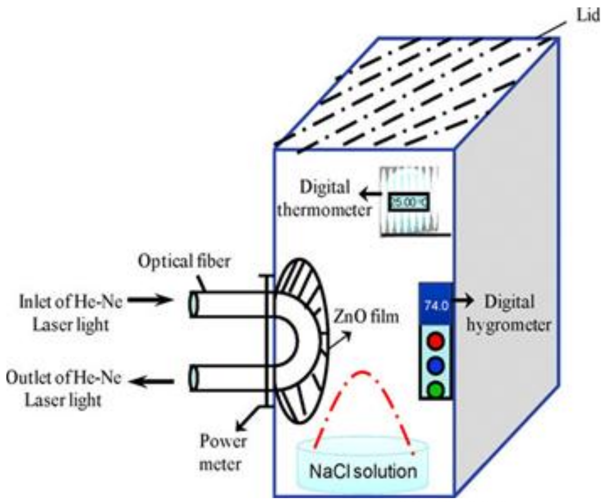
$$M^{+} + H_2O \rightarrow M-OH + H^{+}$$

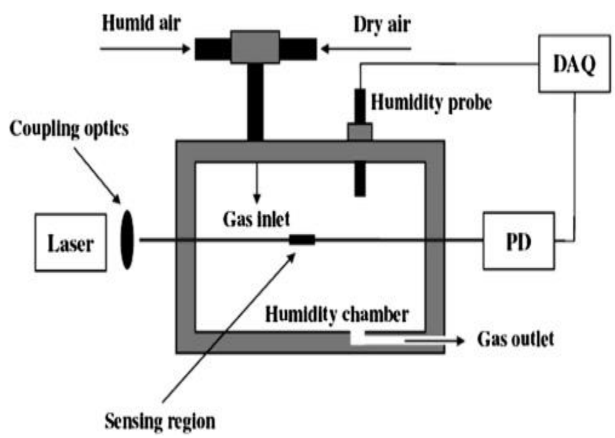
$$2H_2O \rightarrow H_3O^{+} + OH^{-}$$

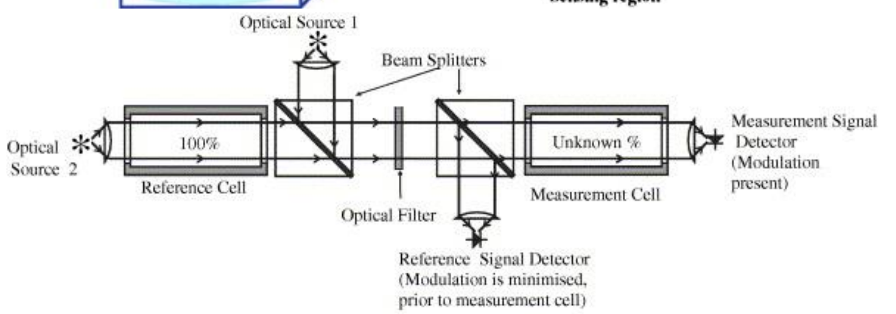
Optical Humidity Sensors

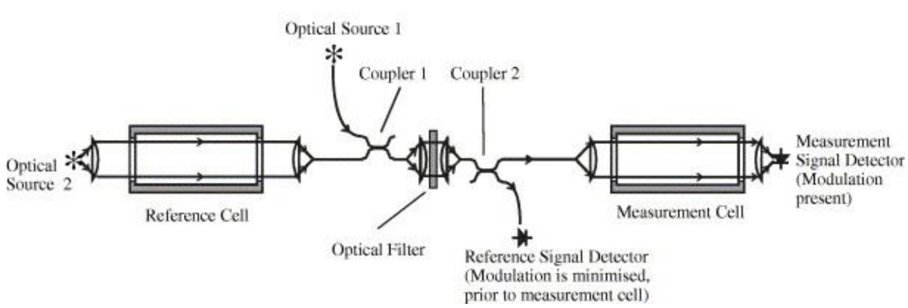
1)Optochemical Humidity Sensors:

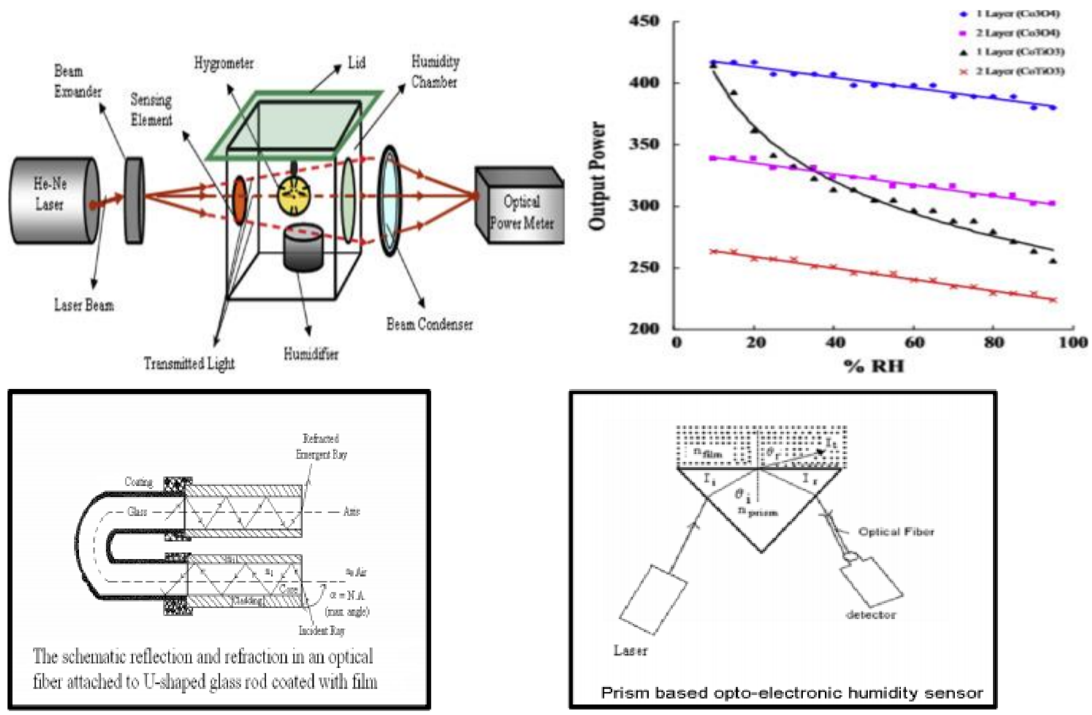
In recent years, optochemical sensors have attracted attention because of their remote analysis capability, high sensitivity, and compactness. Most of the optochemical sensors are composed of a **dye-dispersed polymer** in which optical intensity of the absorption, florescence or phosphorescence peak depends upon the **chemical species and their concentrations.** Various researchers have used this effect for developing optical humidity sensors. Following figure show the proper experimental set-up for optical humidity sensor.











(b) (c)

Fig. 5 (a) Set-up for optical humidity sensor, (b) U-shape optoelectronic sensor, (c) Prism shape optoelectronic humidity sensor.

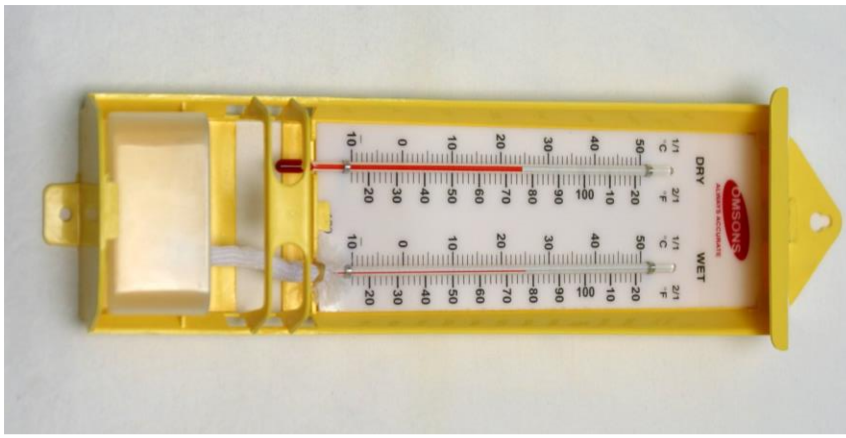
2) Optoelectronic Humidity Sensors:

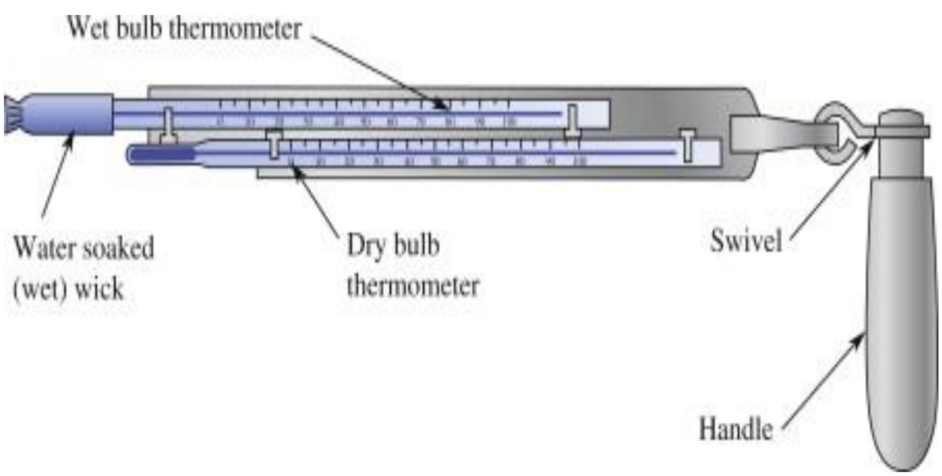
- These sensors are based on variation in refractive indices of material coated on silica fibre, U-shaped glass rod or prism base as shown in Fig. 5.
- As the humidity of environment changes, adsorption takes place through the film and it results in the modulation in output intensity of light.
- Fresnel reflection or Evanescent losses regulate the reflected/transmitted output intensity.
- Interference or polarization may also be taken place in some cases.
- These sensors are opto-electronic in nature so they have remote analysis capability and can be used at very remote places

Wet and Dry Bulb Psychrometer

- This humidity sensor works on the principle **of change in the temperature due to change in the humidity.**
- The temperature difference of two bulbs (wet and dry) of a Psychrometer is affected by the surrounding atmosphere's nature; temperature, pressure, humidity, etc.
- If all the factors governing the change in temperature are kept constant, it is seen that the temperature changes with the variation in humidity.
- The configuration of this type of hygrometer consists of two matched temperature sensors (wet-and-dry bulb, in this case).
- One sensor is covered with a porous medium at the bottom for example a wet sock, shoelace etc.

- Its wetness is maintained by a continuous flow of water on it from reservoir. Humid air is blown over these sensors.
- Due to the presence of humid airflow, water evaporates from the wet sock/shoelace.
- This evaporation causes the wet sensor to be chilled, which reduces the temperature in the sensor.
- This is an indication of the humidity in the environment.
- Readings on both the temperature sensors are recorded and the humidity is calculated with the help of the psychrometric graph.





SLING PSYCHROMETER

- a simple device for determining air humidity, called a *sling psychrometer*.
- It contains two thermometers, one of which is covered with a wick saturated with ambient temperature liquid water.
- These two thermometers are called *dry bulb* and *wet bulb*.
- When the sling psychrometer is spun rapidly in the air, the evaporation of the water from the wick causes the wet bulb thermometer to read lower than the dry bulb thermometer.

- After the psychrometer has been spun long enough for the thermometers to reach equilibrium temperatures, the unit is stopped and the two thermometers are quickly read.
- A psychrometric chart (or table) is then used to convert the
- dry bulb temperature T_{DB} and the
- wet bulb temperature T_{WB} into humidity information.
- The wet bulb temperature is approximately equal to the adiabatic saturation temperature,
- so $T_{WB} \approx T_2 = T_3$ in Eq. (12.31).

Fire Detecting Sensors

There are actually four different types of detectors that are used to sense the presence of a fire

The differences in these four types are found in how they detect a fire – heat is obviously triggered by temperature while the other three are from smoke.

- **Ionization** – Ionization smoke detectors actually have a constant electrical current running between wo metal plates inside of the device. The electrical current is disrupted when smoke enters the device chamber and triggers the alarm. This type of detector is great for quickly identifying fires that are fast-burning.
- **Photoelectric** – Photoelectric detectors work similarly to Ionization detectors, but with a beam of light instead of electricity. When smoke enters the chamber, the light beam is scattered, which then triggers the alarm. This type of devices is good at identifying smaller fires than an ionization detector. They are known to be highly reliable and rarely produce false alarms.
- **Heat** – Heat detectors work by detecting an increase in air temperature caused by flames. While these detectors have been known to trigger a few false alarms, they have a longer reaction time than other smoke detectors. False alarms may be triggered in buildings that are abnormally steamy, dusty, or humid and are best suited for buildings that are not continuously occupied such as warehouses or storage facilities.
- **Ionization/Photoelectric** – A favorite of many professionals, a combination ionization and photoelectric smoke detector is a considered by many to be the best type of detector. These devices house both types of smoke detectors (not heat) in one unit to ensure that any presence of smoke is detected as soon as possible.

Fire Alarm Control Units

The fire alarm control unit (FACU), formerly called the fire alarm control panel (FACP), contains the electronics that supervise and monitorthe integrity of the wiring and components of the fire alarm system. The FACU basically serves as the brain for the alarm system (Figure 14.2).

It receives signals from alarm-initiating devices, processes the signals, and produces output signals that activate audible and visual appliances. The FACU also transmits signals to an off-site monitoring station when provided. Power and fire alarm circuits are connected directly into this panel.

In addition, the remote auxiliary fire control units and notification appliance panels are considered to be part of the fire alarm system and are connected and controlled. Controls for the system are located in the FACU (Figure 14.3).

The FACU can also perform other functions, such as:

- Providing two-way firefighter communication Providing remote annunciator integration.
- Controlling elevators, HVAC, fire doors, dampers, locks, or other fire protection features

The FACU can also provide public address messages and mass notifications alerts through prerecorded evacuation messages or independent voice communications.

Primary Power Supply

- The primary electrical power supply usually comes from the building's main power connection to the local utility provider.
- In rare instances where electrical service is unavailable or unreliable, an engine-driven generator can provide the primary power supply.
- If such a generator is used, either a trained operator must be on duty 24 hours a day or the system must contain multiple engine driven generators.
- One of these generators must always be set for automatic starting. The FACU must supervise the primary power supply and signal an alarm if the power supply is interrupted (Figure 14.4).

Secondary Power Supply

- All fire alarm systems must have a secondary power supply. This requirement is designed so that the system will be operational even if the main power supply fails.
- The secondary power supply must be capable of providing normal, (nonalarm) standby conditions capacity and power to fully operate an alarm condition.
- The time period requirements for secondary power operation capabilities vary and can be found in NFPA® 72.
- Secondary power sources can consist of batteries with chargers, engine-driven generators with a storage battery, or multiple engine-driven generators, of which one must be set for automatic starting (Figure 14.5).
- NOTE: Some fire alarm control units are designed for both security and fire protection. In these types of systems, fire protection is engineered into the system to assume the highest priority.

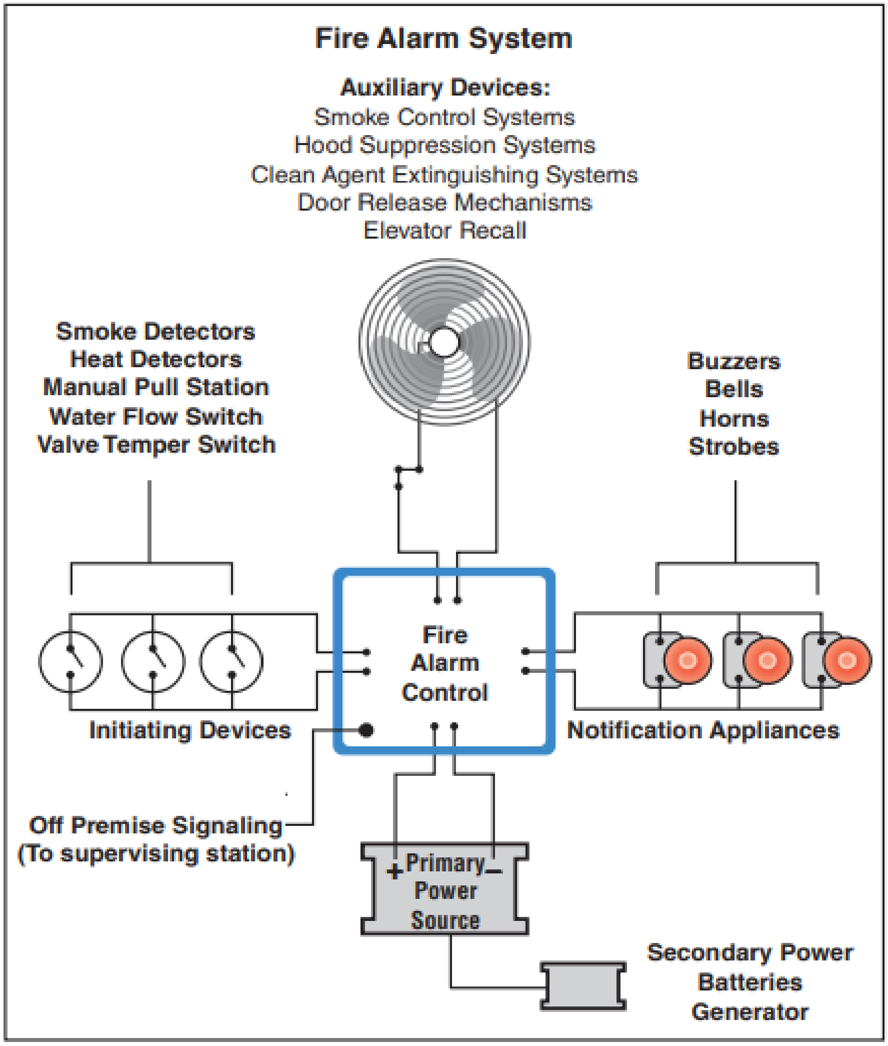


Figure 14.2 This schematic shows the different components of a fire alarm control unit (FACU), the central hub of an alarm system.

Figure 14.3 An FACU can monitor alarms, control elevators, and public address messages.

Figure 14.4 On the power supply circuit board, one switch should be permanently labeled as the FACU (sticker in the photo) to ensure that anyone doing maintenance on the circuit board does not deactivate that switch and create a safety hazard.

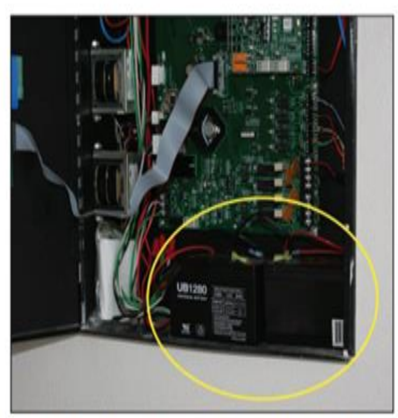


Figure 14.5 A backup battery, like the one under the circuit board in the photo, should be available to all components of a fire detection system if primary power is unavailable. *Courtesy of Ron Moore, McKinney (TX) Fire Department.*

Initiating Devices

- A fire detection system consists of manual and automatic alarm-initiating devices that are activated by the presence of fire, smoke, flame, or heat (Figure 14.6).
- The devices then send a signal to the FACU using one of two methods: a hard-wire system or a generated signal conveyed by radio wave over a special frequency to a radio receiver in the panel.

Both automatic and manual alarm initiating devices are :

- Manual pull stations
- Smoke detectors
- Flame detectors
- Heat detectors
- Combination detectors
- Waterflow devices

Notification Appliances

- Audible notification signaling appliances are the most common types of alarm-signaling systems used for signaling a fire alarm in a structure.
- Once an alarm-initiating device is activated, it sends a signal to the FACU, which then processes the signal and initiates actions.
- The primary action initiated is usually local notification, which can take the form of:
- ➢ • Bells • Buzzers • Horns • Speakers • Strobe lights • Other warning appliances

Depending on the system's design, the local alarm may either activate a single notification appliance, notification appliances within a specific zone, designated floor(s), or the entire facility. Notification appliances fall under the following categories (Figures 14.7 a-c,):

• Audible — Approved sounding devices, such as horns, bells, or speakers, that indicate a fire or emergency condition.

• Visual — Approved lighting devices, such as strobes or flashing lights, that indicate a fire or emergency condition.

• Textual — Visual text or symbols indicating a fire or emergency condition.

• Tactile — Indication of a fire or emergency condition through sense of touch or vibration

Additional Alarm System Functions

- Building codes have special requirements for some types of occupancies in case of fire.
- In these cases, the fire detection and alarm system can be designed to initiate the following actions:
- ➢ Turn off the heating, ventilating, and air-conditioning (HVAC) system
- ➢ Close smoke dampers and/or fire doors (Figure 14.8)
- ➢ Pressurize stairwells and/or operate smoke control systems for evacuation purposes
- ➢ Unlock doors along the path of egress
- ➢ Provide elevator recall to the designated floor and prevent normal operations (Figure 14.9).
- ➢ Operate heat and smoke vents

➢ Activate special fire suppression systems, such as preaction and deluge sprinkler systems or a variety of special-agent fire extinguishing systems

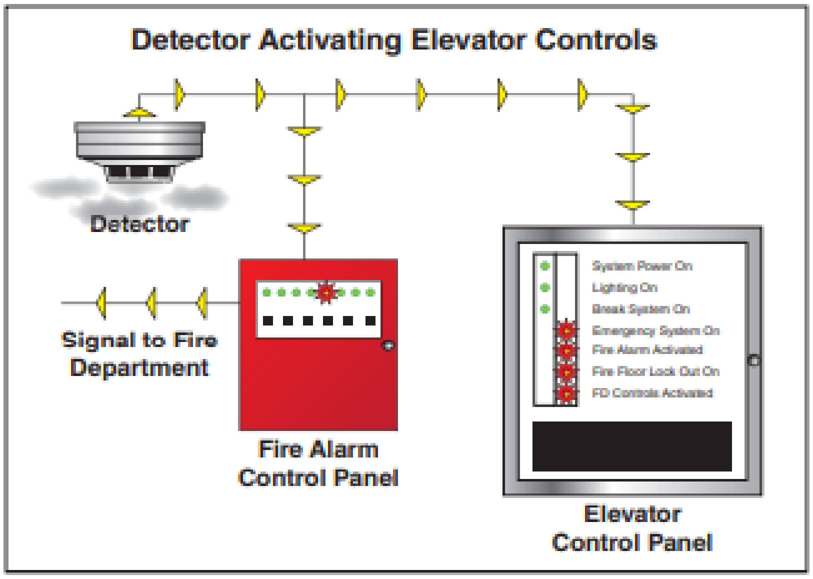


Figure 14.9 In this scenario, the activation of the fire detection system has caused an override of the elevator controls so that the elevator can be used by firefighters.

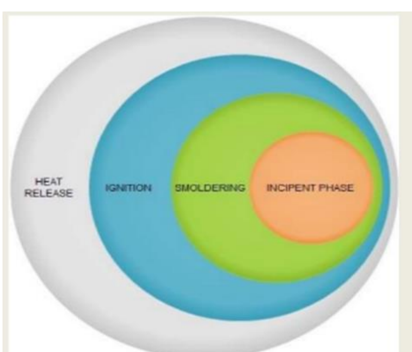
Figure 14.8 Magnetic door closures like this one are designed to remain open during normal building activity and release when alarms are activated to close the door.

Alarm Signaling Systems

- Fire detection and alarm systems are designed to receive certain types of signals from devices and perform an action based upon the type of signal received. Some signals may indicate a fire condition, while others may indicate that a device on the system needs to be serviced.
- The FACU should be programmed to respond to different signal types in an appropriate manner.
- Fire detection and alarm systems are equipped with three types of specialty signals, depending on the type and nature of the alarm they are reporting:

- An alarm signal is a warning of a fire emergency or dangerous condition that demands immediate attention. Locally adopted codes may require fire alarm signals from systems monitored by a supervising station to notify the responding fire department.
- Activation of smoke detectors, manual pull stations, waterflow switches, and other fire extinguishing systems are all initiating devices that send fire alarm signals.
- A supervisory signal indicates an off-normal condition of the complete fire protection system. Supervisory signals also include a returned-to-normal signal, meaning that the condition has been resolved.
- These signals are used to monitor the integrity of the fire protection features of the system.
- A trouble signal indicates a problem with a monitored circuit or component of the fire alarm system or the system's power supply.
- Each signal must be audibly and visually displayed at the FACU in a distinct manner that differentiates one type of signal from another.
- Trouble conditions include loss of primary power or failure or removal of an initiating device, such as a smoke detector.
- Alarm Signal — Signal given by a fire detection and alarm system when there is a fire condition detected.
- **Supervisory Signal** — Signal given by a fire detection and alarm system when a monitored condition in the system is off-normal.
- **Trouble Signal** — Signal given by a fire detection and alarm system when a power failure or other system malfunction occurs.

PHASES OF FIRE



Phases of fire

- **Incipient Phase:** Warming causes the emission of invisible but detectable gases like- CO_2, CO
- **Smoldering Phase:** Smoke is formed in this phase.
- **Ignition Phase:** Ignition temperature is reached and flames are present and therefore they emit radiation: mainly in UV or IR region.
- **Heat release Phase:** heat is released; the temperature of the space starts to rise rapidly.

Smoke Detection

Two types:

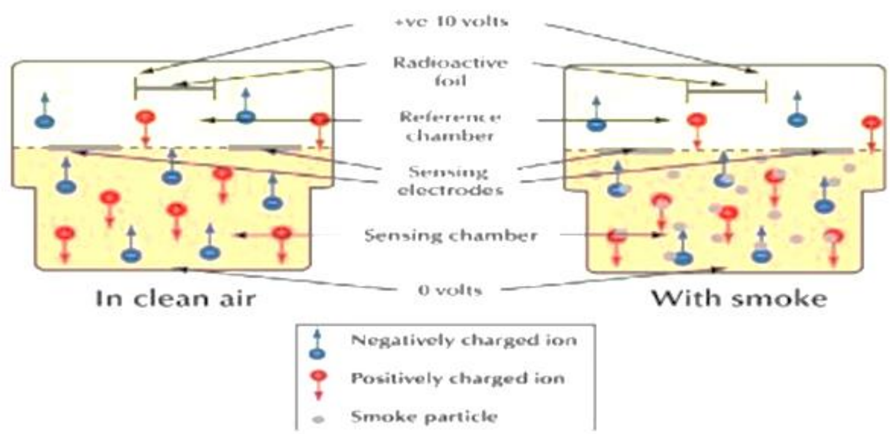
➢ Ionization Chamber Sensor

- Used in the incipient stage for early warning.
- It's inexpensive & better at detecting smaller amount of smokes produced by flaming fire.
- Response is very fast but also causes a lot of false alarm.

➢ Photoelectric Sensor

- It is effective in the smoldering stage.
- It must be maintained so that dust and dirt accumulation doesn't cause false alarm.

Ionization Chamber Detectors



•It contains two electrodes at different potential & alpha particle source that ionizes air in the chamber.

•The sensing part of the detector consists of two chambers - an open, outer chamber and a semi-sealed reference chamber within.

• A low activity radioactive foil of Americium 241 is mounted in the reference chamber which is an emitter of alpha particles.

• This enables formation of ion-pairs & causes current to flow between the inner and outer chambers when the detector is powered up.

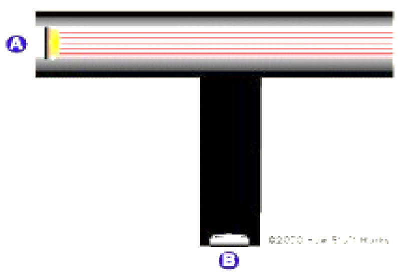
• As smoke enters the detector, particles become attached to the ions, causing a reduction in ion-pairs and consequently current flow in the outer chamber.

• the drop in the ionization current is constantly monitored and an alarm is triggered when it reaches a set point.

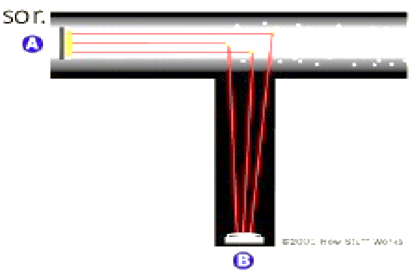
•The ionization current reflects air composition & rises as combustible gas concentration rises.

Photoelectric Detectors

In the normal case, the light from the light source on the left shoots straight across and misses the sensor



When smoke enters the chamber, however, the smoke particles scatter the light and some amount of light hits the sensor.



Advantages/disadvantages

- Detection distance
- Sensitivity
- Speed of response
- Range of applications

- False alarms
- High Cost
- Blinded by thick smoke, vapors, grease and oil deposits on the detector's window

Flame detection

- Basis of detection: Spectral band analysis, Flickering frequency, Radiation intensity threshold and detection algorithm.
- Flame flickering frequency (5-25cps) is different from ambient light sources and bulbs, tube (120cps) which helps in discrimination of the radiations.

Types of Flame detector

❖ **UV Detectors-** Detection is based on Geiger-Muller tube. When the counted pulses exceeds the threshold value fire alarm is activated.

1. Good for H_2 and CH_4 fuelled flames. It's unaffected by hot objects.
2. It's prone to false alarm and it's blinded by thick smoke, oil droplets etc.

❖ **IR Detectors-** Good for hydrocarbon based flames.

> Some IR detectors have flicker and statistical analysis algorithms to minimize the effects of black body sources, a false alarm source.

❖ **UV/IR Detectors-** Both UV "AND" IR sources must be present and exceeding their threshold levels to activate the alarm in one configuration.

> In other, UV "OR" IR source presence can trigger the alarm.

- **Dual IR-** Have longer detection ranges than UV or IR sensors and are more fuel specific in their applications.

  > Desensitized by high background levels of IR, reducing their ability to detect a fire

- **Multispectrum IR-** These detectors offer greater detection ranges and give fewer false alarms.

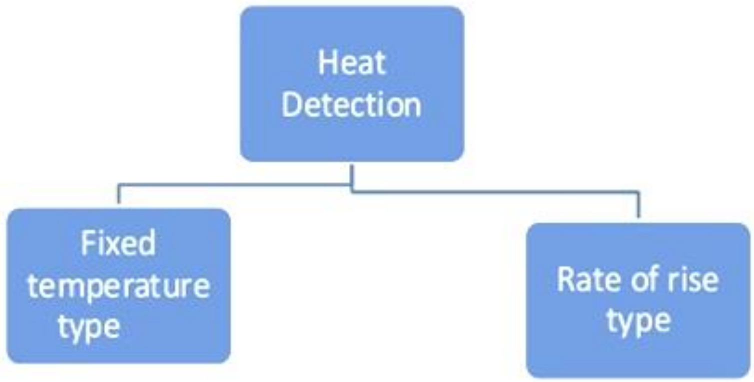
  > Different manufacturer uses different flame detection algorithm.

- **Closed Circuit Television-** Only sensitive to the red-green-blue spectrum and are not suitable for blue/translucent flames from such fuels as hydrogen and methanol.

  User is able to verify the presence of a fire before taking any action

Heat Detection

- Oldest type of automatic fire detection.
- They have the lowest false alarm rate but they are slow in response.
- They can't differentiate between heat of fire and that of furnace.
- Used in confined place where rapid fire is expected or in places where other methods fail.

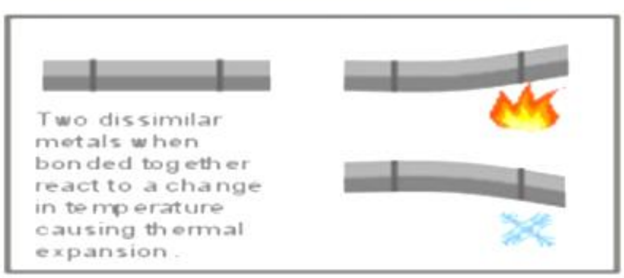


Fixed temperature heat detectors

- Detectors are designed to alarm when the temperature of the operating elements reaches a specific predefined air temperature.
- They cover a wide range of temperature
- Types of fixed temperature heat detectors:

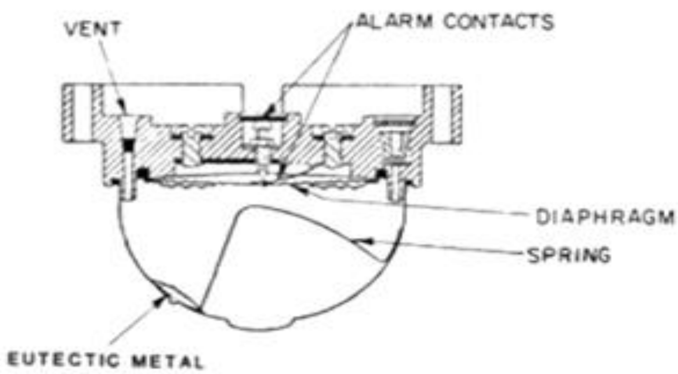
❖ **Electro-mechanical heat detectors-** Contains a bi-metallic strip as a part of electric circuit, that completes the circuit when a particular temperature is reached.

Electromechanical - Bi-Metal Strip



❖ **Fusible link type-** An eutectic alloy is used, which is fixed on a spring. It changes from solid to liquid at a particular temperature and acts as a solder.

> This enables the spring to release & actuate alarm.



❖ **Opto-mechanical type-** Modern variation of electro-mechanical type.

>It contain one or more fiber optic cables separated by a heat sensitive insulator.

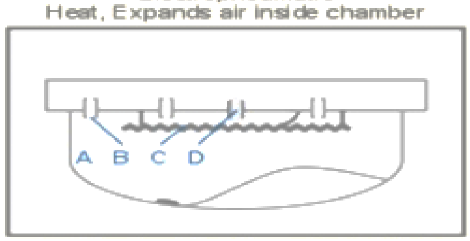
> A focused light signal is passed through the fiber optic cable. When exposed to heat, the heat sensitive insulator changes state from a solid to a molten state which has the effect of discontinuation of the focused light signal.

> This actuates the alarm.

Rate of rise heat detector

- As an effect of flaming fire the air temperature rises rapidly
- The detector functions when the rate of rise in air temperature exceeds a preset value; generally (12-15)F/minute.
- Rate-of-rise detectors are designed to compensate for the normal changes in ambient temperature that are expected under non-fire conditions.

Electropneumatic
Heat, Expands air inside chamber



A - Chamber, B - Atmospheric Vent
C - Diaphragm, D - Electrical Contact

Other detection methods

- <u>Air aspirating system-</u> It draws air draws an air sample into the detection chamber, via the pipe network.

  1. The sample is analyzed for the existence of smoke, and then returned to atmosphere.
  2. If smoke is present in the sample, it is detected and an alarm signal is transmitted to the main fire alarm control pane

- <u>Gas Sensors-</u> New systems are being developed that can analyze the concentration of particular type of gases like- CO, CO_2

  > When the concentration exceeds a limit the alarm is triggered.

Electro-pneumatic type heat detector

•It's a rise-of-rate type heat detector.

•Electro-pneumatic heat detectors comprise a controlled vented chamber containing a diaphragm that moves due to a pressure differential according to the rate of change of the ambient temperature.

•When the ambient temperature changes faster than the calibrated rate which the vent has been designed to release, the diaphragm moves sufficiently to create an electrical circuit to indicate an alarm.

•Electro-pneumatic heat detectors operates at a range of temperatures because they respond to the rate of change in temperature, not at a fixed temperature only.

Metal detectors

INTRODUCTION

Metal detector is a device that can detect metal, the basics can make a sound when it is near some metal. Metal detectors work on the principle of transmitting a magnetic field and analysing a return signal from the target and environment. when some metals are coming close to the coil the amplitude of the reflective pulse is getting little lower and a duration of the pulse a little longer. The need for detection is very clear to protect our self from any kind of danger.

PRINCIPLE OF OPERATION

The operation of a metal detector is based on the **principle of electromagnetic induction.** Metal detectors contain one or more inductor coils. When metal is placed in a close proximity to a varying magnetic field (generated by the coil or coils), currents are induced in the metallic part; These current are called eddy Currents. The eddy Currents, in turn, induce their own magnetic field (**called eddy field**). These fields act in such a direction as to oppose that generated by the coils. The resultant field and using a specially designed electronic circuit can indicate the type of material being magnetized. Here in our metal detector circuit transistor is used as a colpitts oscillator. If we increase L1's inductance it will cause the decrease in frequency and if we decrease this L1's inductance it will cause the increase in frequency.

CIRCUIT DIAGRAM

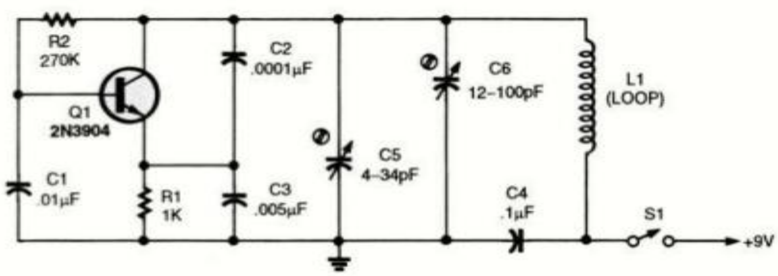


Fig. 1. Here is the schematic for the single-transistor circuit. Transistor Q1 is a general-purpose, NPN transistor; and it serves as the heart of a Colpitts oscillator circuit.

Types of Metal detectors

1) Beat-frequency oscillator (BFO) 2) Pulse induction detector (PI), 3) Very Low Frequency (VLF).

"BFO" DETCTOR DESIGN

- The basic way the beat frequency oscillator (BFO) works, when a detector coil is above some metal, it will change the frequency in the detector oscillator, which has the detector coil in the frequency dependent circuit.
- This relative simple metal detector is not a real BFO, but it is the closest group of detectors. When the metal is near the detector coil the signal is send to a timer pin. Internally the calculation is made, and showed on the LED and some different sounds are made.

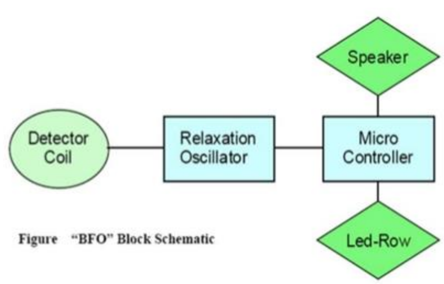


Figure "BFO" Block Schematic

Advantages

1) Circuit diagram is very simple.

2) We can easily measure the oscillation frequency of this circuit.

3) It has some sensitivity through which it can sense the metal easily.

Disadvantages

1) It has less sensitivity.

2) Instead of variable capacitor we cannot use any other capacitor for tuning purposes.

- The equipment is compact, simple in design and can be used practically anywhere needs.
- This circuit may also be constructed by using chip and the chip is CS209A.
- Even the detectors with good coil compensation could not always detect the smaller target to the required depth in all lanes.
- The metal detector gives a respectable range for beat frequency operation (BFO) up to 90mm.

APPLICATIONS

❖ **Airport and Building Security**

- Metal detectors are used for airport and building security to determine whether guns, knives, or other weapons are being transported onto aircraft or into public buildings.

❖ **Construction Industry**

- Metal detectors are also used in the construction industry to locate steel reinforcement bars embedded in concrete, and to pinpoint metal pipes and wires in floors and walls. This is useful in avoiding unnecessary damage when replacing plumbing or wiring in a building or house.

❖ **Civil Engineering**

- In Civil Engineering, metal detector are used to locate rebar (strengthen steel used as rod in concrete) .
- Rebar detectors are less sophisticated. Detectors can only locate metallic objects below the surface.

❖ **Land Mine Detection**

- Land mine detector can sense as little as 0.5 grams of metal.
- So, now-a-days militaries are using land mine detector to identify the land mine.
- Military has used metal detector to pinpoint buried land mines since world war1.

❖ **Archaeological exploration, Geological research and Item recovery.**

Model Questions

1. Explain the sensors used for the measurement of Linear and angular displacement
2. Explain the working of potentiometer resistive sensor and capacitive sensor with neat diagrams
3. Write notes on inductive, optical encoders and proximity sensors with diagrams
4. Discuss about different types of Tachometers and their applications
5. Explain tacho-generators and resolvers with neat sketches
6. Demonstrate the construction and working of Bimetallic and RTDs.
7. Explain the working principle of thermocouple and thermistor with neat sketches
8. Discuss about the working of radiation and optical pyrometer with neat diagrams
9. Explain how to use Optochemical, optoelectronic and sling psychrometer humidity sensors.
10. Compare capacitive and resistive humidity measurement.
11. Write short notes on (a) strain gauges (b) fire, smoke and metal detectors (c) hot and wet bulbs humidity measurement

SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHATRONICS ENGINEERING

Unit III - Measurement of Non Electrical Parameters – 2 - SMR1302

SMR1302 SENSORS AND INSTRUMENTATION
UNIT III MEASUREMENT OF NON ELECTRICAL PARAMETERS - 2

TOPICS:

Force measurement: Resistive type strain gauges: Bridge configurations, Temperature compensation, Load cells, Fiber optic strain gauge - Semiconductor strain gauges- Piezo electric transducers. Vacuum Measurement: McLeod Gauge, Thermal Conductivity Gauge – Ionization Gauge. Airflow: Anemometers Light: UV, IR, Light emitter and detector - Introduction to Acoustics and acoustic sensors: Ultrasonic sensor - Types and working of Microphones and Hydrophones – Sound level meters- Nuclear radiation sensors.

Force measurement

FORCE SENSORS are devices that are designed to translate applied mechanical forces, such as tensile and compressive forces, into output signals whose value can be used to reflect the magnitude of the force.

The signals may be sent to indicators, controllers, or computers to inform operators or serve as inputs to provide control over machinery and processes. Although strictly speaking force sensors and force transducers differ from each other, the two terms are most commonly used interchangeably.

Force sensors are available in a wide range of sizes and can be used to detect forces from fractions of an ounce to hundreds of tons.

They are used in a wide range of products and applications such as musical instruments, medical applications, automobiles to detect seat occupancy, and process control in manufacturing facilities.

Types of Force Sensors

- Several different types of force sensors exist, each of which makes use of different technologies to sense the magnitude of a given force and create an output signal. The most common types of force sensors include

➢ Load Cells,

➢ Strain Gages, and

➢ Force Sensing Resistors (FSRs)

Other types of force sensors

❖ Two additional force sensor types are

❖ Optical force sensors and

❖ Ultrasonic force sensors.

Load Cells

- Load cells (sometimes spelled as loadcells) are a type of force sensor/force transducer that converts an applied force into an output signal that can be used to measure forces such as compressive forces, most commonly weight.
- Load cells can use different technologies to produce an output and so different types of load cells are available, including:

Pneumatic load cells consist of a source of pressurized air or gas that is fed through a pressure regulator to a chamber inside the load cell.

- A flexible diaphragm is compressed when a compressive force is applied to the plate on the top surface of the load cell.
- A pressure gauge measures the pneumatic pressure resulting from the weight applied.
- The amount of pressure needed to balance out the weight of the object being measured can be used to measure the weight and can be converted to an electrical signal if needed.

Hydraulic load cells are similar to pneumatic load cells and make use of a pressurized liquid such as hydraulic oil or water to balance out the applied load.

- A flexible diaphragm inside the load cell is mounted beneath a piston attached to a plate called the load platform.
- As a load is applied to the load cell, the weight of the object moves the piston which flexes the diaphragm and compresses the fluid in the chamber, causing an increase in the fluid pressure.
- A pressure gauge monitors the change in pressure, whose value is directly proportional to applied weight or force. After proper calibration, the pressure reading can be converted into weight and read directly from an analog gauge or may be converted into an electrical output signal such a standard 4-20mA output.
- Hydraulic load cells, as well as the similar pneumatic type, share the characteristic that they do not directly rely on the use of electrical current and therefore can be used in conditions where there is the risk of a potential explosive hazard.

Piezoelectric crystal load cells are based on the concept of the piezoelectric effect, piezo a Greek word meaning “to squeeze”.

- Within the load cell are a set of crystal elements containing an electrode between the crystals. In the absence of mechanical stress, the crystals are unstressed and exhibit a balanced electrical charge. When subjected to a load or mechanical stress, the crystal becomes deformed which results in a change to the center of symmetry of the electrical charges for the crystal which produces a proportional change in the electrical charge, which then can be measured.

- Measuring the amount of charge provides an indication of the magnitude of the weight or force applied to the piezoelectric crystal load cell. A device called a charge amplifier can be employed to convert the magnitude of the electrical charge in the crystal to an analog or digital output signal for display or processing.

Inductive load cells feature a ferromagnetic core within the coil of a solenoid. As a load is applied to the sensor, the applied force changes the position of the core within the coil resulting in a change to the inductance of the coil or inductor.

- The measured change in inductance can be used to establish the magnitude of the movement of the coil and can be calibrated to a measurement of the applied force. A device called a reluctance load cell operates similarly, changing the magnetic reluctance of an air gap in direct response to the application of a force.

Capacitive load cells use the principle of variation in the capacitance of the sensor to measure the magnitude of the applied load. Within the device are a set of parallel plates that are electrically charged by a current until a stable charge state is reached, forming a capacitor.

- The amount of stored charge on the plates is directly proportional to the plate area and inversely proportional to the separation distance or gap between the plates.
- As a load is applied to the load cell, the applied force changes the separation distance between the plates, thereby changing the capacitance. This change can be measured electrically and converted into an indication of the weight that has been applied to the load cell.

Magnetostrictive load cells operate based on the principle of magnetostriction, wherein the magnetic permeability of ferromagnetic materials will change when those materials are subjected to applied stress. This means that when the material becomes magnetized, it will be subjected to a stress or strain changing its length or inducing a torque.

- The principal also works in reverse – induced stress applied to the material will result in a change to the magnetic state of the material. Magnetostrictive force sensors make use of this property to sense the amount of deflection that has occurred in the force sensor as a result of the applied load.
- The deflection can then be translated into a value representing the weight of the object or the magnitude of the applied force.

Strain gage load cells are ones that make use of a strain gage as the sensing element. The following section explains what strain gages are and how they function.

Strain gages

- Strain gages (also spelled as strain gauges) are a type of sensor element whose electrical resistance varies as a result of an applied force. Stress is the term used to describe the internal resistance force that an object will exhibit to the external application of force, while a strain is the measure of the amount of deformation and displacement that the object will experience as a result of the applied external force.

- The typical strain gage consists of an insulating substrate onto which a conductive metallic foil pattern has been deposited in a zig-zag pattern. When the strain gage is subjected to a force, the device will either compress or elongate depending on the direction of the applied force. The elongation or compression of the strain gage distorts the metallic foil pattern on the substrate, which changes its electrical resistance. The change in electrical resistance can be used to measure the applied force to the strain gage. An electrical bridge network known as a Wheatstone bridge circuit is typically used to convert the change in resistance of the strain gage to a voltage measurement.

Force Sensing Resistors (FSRs)

- Force Sensing Resistors (FSRs), also known as printed force sensors or force-sensitive resistors, are a type of piezoresistive sensing technology that consists of a semi-conductive material or ink which is sandwiched between two substrates that are separated by a spacer.
- When a force is applied to the device, a conductive film is deformed and presses against a conductive ink printed on the substrate.
- As more of the conductive film comes in contact with the printed conductive layer, the resistance of the device decreases. With zero force applied, the sensor exhibits a very high resistance (on the order of Meg-ohms).
- The resistance drops inversely proportional to the applied force.
- Since conductance is the inverse of resistance, the FSRs exhibit a linear increase in conductance with increased force.
- Force sensing resistors can be used in several types of force sensing use cases:

➢ To detect the rate of change of an applied force and

➢ To detect the that a relative change in the applied force

➢ To detect contact or touch

➢ To detect that a force has exceeded a set threshold

➢ FSRs can be configured for point source detection or used in an array design for detecting force distribution applied over an area (pressure).

- The advantages of FSRs are that they are thin and flexible, are available in a variety of styles & sizes, are durable, have lower power consumption, and are low in cost.
- The primary disadvantage lies in their precision and repeatability, where repeated measurements may vary by 10% or more.

Strain Gage

Strain gage is one of the most popular types of transducer. It has got a wide range of applications. It can be used for measurement of force, torque, pressure, acceleration and many other parameters.

The basic principle of operation of a strain gage is simple:

when strain is applied to a thin metallic wire, its dimension changes, thus changing the resistance of the wire. Let us first investigate what are the factors, responsible for the change in resistance.

Metallic Strain Gage

- Most of the strain gages are metallic type. They can be of two types: Unbonded and Bonded.
- The unbonded strain gage is normally used for measuring strain (or displacement) between a fixed and a moving structure by fixing four metallic wires in such a way, so that two are in compression and two are in tension, as shown in fig. (a).
- On the other hand, in the bonded strain gage, the element is fixed on a backing material, which is permanently fixed over a structure, whose strain has to be measured, with adhesive. Most commonly used bonded strain gages are metal foil type. The construction of such a strain gage is shown in fig. (b).
- The metal foil type strain gage is manufactured by photo-etching technique. Here the thin strips of the foil are the active elements of the strain gage, while the thick ones are for providing electrical connections. Because of large area of the thick portion, their resistance is small and they do not contribute to any change in resistance due to strain, but increase the heat dissipation area.
- Also it is easier to connect the lead wires with the strain gage. The strain gage in fig. 6(b) can measure strain in one direction only. But if we want to measure the strain in two or more directions at the same point, strain gage rosette, which is manufactured by stacking multiple strain gages in different directions, is used. Fig. shows a three-element strain gage rosette stacked at 45 Degrees.
- The backing material, over which the strain gage is fabricated and which is fixed with the strain measuring structure has to satisfy several important properties. Firstly, it should have high mechanical strength; it should also have high dielectric strength.
- But the most important it should have that it should be non-hygroscopic, otherwise, absorption of moisture will cause bulging and generate local strain. The backing materials normally used are impregnated paper, fibre glass, etc. The bonding material used for fixing the strain gage permanently to the structure should also be non-hygroscopic. Epoxy and Cellulose are the bonding materials normally used.

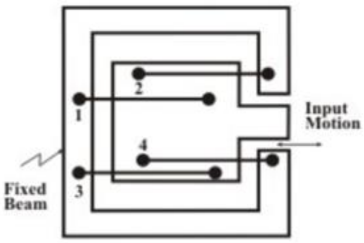


Fig. (a) Unbonded metallic strain gage

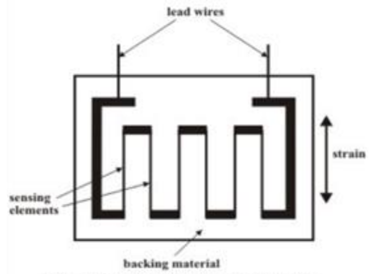


Fig. (b) bonded metal foil type strain gage

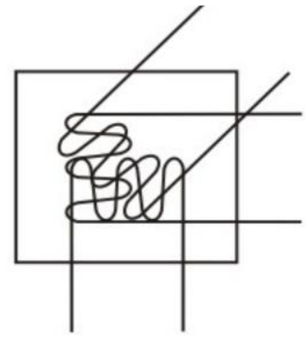


Fig. Three-element strain gage rosette- 45° stacked.

Gauge Factor

- Let us consider a long straight metallic wire of length l circular cross section with diameter d (fig.).
- When this wire is subjected to a force applied at the two ends, a strain will be generated and as a result, the dimension will change (l changing to $l+\Delta l$, d changing to and A changing to $A+\Delta A$).
- For the time being, we are considering that all the changes are in positive direction. Now the resistance of the wire:

$R = \frac{\rho l}{A}$, where ρ is the resistivity.

From the above expression, the change in resistance due to strain:

$$\Delta R = \left(\frac{\partial R}{\partial l}\right)\Delta l + \left(\frac{\partial R}{\partial A}\right)\Delta A + \left(\frac{\partial R}{\partial \rho}\right)\Delta \rho$$

$$= \frac{\rho}{A}\Delta l - \frac{\rho}{A^2}\Delta A + \frac{l}{A}\Delta \rho$$

$$= R\frac{\Delta l}{l} - R\frac{\Delta A}{A} + R\frac{\Delta \rho}{\rho}$$

or,

$$\frac{\Delta R}{R} = \frac{\Delta l}{l} - \frac{\Delta A}{A} + \frac{\Delta \rho}{\rho} \qquad \textbf{(1)}$$

Now, for a circular cross section, $A = \frac{\pi d^2}{4}$; from which, $\Delta A = \frac{\pi d}{2}\Delta d$.

Alternatively,

$$\frac{\Delta A}{A} = 2\frac{\Delta d}{d}$$

Hence,

$$\frac{\Delta R}{R} = \frac{\Delta l}{l} - 2\frac{\Delta d}{d} + \frac{\Delta \rho}{\rho} \qquad \textbf{(2)}$$

Now, the *Poisson's Ratio* is defined as:

$$\upsilon = -\frac{lateral \quad strain}{longitudinal \quad strain} = -\frac{\Delta d / d}{\Delta l / l}$$

The Poisson's Ratio is the property of the material, and does not depend on the dimension.

So, **(2)** can be rewritten as:

$$\frac{\Delta R}{R} = (1+2\upsilon)\frac{\Delta l}{l} + \frac{\Delta\rho}{\rho}$$

Hence,

$$\frac{\Delta R/R}{\Delta l/l} = 1 + 2\upsilon + \frac{\Delta\rho/\rho}{\Delta l/l}$$

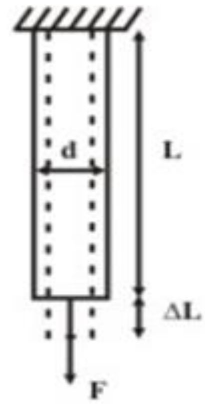


Figure Change of resistance with strain

The last term in the right hand side of the above expression, represents the change in resistivity of the material due to applied strain that occurs due to the *piezo-resistance property* of the material.

In fact, all the elements in the right hand side of the above equation are independent of the geometry of the wire, subjected to strain, but rather depend on the material property of the wire.

Due to this reason, a term *Gage Factor* is used to characterize the performance of a strain gage.

The Gage Factor is defined as:

$$G := \frac{\Delta R/R}{\Delta l/l} = 1 + 2\upsilon + \frac{\Delta\rho/\rho}{\Delta l/l} \qquad \textbf{(3)}$$

- For normal metals the Poisson's ratio υ varies in the range:

  $0.3 \leq \upsilon \leq 0.6$, while the piezo-resistance coefficient varies in the range:

$$0.2 \leq \frac{\Delta\rho/\rho}{\Delta l/l} \leq 0.6 .$$

Thus, the Gage Factor of metallic strain gages varies in the range 1.8 to 2.6. However, the semiconductor type strain gages have a very large Gage Factor, in the range of 100-150.

This is attained due to dominant piezo-resistance property of semiconductors. The commercially available strain gages have certain fixed resistance values, such as, 120Ω, 350 Ω, 1000 Ω, etc. The manufacturer also specifies the Gage Factor and the maximum gage current to avoid self-heating (normally in the range 15 mA to 100 mA). The choice of material for a metallic strain gage should depend on several factors. The material should have low temperature coefficient of resistance. It should also have low coefficient for thermal expansion. Judging from all these factors, only few alloys qualify for a commercial metallic strain gage.

They are:

- *Advance* (55% Cu, 45% Ni): Gage Factor between 2.0 to 2.2
- *Nichrome* (80% Ni, 20% Co): Gage Factor between 2.2 to 2.5
- Apart from these two, *Isoelastic* -another trademarked alloy with Gage Factor around 3.5 is also in use.
- Semiconductor type strain gages, though having large Gage Factor, find limited use, because of their high sensitivity and nonlinear characteristics.

Semiconductor type strain gage

Semiconductor type strain gage is made of a thin wire of silicon, typically 0.005 inch to 0.0005 inch, and length 0.05 inch to 0.5 inch. They can be of two types: p-type and n-type. In the former the resistance increases with positive strain, while, in the later the resistance decreases with temperature. The construction and the typical characteristics of a semiconductor strain gage are shown in fig.8. MEMS pressure sensors is now a days becoming increasingly popular for measurement of pressure. It is made of a small silicon diagram with four piezo-resistive strain gages mounted on it. It has an in-built signal conditioning circuits and delivers measurable output voltage corresponding to the pressure applied. Low weight and small size of the sensor make it suitable for measurement of pressure in specific applications.

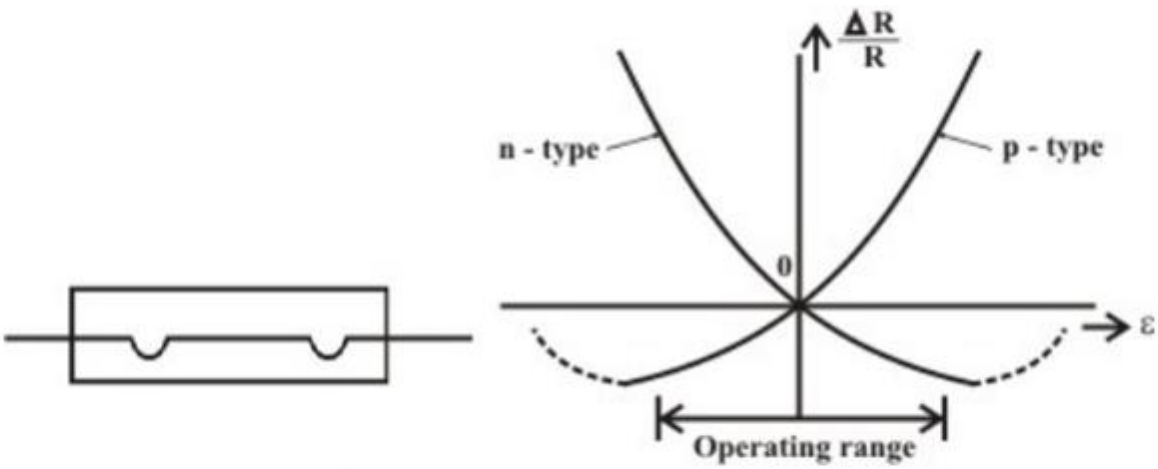


Fig. (a) construction and (b) characteristics of a semiconductor strain gage

Strain Gage Bridge

Normal strain experienced by a strain gage is in the range of micro strain (typical value: 100 x 10-6). As a result, the change in resistance associated with it is small (Δ RR = Gε). So if a single strain gage is connected to a wheatstone bridge, with three fixed resistances, the bridge output voltage is going to be linear (recall, that we say the bridge output voltage would be linearly varying with Δ RR , if Δ RR does not exceed 0.1).

But still then, a single strain gage is normally never used in a wheatstone bridge. This is not because of improving linearity, but for obtaining perfect temperature compensation. Suppose one strain gage is connected to a bridge with three fixed arms. Due to temperature rise, the strain gage resistance will change, thus making the bridge unbalance, thus giving an erroneous signal, even if no strain is applied. If two identical strain gages are fixed to the same structure, one measuring compressional strain and the other tensile strain, and connected in the adjacent arms of the bridge, temperature compensation can be achieved.

If the temperature increases, both the strain gage resistances will be affected in the same way, thus maintaining the bridge balance under no strain condition. One more advantage of using the push-pull configuration is increasing the sensitivity. In fact, all the four arms of the bridge can be formed by four active gages; this will improve the sensitivity further, while retaining the temperature compensation property. A typical strain gage bridge is shown in fig. It can be shown that if nominal resistances of the strain gages are same and also equal gage factor G, then the unbalanced voltage is given be: where ε1 , ε2 , ε3 , ε4 are the strains developed with appropriate signs.

$$e_0 = \frac{EG}{4}\left(\varepsilon_1 + \varepsilon_3 - \varepsilon_2 - \varepsilon_4\right)$$

where ε_1, ε_2, ε_3, ε_4 are the strains developed with appropriate signs.

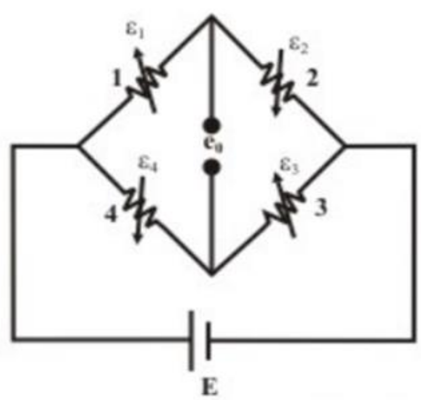


Fig. Strain gage bridge with four active gages

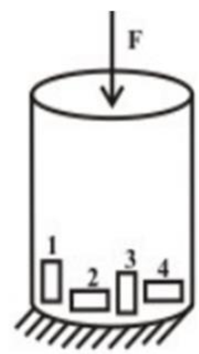


Fig. Load cell with four strain gages

Load cells

Load cells are extensively used for measurement of force; weigh bridge is one of the most common applications of load cell. Here two strain gages are fixed so as to measure the longitudinal strain, while two other measuring the transverse strain, as shown in fig.

The strain gages, measuring the similar strain (say, tensile) are placed in the opposite arms, while the adjacent arms in the bridge should measure opposite strains (one tensile, the other compressional). If the strain gages are identical in characteristics, this will provide not only the perfect temperature coefficient, but also maximum obtainable sensitivity from the bridge.

The longitudinal strain developed in the load cell would be compressional in nature, and is given by:

The strain gages 1 and 3 will experience this strain, while for 2 and 4 the strain will be

$$\varepsilon_1 = -\frac{F}{A\ E} \qquad \varepsilon_2 = \frac{\nu F}{A E}$$

where F is the force applied, A is the cross sectional area and Y is the Young's modulus of elasticity and where ν is the Poisson's ratio.

Cantilever beam can be used for measurement up to 10 kg of weight. One end of the cantilever is fixed, while the other end is free; load is applied at this end, as shown in fig. 12. The strain developed at the fixed end is given by the expression:

where, l = length of the beam t = thickness of the cantilever b = width of the beam E = Young's modulus of the material The strain developed can be measured by fixing strain gages at the fixed end: two on the top side of the beam, measuring tensile strain +ε and two on the bottom measuring compressional strain – ε (as shown in fig. 12) and using eqn.

$$\varepsilon = \frac{1.08FR}{Ebt^2}$$

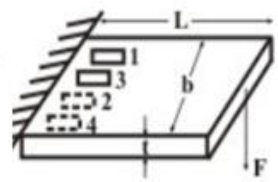


Fig. Cantilever Beam

Proving Rings can be used for measurement of both compressional and tensile forces. The advantage of a Proving Ring is that, because of its construction more strain can be developed compared to a load cell. The typical construction of a Proving Ring is shown in fig.11. It consists of a hollow cylindrical beam of radius R, thickness t and axial width b. The two ends of the ring are fixed with the structures between which force is measured. Four strain gages are mounted on the walls of the proving ring, two on the inner wall, and two on the outer wall. When force is applied as shown, gages 2 and 4 will experience strain –ε (compression), while gages 1 and 3 will experience strain + ε (tension).

The magnitude of the strain is given by the expression:

$$e_0 = \frac{EG}{4}\left(\varepsilon_1 + \varepsilon_3 - \varepsilon_2 - \varepsilon_4\right)$$

where ε_1, ε_2, ε_3, ε_4 are the strains developed with appropriate signs.

The four strain gages are connected in a bridge and the unbalanced voltage can easily be calibrated in terms of force to be measured.

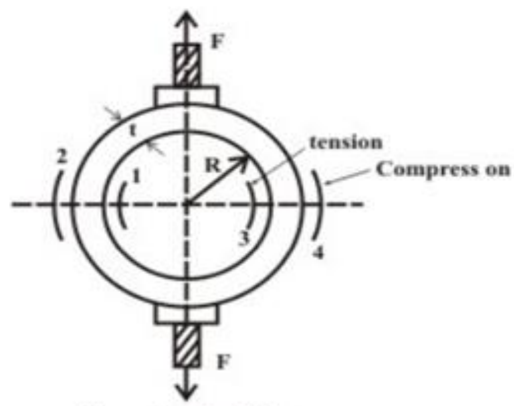


Fig. Proving Ring

Optical force sensors

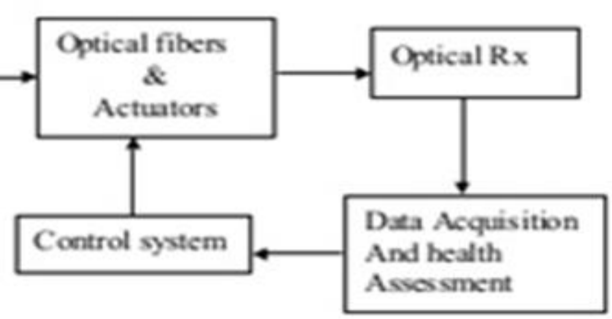
Optical force sensors typically employ a fiber optic cable into which has been inscribed a Fiber Bragg Grating (FBG) at specific intervals along the length of the cable. When the cable is subjected to stress or strain, the separation distance of the grating changes. By monitoring the reflections from light as it is passed through the cable, the degree of deformation (elongation or compression) can be established and used to determine the force applied.

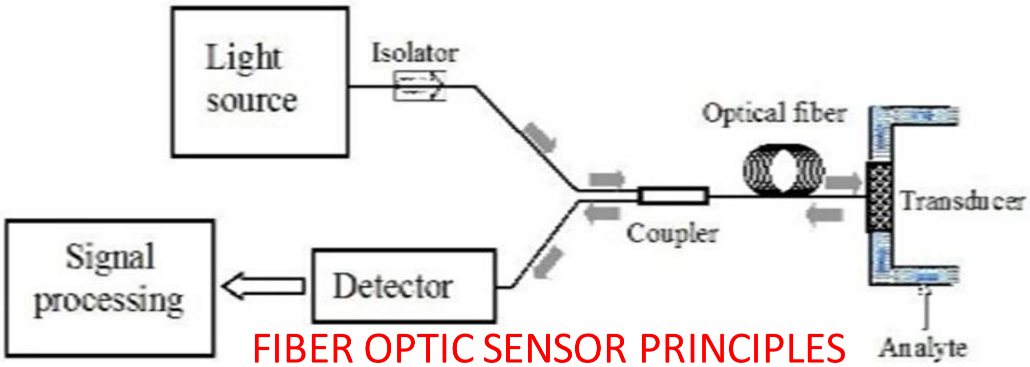
Ultrasonic force sensors

Ultrasonic force sensors emit high-frequency sound waves from an ultrasonic transducer and sense any changes to received pulses as a result of external forces to determine their presence.

Optical strain gauges or fiber optical (strain) sensors:

They consist of an optical source (Laser, LED, Laser diode, etc.), optical fiber, sensing or modulator element which transduces the measurand to an optical signal), an optical detector and processing electronics (oscilloscope, optical spectrum analyzer etc.)





FIBER OPTIC SENSOR PRINCIPLES

FORCE Measurement: Resistive Type

Strain Gauge as force Sensor

- Strain gauge based sensors work on the principle of change in electrical resistance.
- When, a mechanical element subjects to a tension or a compression the electric resistance of the material changes.
- This is used to measure the force acted upon the element.
- Figure shows a strain gauge load cell.
- It comprises of cylindrical tube to which strain gauges are attached.
- A load applied on the top collar of the cylinder compress the strain gauge element which changes its electrical resistance.
- Generally strain gauges are used to measure forces up to 10 MN.
- The non-linearity and repeatability errors of this transducer are ±0.03% and ±0.02% respectively.

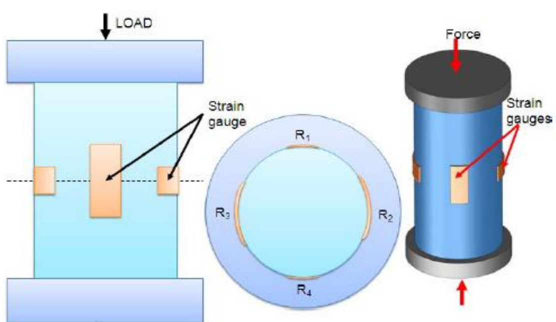


Figure: Strain gauge load cell

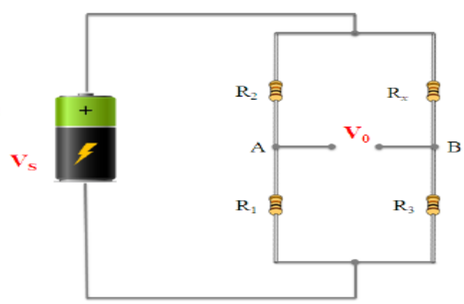
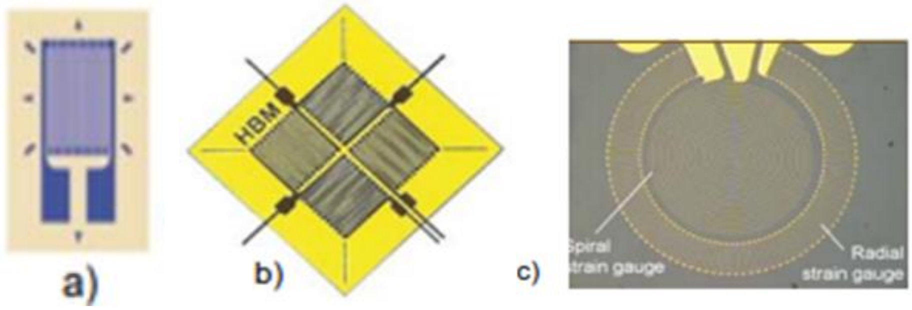


Figure: Wheatstone's bridge

Strain gauges and Wheatstone bridges constitute the basic instrumentation for electrical measurement of non-electrical quantities.The strain gauge is a device for measuring the changes in distances between two points in solid bodies that occur when the body is deformed. They respond to mechanical strain (unit deformation), as a function of the applied force / load.



(a) typical foil strain gauge (b) a group of four shear SGs for torque measuring (c) a pressure rosette with spiral and radial grids

Figure 1. Different types of strain gauges and rosettes

Strain gauges experience a change of an electrical parameter, usually their resistance when they are stretched or strained, being permanently located on special elastic elements and influenced by a large variety of measurands such as: Mechanical (force, torque, acceleration, pressure, flow rate, viscosity) Biomedical or Chemical quantities. Three examples are given in Figure 1: Their principal parameter is the gauge factor k, also called strain coefficient of resistance, defined as

$$k = \frac{\Delta R / R}{\Delta l / l} = 1 + 2\,\nu + \frac{\Delta \rho / \rho}{\Delta l / l} \qquad (1)$$

where ν is the Poisson's ratio (transverse sensitivity), while the relative variation of length Δl /l is just the strain ε, and ρ is the wire resistivity.

Wheatstone Bridges

The classic configuration associated to the strain gauge sensors is the low-power, Wheatstone bridge in Figure 2 as an input-output device (a two-port element). This is a complete network made of four sides (usual strain gauge values are: 120 Ω, 350 Ω or 1 kΩ), four nodes (A, B, C, D) and two diagonals (UA – supply, UE – signal). Considering that the bridge is supplied from a constant voltage source of negligible internal resistance and its load is an amplifier having practically infinite input impedance

Applying Kirchhoff's laws, the following relationship is resulting as in Eq (2) and (3)

$$\frac{U_E}{U_A} = \frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \qquad (2)$$

The initial balance condition is: $R_1 \cdot R_3 = R_2 \cdot R_4$ (3)

Meaning that the products of the resistances in the opposed arms should be equal, confirming the golden rule of strain measurement by Wheatstone bridge:

- the effects from two opposite arms are added, and the effects from two adjacent arms are subtracted.
- It was demonstrated that the output voltage variation in the signal diagonal is proportional to the relative resistance variation of the Wheatstone bridge.

As a ratiometric device, this bridge is extremely sensitive, its tensometrical sensitivity being well approximated by the relationship

$$S = \frac{\Delta U_E}{U_A} = \frac{n}{4} \cdot k \cdot \varepsilon \qquad (4)$$

where n is the number of active arms, also called the bridge factor

A complete (Wheatstone) bridge is made of four strain gauges (n = 4), all of them being fully sensitive to the applied principal strain. In Figure 2,b strain gauges R1 and R3, bonded on the upper face of the cantilever beam, are stretched while strain gauges R2 and R4, bonded on its lower face, are compressed.

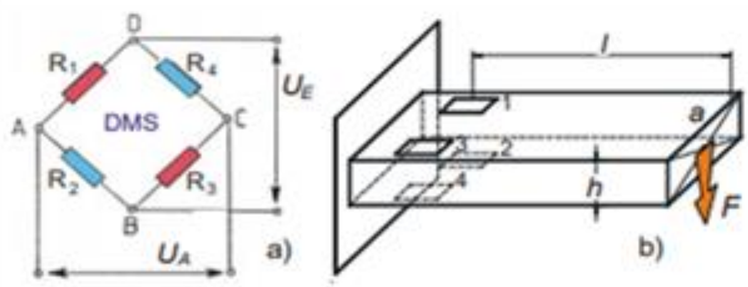


Figure 2. Wheatstone bridge convention and strain gauges positioning

Piezoelectric Transducer

Definition: The Piezoelectric transducer is an **electroacoustic transducer** use for **conversion** of **pressure** or mechanical stress into an alternating **electrical force.** It is used for measuring the physical quantity like force, pressure, stress, etc., which is directly not possible to measure. The piezo transducer converts the physical quantity into an electrical voltage which is easily measured by analogue and digital meter. The piezoelectric transducer uses the piezoelectric material which has a special property, i.e. the material induces voltage when the pressure or stress applied to it. The material which shows such property is known as the electro-resistive element. The word piezoelectric means the electricity produces by the pressure. The Quartz is the examples of the natural piezoelectric crystals, whereas the Rochelle salts, ammonium dehydration, phosphate, lithium sulphate, dipotassium tartrate are the examples of the man made crystals. The ceramic material is also used for piezoelectric transducer. The ceramic material does not have the piezoelectric property. The property is developed on it by special polarizing treatment. The ceramic material has several advantages. It is available in different shapes and sizes. The material has the capability of working at low voltages, and also it can operate at the temperature more than 3000ºC

Piezoelectric Effect

The EMF develops because of the displacement of the charges. The effect is changeable, i.e. if the varying potential applies to a piezoelectric transducer, it will change the dimension of the material or deform it. This effect is known as the piezoelectric effect. The pressure is applied to the crystals with the help of the force summing devices for examples the stress is applied through mechanical pressure gauges and pressure sensors, etc. The deformation induces the EMF which determines the value of applied pressure.

Properties of Piezo Electric-Crystal

The following are the properties of the Piezoelectric Crystals.

1. The piezoelectric material has high stability.
2. It is available in various shapes and sizes.
3. The piezoelectric material has output insensitive to temperature and humidity.

Uses of Piezoelectric Crystal

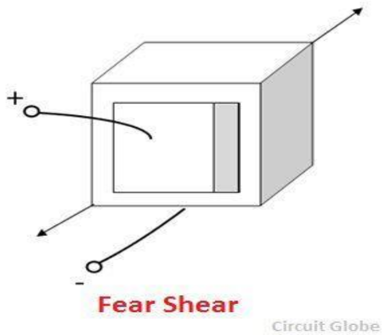
The following are the uses of the Piezoelectric transducers.

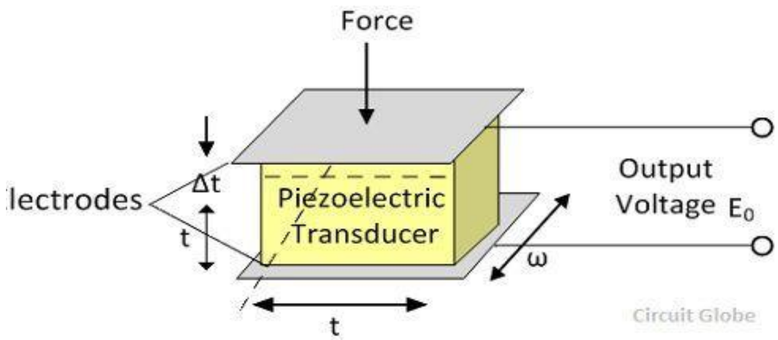
1. The piezoelectric material has high stability and hence it is used for **stabilizing the electronic oscillator.**
2. The **ultrasonic generators** use the piezoelectric material.
3. This generator is used in SONAR for underwater detection and in industrials apparatus for cleaning.
4. It is used **in microphones and speakers for** converting the electric signal into sound.
5. The piezoelectric material is used in **electric lighter**.

The transducer has low output, and hence external circuit is associated with it.

Modes of Operation of Piezo-Electric Crystal

The Piezoelectric crystals are used in many modes likes, thickness shear, face shear, thickness expansion, Transverse expansion, etc. The figure of the fear shear is shown in the figure below

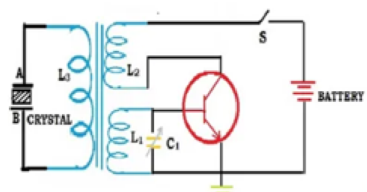


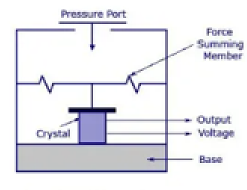


Piezoelectric Transducer

- A **piezoelectric transducer** (also known as a piezoelectric sensor) is a device that uses the piezoelectric effect to measure changes in acceleration, pressure, strain, temperature or force by converting this energy into an electrical charge.
- A transducer can be anything that converts one form of energy to another. The piezoelectric **material** is one kind of transducers. When we squeeze this piezoelectric material or apply any force or pressure, the transducer converts this energy into voltage. This voltage is a function of the force or pressure applied to it.
- The electric voltage produced by a piezoelectric transducer can be easily measured by the voltage measuring instruments. Since this voltage will be a function of the force or pressure applied to it, we can infer what the force/pressure was by the voltage reading. In this way, physical quantities like mechanical stress or force can be measured directly by using a piezoelectric transducer.
- **Piezoelectric Actuator**
- A piezoelectric actuator behaves in the reverse manner of the piezoelectric sensor. It is the one in which the electric effect will cause the material to deform i.e. stretch or bend.
- That means in a piezoelectric sensor, when force is applied to stretch or bend it, an electric potential is generated and in opposite when on a **piezoelectric actuator**, an electric potential is applied it is deformed i.e. stretched or bend.

Piezoelectric Transducer

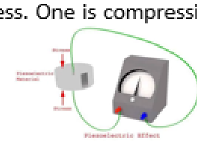


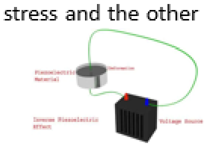


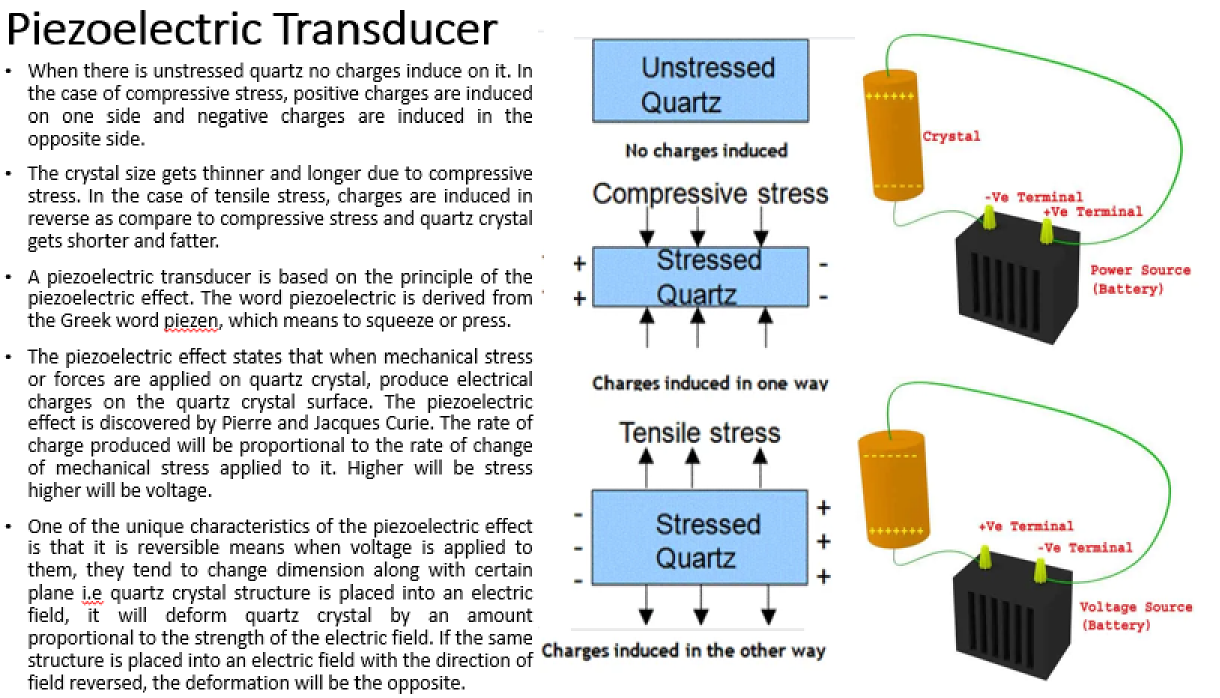
Piezo-Electric Transducer

A piezoelectric transducer consists of quartz crystal which is made from silicon and oxygen arranged in crystalline structure (SiO_2). Generally, unit cell (basic repeating unit) of all crystal is symmetrical but in piezoelectric quartz crystal, it is not. Piezoelectric crystals are electrically neutral.

The atoms inside them may not be symmetrically arranged but their electrical charges are balanced means positive charges cancel out negative charge. The quartz crystal has the unique property of generating electrical polarity when mechanical stress applied to it along a certain plane. Basically, There are two types of stress. One is compressive stress and the other is tensile stress.







Quartz crystal becomes longer due to the electric field applied. Quartz crystal becomes shorter due to the electric field applied in a reversed direction. It is a **self-generating transducer**. It does not require an electric voltage source for operation. The electric voltage produced by the piezoelectric transducer is linearly varied to applied stress or force.The piezoelectric transducer has high sensitivity. So, it acts as a sensor and used in accelerometer due to its excellent frequency of response. The piezoelectric effect is used in many applications that involve the production and detection of sound, electronic frequency generation. It acts as an ignition source for cigarette lighter and used in sonar, microphone, force, pressure, and displacement measurement

Application of Piezoelectric Materials

Using piezoelectric materials, piezoelectric transducers can be used in a variety of applications, including: **In microphones**, the sound pressure is converted into an electric signal and this signal is ultimately amplified to produce a louder sound. **Automobile seat belts lock** in response to a rapid deceleration is also done using a piezoelectric material. It is also used in **medical diagnostics**. It is used in **Electric lighter used in kitchens**. The pressure made on piezoelectric sensor creates an electric signal which ultimately causes the flash to fire up. They are used for **studying high-speed shock waves and blast waves**. Used **in Inkjet printers.** It is also used **in restaurants or airports where when a person steps near the door and the door opens automatically.** In this, the concept used is when a person is near the door pressure is exerted person weight on the sensors due to which the electric effect is produced and the door opens automatically.

Examples of Piezoelectric Material

The materials are :

- **Barium Titanate.**
- **Lead zirconate titanate (PZT).**
- **Rochelle salt.**

The Piezoelectric Ultrasonic Transducer

- It produces frequencies that are far above that which can be heard by the human ear.
- It expands and contracts rapidly when subjected to any voltage. It is typically used in a vacuum cleaner.

Piezo Buzzer

- A buzzer is anything that produces **sound**. They are driven by the oscillating electronic circuit.
- A piezoelectric element may be driven by an oscillating electronic circuit or another audio signal source, driven with a piezoelectric audio amplifier.
- A blick, a ring, or a beep are commonly sued sound to indicate that a button has been pressed.

A piezoelectric buzzer (or piezoelectric beeper) depends on acoustic cavity resonance (or Helmholtz resonance) to produce an audible beep.

Piezoelectric Transducer Advantages

The advantages of piezoelectric transducers are:

- ➢ No need for an external force
- ➢ Easy to handle and use as it has small dimensions
- ➢ High-frequency response it means the parameters change very rapidly

Piezoelectric Transducer Disadvantages

The disadvantages of piezoelectric transducers are:

- ➢ It is not suitable for measurement in static condition
- ➢ It is affected by temperatures
- ➢ The output is low so some external circuit is attached to it
- ➢ It is very difficult to give the desired shape to this material and also desired strength

Piezoelectric sensor

- Piezoelectric sensor is used for the measurement of pressure, acceleration and dynamic-forces such as oscillation, impact, or high speed compression or tension.
- It contains piezoelectric ionic crystal materials such as Quartz.

- On application of force or pressure these materials get stretched or compressed.
- During this process, the charge over the material changes and redistributes.
- One face of the material becomes positively charged and the other negatively charged.
- The net charge q on the surface is proportional to the amount x by which the charges have been displaced.
- The displacement is proportion to force.
- Therefore we can write,

$$q = kx = SF \qquad (1)$$

- where k is constant and S is a constant termed the charge sensitivity.

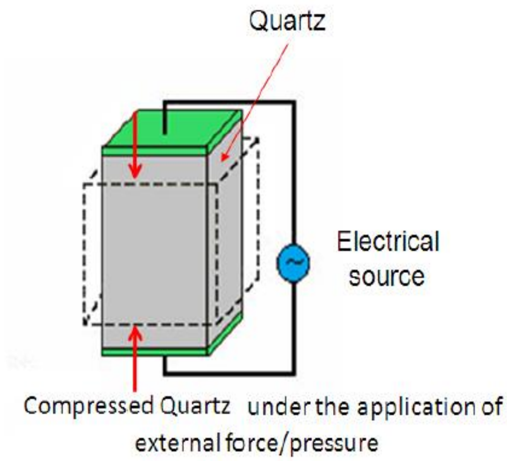


Figure: Principle of working of Piezoelectric sensor

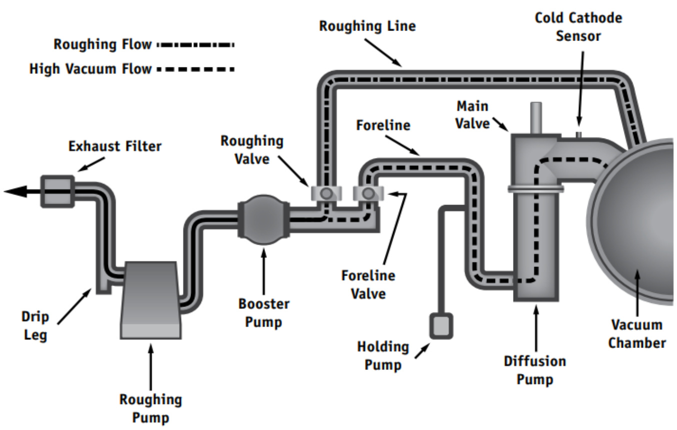
Vacuum Measurement

- Vacuum can be defined as a space that is empty of matter; however, achieving such an empty space is essentially impossible on earth.
- Instead, vacuum is best described as a space with gaseous pressure much less than atmospheric pressure.
- Physicists and vacuum scientists describe this lack of a "perfect vacuum" in manmade chambers, such as production furnaces, as partial pressure or partial vacuum.
- The quality of a vacuum is indicated by the amount of matter remaining in the system, so that a high quality vacuum is one with very little matter left in it.
- Vacuum is primarily measured by its absolute pressure. Measuring vacuum, as with any kind of measuring, requires standard units of measure.
- Inches or millimeters of mercury, torr, and micron are three units of measure typically associated with the vacuum furnace industry.
- Other fields of vacuum use Pascals (Pa or kPa.)

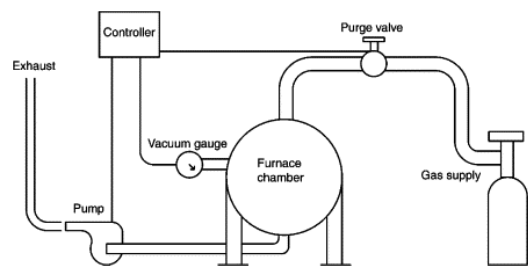
Measuring vacuum is a very complex subject requiring a good understanding of the best instrumentation available for the application. Vacuum instruments are very sensitive to the pressures being measured and to any contaminating particles that might be present within the chamber being measured. The type of partial pressure gas used to establish safe operating pressure can seriously affect the vacuum gauge reading if not properly referenced for accurate reading. Vacuum gauges must be properly calibrated periodically to maintain accuracy and prior to processing critical furnace cycles. Vapor pressures of materials are a serious consideration when establishing proper partial pressure operating levels. Thermocouple vacuum gauge readings vary significantly when measuring different partial pressure gasses above 1 Torr levels of vacuum.

Types of Vacuum Measuring Instruments

- Many gauges are available to measure vacuum within a vacuum furnace chamber. These gauges vary in design based on the particular range of vacuum they are analyzing.



Typical Vacuum Furnace Pump Configuration



Vacuum Measurement -Hydrostatic Gauges

Torricelli’s Discovery Instruments for measuring the emptiness of a given space have been used for hundreds of years, making use of the properties of gases to determine their relative absence.

The barometer, a device used for measuring air pressure, was invented in 1643 by the Renaissance Florentine scientist Evangelista Torricelli. Because we are living submerged in an ocean of air, the atmosphere is pressing down on us.

Due to local heating and cooling, areas of lower and higher atmospheric pressure periodically sweep over us. The areas of lower pressure are in a sense areas of vacuum, as the gasses of the air around us are relatively less dense there.

Torricelli found that the pressure of the atmosphere at sea level pressing down on a well of mercury would support a nearly 30-inch column of mercury in a tube upended in the reservoir of mercury.

The mercury in the column would not flow down into the well because of the counterbalancing atmospheric pressure on the surface of the mercury in the well.

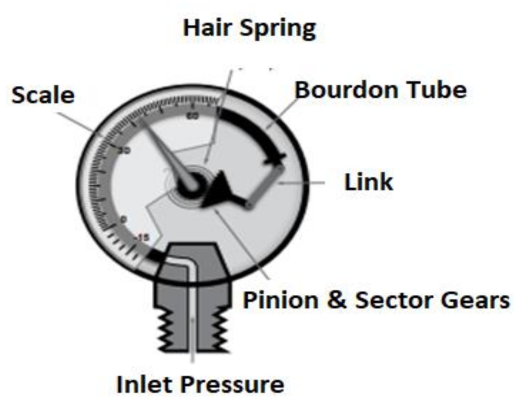
From that beginning, more sophisticated and precise devices have been designed to measure lower and lower masses of gas in a given volume.

The Bourdon Tube Gauge/Diaphragm Gauge

- The Bourdon gauge, also known as the diaphragm gauge, shown in the Figure, accurately and continuously

  indicates the pressure from approximately atmospheric pressure (760 Torr) to 20 Torr.

- The pressure gauge uses the principle that a flattened tube tends to straighten or regain its circular form in cross-section when pressurized.
- Although this change in cross-section may be hardly noticeable, and thus involving moderate stresses within the elastic range of easily workable materials, the strain of the material of the tube is magnified by forming the tube into a C shape or even a helix, such that the entire tube tends to straighten out or uncoil, elastically, as it is pressurized.
- Eugene Bourdon patented his gauge in France in 1849, and it was widely adopted because of its superior sensitivity, linearity, and accuracy.

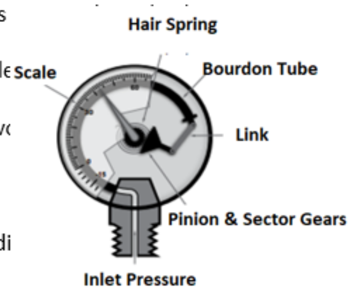


Bourdon Tube Gauge

Two of the most common hydrostatic measuring devices are (1)Bourdon gauge and (2) McLeod gauge.

Hydrostatic Gauges - Bourdon Gauge/Diaphragm Gauge

- In practice, a flattened thin-wall, closed-end tube is connected at the hollow end to a fixed pipe containing the fluid pressure to be measured.
- As the pressure increases, the closed end moves in an arc, and this motion is converted into the rotation of a segment of a gear by a connecting link that is usually adjustable.
- A small-diameter pinion gear is on the pointer shaft, so the motion is magnified further by the gear ratio.
- The positioning of the indicator card behind the pointer, the initial pointer shaft position, the linkage length and initial position all provide means to calibrate the pointer to indicate the desired range of pressure for variations in the behavior of the Bourdon tube itself.
- Differential pressure can be measured by gauges containing two different Bourdon tubes, with connecting linkages.
- Bourdon tubes measure gauge pressure relative to ambient atmospheric pressure, as vacuum is sensed as a reverse motion.
- Some barometers use Bourdon tubes closed at ends (but most use diaphragms or capsule
- When the measured pressure is rapidly pulsing, such as when the gauge is near a reciprocating pump, an orifice restriction in the connecting pipe is frequently used to avo unnecessary wear on the gears and provide an average reading.
- When the whole gauge is subject to mechanical vibration, the entire case including the pointer and indicator card can be filled with an oil or glycerin.
- Tapping on the face of the gauge is not recommended as it will tend to falsify actual readi initially presented by the gauge.
- The Bourdon tube is separate from the face of the gauge and thus has no effect on the ac reading of pressure.



Bourdon Tube Gauge

- Typical high-quality modern gauges provide an accuracy of ±2% of span, and a special high-precision gauge can be as accurate as 0.1% of full scale

Hydrostatic Gauges - McLeod Gauge

- McLeod Gauge is a modification of a manometer that can measure absolute pressure of gasses quite accurately.
- The main advantage of the McLeod gauge is that its calibration is unaffected by the type of gas in the system.
- Many gasses such as hydrogen, helium, carbon dioxide, and many other gasses in a vacuum system will create confusion with the calibration of most other types of vacuum gauges.
- However, as long as the condensable vapors are trapped out, readings from the McLeod gauge can be used to calibrate other gauges.
- As shown in Figure, it traps a fixed volume and then compresses its volume, raising the pressure to a point where it can be easily read.
- The McLeod gauge measures pressure intermittently rather than continuously.
- A vacuum is established with the mercury level shown in dark gray (Figure (B)).
- The mercury is raised until the level in the tube connected to the vacuum is equal to the top of the sealed capillary.
- The reading difference now indicates the vacuum measurement.
- The McLeod gauge was invented by H.G. McLeod in 1974 to measure gas pressure of or between 10-2 and 10-7 Torr.

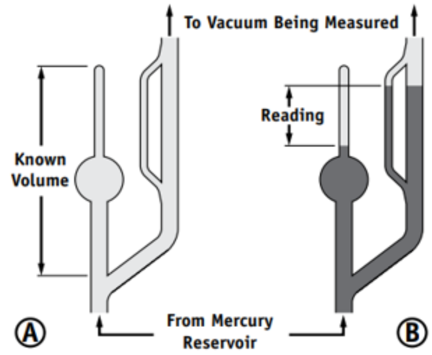


Figure - McLeod Gauge Operation

Capacitance Manometer Gauges

- The capacitance manometer gauge is a pressure gauge used to measure vacuum from atmospheric pressure to 10-5 Torr dependent on the given sensor applied.
- A capacitance sensor operates by measuring the change in electrical capacitance that results from the movement of a sensing diaphragm relative to some fixed capacitance electrodes (Figure).
- The higher the process vacuum, the farther it will pull the measuring diaphragm away from the fixed capacitance plates.
- In some designs, the diaphragm is allowed to move. In others, a variable DC voltage is applied to keep the sensor's Wheatstone bridge in a balanced condition.
- The amount of voltage required is directly related to the pressure.
- The great advantage of a capacitance gauge is its ability to detect extremely small diaphragm movements.
- Accuracy is typically 0.25 to 0.5% of reading.
- Thin diaphragms can measure down to 10-5 Torr, while thicker diaphragms can measure in the low vacuum to atmospheric range.
- To cover a wide vacuum range, one can connect two or more capacitance sensing heads into a multi-range package.
- The capacitance diaphragm gauge is widely used in the semiconductor industry, because its Inconel body and diaphragm are suitable for the corrosive services of this industry.
- They are also favored because of their high accuracy, immunity to contamination, and gas type species.

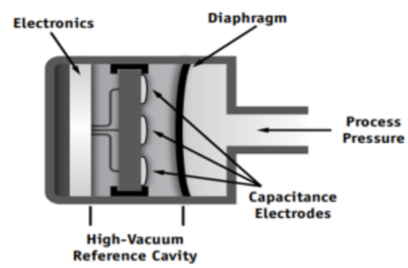


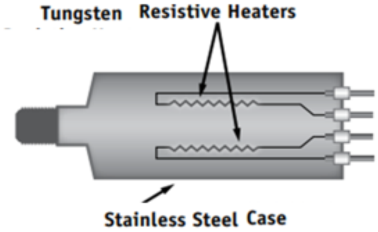
Figure - Capacitance Manometer Gauge

Thermal Conductivity Gauges **Pirani gauge**

- Pirani gauges also take advantage of the change in temperature of a heated wire, but unlike thermocouple gauges, they don't measure the wire temperature directly. Instead they make use of the fact that the resistance of a metal wire changes with the wire's temperature.
- If the heated wire is made to be one leg of a wheatstone bridge with a balancing leg exposed to ambient temperature as a compensator, and both of these are set against two fixed resistors, a balanced circuit will go out of balance as the sensor wire changes resistance with pressure changes that change the wire's temperature.
- Pirani gauges, in general, operate with a heated wire that is much cooler (120-2000 C) than a thermocouple gauge, and this makes them less likely to become contaminated by mechanical pump oil.
- Pirani gauges that are heated with constant current will usually have a faster response time than thermocouple gauges due to such differences as smaller electrodes.
- Many modern gauges now operate in a constant temperature mode.
- A separate circuit constantly changes power input to maintain a constant sensor resistance. This produces full-scale response times in milliseconds.

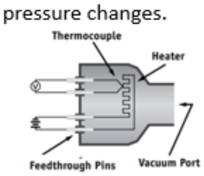
Applications:

- Like all vacuum devices, thermal conductivity gauges are application sensitive.
- In general, these devices are at their best when used to monitor a pumpdown cycle. They are inexpensive and reliable, but they do not generally have the accuracy required for stringent measuring of process gases.
- Their varying response to different gas species makes them into good practical leak detectors since a probe gas other than air, such as helium, will produce a sudden and large reading difference.
- Proper application can make them very useful devices



Thermocouple Gauges

- Thermocouple gauges use a thermocouple attached to the hot wire to measure its temperature It is used to monitor a pumpdown cycle, the wire will become hotter and hotter as the pressure drops and fewer and fewer molecules are available to transfer heat away from the wire.
- Heat is also transferred by flow through both the thermocouple wire and the support/feedthrough pins for the hot wire.
- This means that the entire sensing array must be constructed of conducting metal leads that are of as small a diameter as possible to avoid excess heat loss.
- This problem becomes more acute at the gauge's lowest pressures when the wire is at it hottest. Since the heated wire, in most thermocuple gauges, needs to operate at maximum temperatures between 200-300o C, it's made from a noble metal such as platinum to avoid oxidation problems.
- At the lowest pressures, the hot wire is often exposed to oil vapors if oil-sealed mechanical pumps are used. The oil vapors can either crack to leave carbon deposits or polymerize to leave a layer of thermal insulation on the wire.
- Since the backstreaming rate of pump's oil is greatest at low pressures, this can be a significant problem since it will change the gauge's calibration.
- Although it is sometimes possible to clean the gauges by rinsing with solvents, success is by no means assured.
- The solvents might not totally remove coatings and the electrode arrays need to be delicate enough that sloshing liquids can easily cause mechanical damage.
- The necessary delicacy also means that they will not withstand mishandling shocks such as a free drop onto a concrete floor.
- Thermocouple gauges are calibrated such that the wire's temperature is displayed as a pressure reading.
- This allows such problems as variations in heat flow through the supporting electrodes to be taken into account.
- One problem that can't be calibrated for is based on the fact that the wire must change temperature with pressure changes.
- Even though the heat capacity and thermal flow characteristics of the sensing array is kept to a minimum, there is some lag time associated with temperature changes in response to pressure changes.
- In most applications, this is not a problem, but rapid pressure changes such as might be found in rapid pumpdowns or backfilling operations can show significant delays in response time.



Ionization Gauges

- Every modern vacuum furnace capable of operating in high vacuum relies on some form of ionization gauge for pressure measurements under 10-3 Torr.
- There are two competing ionization gauge technologies to choose from which are viable means for pressure measurements between 10-2 and 10-10 Torr.
- They sense pressure indirectly by measuring the electrical ions produced when gas is bombarded with electrons. Fewer ions will be produced by lower density gasses.

Hot Cathode Ionization Gauge

- A hot cathode ionization gauge like the one in Figure is composed mainly of three electrodes acting together in a triode, wherein the cathode is the filament.
- The three electrodes are a collector or plate, a filament and a grid. Electrons emitted from the filament move several times in back and forth movements around the grid before finally entering the grid.
- During these movements, some electrons collide with a gaseous molecule to form a pair of an ion and an electron.
- The number of these ions is proportional to the gaseous molecule density multiplied by the electron current emitted from the filament, and these ions enter into the collector to form the ion current.
- Since the gaseous molecule density is proportional to the pressure, the pressure is estimated by measuring the ion current.

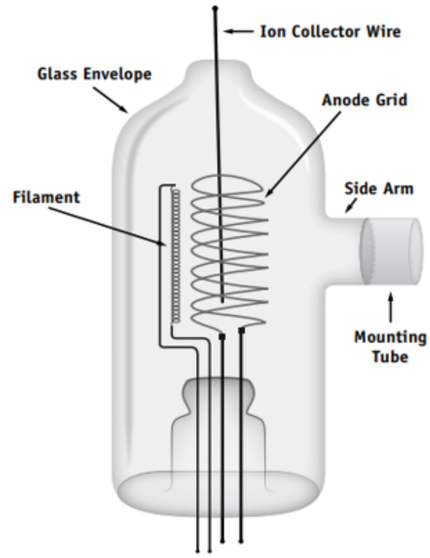


Figure - Hot Cathode Gauge [17]

Ionization Gauges

Cold Cathode Gauge

- A cathode is an electrode that emits electrons, that is not electrically heated by a filament.
- There are two types of cold cathode ionization gauges: the Penning gauge and the inverted magnetron, also known as the redhead gauge.
- This gauge, like the one in Figure 9, makes use of the fact that the rate of ion production by a stream of electrons in a vacuum system is dependent on pressure and the ionization probability of the residual gas.
- Two parallel connecting cathodes and the anode is placed midway between them. The cathodes are metal plates or shaped metal bosses.
- The anode is a loop of flattened metal wire, the plane of which is parallel to that of the cathode.
- A high voltage potential is maintained between the anodes and the cathodes.
- In addition, a magnetic field intensity is applied between the elements by a permanent magnet, which is usually external to the gauge tube body.
- Electrons emitted travel in helical paths (due to the magnetic field), eventually reaching the anode, thus increasing the amount of ionization occurring within the gauge.

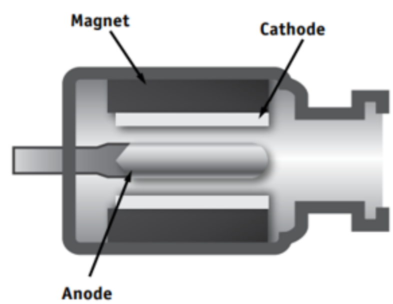
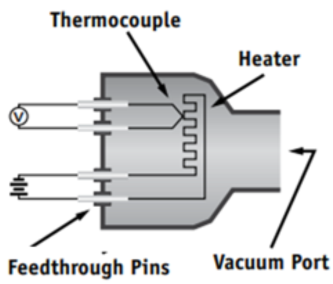
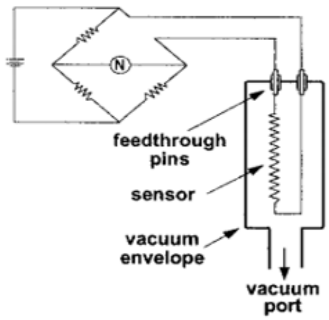


Figure - Cold Cathode Gauge

Thermocouple Gauges

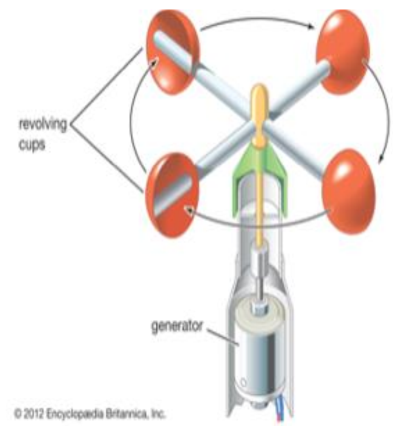
- A thermocouple (T/C) gauge works very similarly to a Pirani gauge. The difference is that the temperature of the wire is measured precisely by the T/C, which is attached to the wire.
- The current is determined based on the resistance. This gauge is normally used for comparison purposes and the sensitivity varies based on the pressure and the strength of the current. The reading is on a minivolt meter calibrated to show pressure, but it must be calibrated for each different gas other than air and nitrogen.
- Another disadvantage is that it is not marked in a linear order. At low pressures, the scale markings are spread apart and in higher ranges, the marks are closer together.
- For the most part, the thermocouple gauges have the same advantages and disadvantages as the Pirani gauge.
- But the thermocouple gauge is considered to be less expensive and more user friendlv.

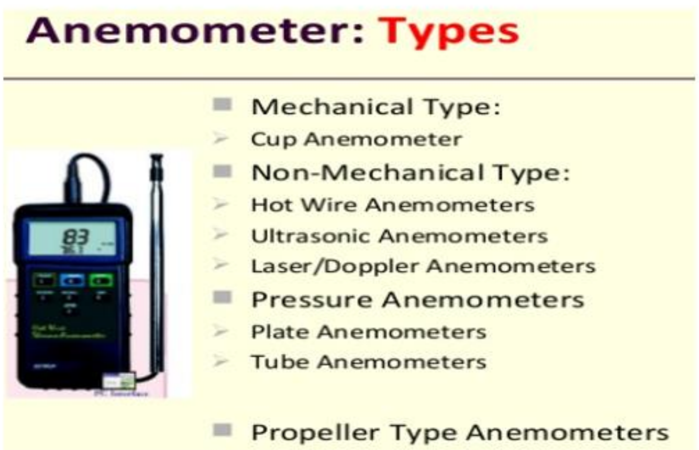




Airflow Measurement - ANEMOMETER

- An anemometer is a device for measuring the force or speed of the wind.
- This instrument has been around since at least 1450.
- Many different types of anemometers are on the market, each with unique characteristics.
- Some of the devices measure more than just wind speed.





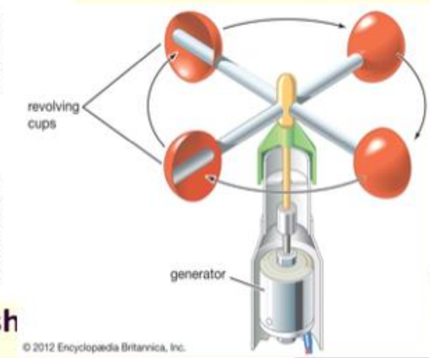
Airflow Measurement - ANEMOMETER

- An anemometer is a device for measuring the force or speed of the wind. This instrument has been around since at least 1450. Many different types of anemometers are on the market, each with unique characteristics. Some of the devices measure more than just wind speed. Some people for fun build their own anometers -- that's something you might want to try as well.

Cup

- The cup or rotational anemometer is one of the oldest types of anemometers. The cups are placed onto a vertical axis, and when the wind presses against them, this causes the cups to rotate around. The faster the cups rotate, the faster the wind speed. Cup anemometers usually have digital readouts. Researchers, educational institutions and meteorologists worldwide use this type of anemometer for research and commercial activities.

Anemometer: Types



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Cup Anemometers

- Most common wind speed measurement device
- It consists of hemispherical cups, each mounted on one end of horizontal arms
- And the arms were mounted at equal angles to each other on a vertical shaft
- The air flow past the cups in any horizontal direction turned the shaft in a manner that is proportional to the wind speed
- On counting the turns of the shaft over a set time period produced the average wind speed for a wide range of speeds

In a Nutsh

- Many cup anemometers have a vane attached to measure wind direction

Advantages	Disadvantages
➢ Low Price ➢ Flexible Design ➢ Simple Installation ➢ Most technicians understand operating principles and necessary connections	➢ Moving parts wear out ➢ Without provisions for heating, they don't work well in snow or freezing rain ➢ They don't work well in rapidly fluctuating winds

Airflow Measurement - ANEMOMETER

Hot Wire

- Hot wire or thermal flow anemometers measure both the wind speed and pressure. The device is a long rod and at the tip is a hot wire or hot bead. The anemometer is placed into a location and as wind moves over the hot wire, the wire is cooled. A direct relationship exists between the rate at which the wind is flowing and how cool the wire becomes. You can find this type of anemometer in the heating, ventilating and air-conditioning businesses -- it measures the airflow through building ducts.

Hot Wire Anemometers

- Uses a very fine wire (on the order of several micro-metres)
- Electrically heated up to some temperature above the ambient
- Air flowing past the wire has a cooling effect on the wire

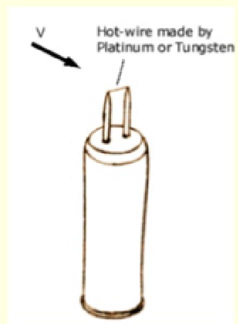
"The electrical resistance of most metals is dependent upon the temperature of the metal"

- Using above a relationship can be obtained between the resistance of the wire and the flow speed

Probe Specifications

"Tungsten is a popular choice for hot-wires"

- Tungsten or Platinum filament
  - ~1 mm long
  - 4-10 mm diameter
- Benefits
  - Good spatial resolution
  - Flat frequency response
- Limitations
  - Fragile
  - Requires clean flow
  - Cost (start at $300-400)



Airflow Measurement - ANEMOMETER

- Ultrasonic
- Ultrasonic anemometers send sonic pulses across a path to a sensor on the opposite side. As the wind moves more quickly, the pulses are disrupted. A measurement of this disruption provides accurate wind data. An ultrasonic anemometer has no moving parts and can detect even small changes in the wind. The device typically has four sensors arranged in a square pattern. Some units come with built-in heaters.

Ultrasonic Anemometers

- First developed in the 1950s
- Use of ultrasonic sound waves to measure wind velocity
- They measure wind speed based on the time of flight of sonic pulses between pairs of transducers
- Measurements from pairs of transducers can be combined to yield a measurement of velocity in 1-, 2-, or 3-dimensional flow

Figure: 2D ultrasonic anemometer with 3 paths

Ultrasonic Anemometers

Advantage	Disadvantage
➢ The lack of moving parts makes them appropriate for long-term use in exposed automated weather stations and weather buoys where the accuracy and reliability of traditional cup-and-vane anemometers is adversely affected by salty air or large amounts of dust	➢ Main disadvantage is the distortion of the flow itself by the structure supporting the transducers, which requires a correction based upon wind tunnel measurements to minimize the effect

Airflow Measurement - ANEMOMETER

Laser Doppler

- Laser Doppler anemometers utilize the Doppler effect to determine the flow of air. Commonly used for high-tech applications such as in jet engines, the laser Doppler can measure even the slightest changes in airflow. This type of anemometer is also used in river hydrology.

Windmill

The windmill anemometer measures both wind speed and direction. The anemometer has a propeller located at the front of the device and a large tail section.
As the wind blows, it presses against the propeller, making it spin.
The rotational speed of the propeller indicates how fast the wind is moving at any time.

Laser/Doppler Anemometers

- Laser/Doppler anemometers use a beam of light from a laser that is divided into two beams, with one propagated out of the anemometer
- Particulates (or deliberately introduced seed material) flowing along with air molecules near where the beam exits reflect, or backscatter, the light back into a detector, where it is measured relative to the original laser beam
- When the particles are in great motion, they produce a Doppler shift for measuring wind speed in the laser light, which is used to calculate the speed of the particles, and therefore the air around the anemometer

Propeller Type/Vane Anemometers

- The axis on the vane anemometer is parallel to the direction of the wind and therefore horizontal
- Since the wind varies in direction and the axis has to follow its changes
- Combines a propeller and a tail on the same axis to obtain accurate and precise wind speed and direction measurements from the same instrument

Airflow Measurement - ANEMOMETER

Pressure Tube

- A pressure tube anemometer is called a wind sock.
- These devices are found around airports. Material is made into a tube shape and is connected to wires.
- As the wind blows, it catches the larger end of the tube.
- This anemometer provides wind direction because the larger end of the sock will move into the wind.
- The faster the wind blows, the higher the tube raises off the ground. Pressure tubes do not provide readouts but are relative measurements of wind speed.

Tube Anemometers

- A tube anemometer uses air pressure to determine the wind pressure, or speed
- A tube anemometer measures the air pressure inside a glass tube that is closed at one end
- By comparing the air pressure inside the tube to the air pressure outside the tube, wind speed can be calculated

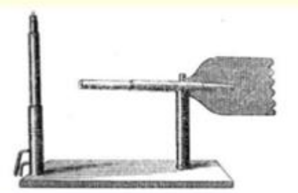
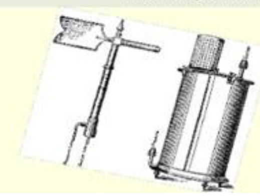


Figure: Invented by William Henry Dines in 1892, The movable part (right) to be put on top of the fixed part (left)

Plate Anemometers

- Modern anemometers
- Are simply a flat plate suspended from the top so that the wind deflects the plate
- The pressure of the wind on its face is balanced by a spring
- The compression of the spring determines the actual force which the wind is exerting on the plate
- This is either read off on a suitable gauge, or on a recorder

Advantage	Disadvantage
➢ They are used on these high places because they are in a plate shape; has a good measurement status on higher altitudes	➢ Instruments of this kind do not respond to light winds, are inaccurate for high wind readings, and are slow at responding to variable winds.



Airflow Measurement - ANEMOMETER

Output from Anemometers

- Signal conditioning is usually done within the instrument
- The output can be an electrical signal to a data-logger or readout device:
  - Pulse signal
  - Voltage signal
    - For example, 0-10 V corresponds to the velocity measurement range of the instrument.
  - Current signal
    - Typically, 4-20 mA corresponding to the instrument range.
    - Eliminates voltage drop when the signal is transmitted over larger distances.

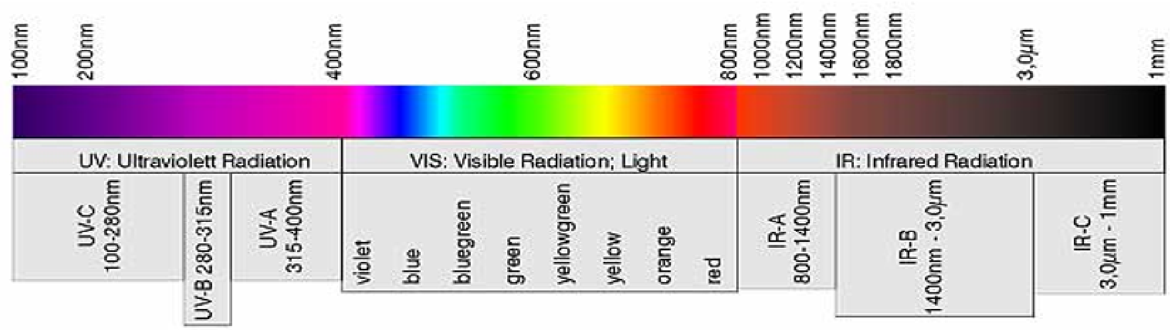
Importance of Accurate Wind Speed Measurements

- The power obtained from the wind goes with the cube of the wind speed
- A small error in the measurement results in a much larger error in the predicted wind power
- For example, a 5% error at a wind speed of 10 meters/sec leads to a 16% error in predicted wind power
- 10% anemometer error leads to 33% errors in power prediction

Light Measurement

The wavelength range of optical radiation

- According to DIN 5031, the term "**optical radiation**" refers to electromagnetic radiation in the wavelength range between 100 nm and 1 mm.
- The terms "**light**" and "**visible radiation**" (VIS) refer to the wavelength range between 400 nm and 800 nm, which can be perceived by the human eye.
- Optical radiation with wavelengths shorter than 400 nm is called **ultraviolet (UV) radiation** and is further subdivided in UV-A, UV-B and UV-C ranges.
- Similarly, **infrared (IR) radiation** covers the wavelength range above 800 nm and is subdivided in IR-A, IR-B and IR-C ranges (DIN 5031, part 7).



Light Measurement

UV Light

- UV light is measured in microwatts of ultraviolet radiation per lumen of visible light (µW/l).
- The high energy of UV radiation is particularly damaging to artifacts.
- UV light is not visible to the human eye and therefore removing it from museum lighting causes no change in appearance.
- Daylight is generally the strongest source of UV light; fluorescent, metal halide and mercury vapor lights also emit UV radiation.
- UV light can be measured using a UV meter. Ideally UV light should be as close to zero µW/l as possible, and light sources emitting UV measurements above 75 µW/l should be reduced.

Visible Light

- Visible light is, of course, necessary in museum environments. The standards that have evolved in the preservation community recognize that levels of light must be high enough to allow for appropriate work environments in storage and adequately view artifacts on display, but anything more than that causes unnecessary damage and should be limited.
- Visible light levels are measured in lux (lumens per square meter) or foot candles (fc). One foot candle is slightly more than 10 lux. Visible light levels can be measured using a light meter.
- Commonly recommended acceptable levels of light required for viewing museum artifacts on exhibition, based on experience and a number of studies, are given below.
- The underlying logic behind these numbers is that any level of light in excess of the minimum amount necessary to adequately view an object on exhibition causes unjustifiable damage.

Infrared Light

- When absorbed, infrared (IR) radiation causes a rise in temperature. IR light is also beyond the detection of the human eye.
- The effects of heat on collections are covered more specifically in the section on temperatures but it is important to recognize that light radiation acts as a catalyst in the oxidation of materials – particularly organic artifacts.

Light Measurement

Light : Electromagnetic energy that falls within a specific range of frequencies.

Light Emitters and Detectors

- Light emitter – Optoelectronic devices that produce light.
- The LED is an example of a light emitter.
- Light detector – Optoelectronic devices that respond to light.

Light measurement

- Optical radiometry is the science of light measurement, spanning across the ultraviolet, visible and infrared regions of the electromagnetic spectrum.
- Photometry is the subset of radiometry dedicated to the measurement of visible light as it is perceived by the average human eye.
- International Light Technologies (ILT) has been the most respected name in research oriented light measurement for 40 years. They offer a variety of modular light meters. Optical radiation is perhaps the most difficult form of energy to measure accurately. Light energy is distributed over wavelength, position, direction, time and polarization.
- A light meter or a radiometric light measurement system must be designed to measure the distribution of energy over one parameter while holding all others constant.
- In addition to high levels of measurement uncertainty, the field of radiometry and photometry has been characterized by confusion of terminology, symbols, definitions and units.
- International Light Technology goal is to provide customers with light measurement solutions to these problems by offering a comprehensive line of accurate modular light meters, i.e. radiometers and photometers.
- There are many (low-cost) instruments called radiometers on the market, which were designed to measure power from a light source with a constant known spectrum. These give erroneous results when measuring any other radiation.
- The extremely flexible light measuring system concept of International Light Technology is based on a choice of suitable radiometer display devices and a wide range of different detectors.
- As a special feature the detector head allows a custom-designed modular configuration by using special matched filters and input optics.

Light Measurement

Measurement of Light with integral detectors

- Spectroradiometry - the measurement of radiation intensity as a function of wavelength
- - is the only way to provide full spectral information about optical radiation emitted by a light source or impinging upon a surface.
- Spectroradiometers are highly sophisticated optical measurement devices and in general, their proper calibration, operation and maintenance is rather time consuming.
- However, for the vast majority of applications, integral detectors (the term Nintegrali describes the fact that the output signal of an integral detector is proportional to the wavelength integral over the measured quantity's spectral distribution, multiplied with the detector's spectral sensitivity offer an economical and user friendly alternative.
- In most cases, it is not necessary to determine the exact spectral distribution of the measured quantity, and it is sufficient to use a detector especially designed to match a certain predefined spectral sensitivity function.
- As an example, the spectral sensitivity of photometric detectors is matched to the CIE spectral luminous sensitivity function V(I), and detectors for solar UV irradiance potentially harmful to the human skin are matched to the CIE erythema action spectrum.
- As integral detectors provide just a single output signal (usually voltage or photocurrent), they are much easier to characterize than spectroradiometers.

The main parameters determining the usability and the quality of an integral detector are

- The detector's input optics, which determines its directional sensitivity
- The detector's spectral sensitivity
- The dynamic range, over which the detector's output is proportional to the input signal's intensity
- The detector's time behaviour

Modular Light Detectors

Compact Size Modular Detectors

- Modular light detectors are designed for stand alone use or combined with optics and mechanical components to form a complete light detector assembly set-up for a particular application.
- A compact size T type housing allows accessory components such as optical filters, integrating spheres, diffuser windows and other front-end optics to be easily attached and interchanged.
- **The VL-1101 detector** offers a compact package with flange mount that allows arrangement of discrete linear arrays (11 mm grid size) to measure the luminous intensity distribution of spot lamps.
- The detector can be combined with integrating spheres with 11- type adapter for luminous flux measurements.
- Calibration is offered with or without accessory. The detectors are supplied with a 2m long coaxial cable with selectable -1, -2 or -4 type connector for use with Gigahertz-Optik's range of optometers.
- Internationally traceable calibration & certification of illuminance in lux and UV irradiance in W/m² and W/cm² within the specified spectral sensitivity range is provided.
- **The PD-11 series modular detectors** are primarily designed to be used in combination with Gigahertz-Optik integrating spheres.
- A typical application example for sphere based detectors is the measurement of radiant power of lasers, laser diodes and other monochromatic light sources.
- The PD-11 detectors offer a compact package with flange mount to allow direct mounting to all spheres with 11-type port adapters.
- Arrangement of discrete linear arrays with a grid size of 11 mm are also possible. Calibrations are offered with or without accessory.

VL-1101: Compact Size Illuminance Detector

PD-11: Compact Size Modular Detectors

UV Irradiance Detectors

UV Irradiance Detectors

- **UV-37 series detectors** are high sensitivity irradiance detectors for UV radiometric applications involving polychromatic optical radiation. Each detector is supplied with a diffuser window and shadow ring for a cosine corrected field-of-view.
- The relevant components of the detector are UV aged prior to calibration to minimize degradation in long term use under UV radiation.
- The compact low profile 37-type housing fits into tight spaces and includes a M6 tapped hole for post mount stands. A machined V-groove allows other components like quartz radiance barrels to be attached expanding application capability.
- The detectors are supplied with a 2m long coaxial cable with selectable -1, -2 or -4 type connector for use with Gigahertz-Optik's range of optometers.
- Internationally traceable calibration & certification of UV irradiance in W/m² and W/cm² within the specified spectral sensitivity range is provided.

UV-37 Series

UV-3711

UV-3718

Visible and Near-Infrared Irradiance Detectors

Visible and Near-Infrared Irradiance Detectors

- The **RW-37** series irradiance detectors are compact 37mm diameter detectors with wavelength selective spectral responsivities within the visible to near infrared spectrum.
- Several models with different spectral responses are available.
- All detectors are supplied with a diffuser window and shadow ring for cosine response field of view.
- The detectors are supplied with a 2m long coaxial cable with selectable -1, -2 or -4 type connector for use with Gigahertz-Optik's range of optometers.
- Internationally traceable calibration & certification of UV irradiance in W/m² and W/cm² within the specified spectral sensitivity range is provided.

RW-37 Series Detectors

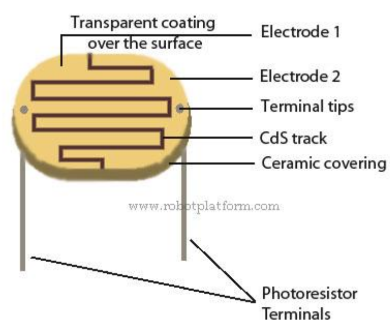
SRT Luminance/Radiance Attachments for RW-37 Series Detectors

Light Measurement -Photoresistors

- Photoresistors are also known as light-dependent resistors. Photoresistors consist of semiconductors.
- When light hits an object, the object absorbs the radiation from the light, and electrons move from the valance band of the semiconductor to the conduction band.
- If there are tons of electrons in the conduction band, the resistance will be incredibly low. Essentially, as the light increases, the resistance decreases. This means that if a photoresistor was in a completely dark room, the resistance would be at 100%. These devices are generally used in streetlamps or some photography equipment, such as a light meter.
- These light measurement sensors help photographers capture more accurate pictures because they help professionals understand how the light will impact the scene of the photo they're trying to take.

Working principle

- If you have already read electricity basics, you know that electricity is nothing but movement of electrons within a material. Conductors have low resistance and insulators have high resistance.
- The third category is the semiconductors which stand between a conductor and an insulator. Photoresistor is made of one such semiconductor with very high resistance with only a few free electrons.
- When light falls on this material, photons from light is absorbed by these materials and energy is transferred to electrons which break up resulting in lower resistance and higher conductivity. The resistance in low light to bright light can be thousands of ohms.
- When exposed to low light, the resistance in a Photoresistor can be several mega-ohms (5-20 MΩ dependent on the type & size) and in bright light it results in only a few hundred ohms.
- Also photoresistors are non-polarized, meaning it can be connected either way in a circuit. You can easily connect the leads with a multimeter on resistance mode and check resistance of your photoresistor.
- Face it towards bright light and check the resistance. Now place your hand or cover it up with a black tape and check the resistance again. You see that the resistance drastically increases once you cover the photoresistor.
- For our robot circuitry we tend to use Cadmium Sulfide cells which come with their own advantages and disadvantages. Knowing the demerits beforehand helps in deciding whether we need to use it or consider any other available options.



Photoresistors

- Photo" is for light and "resistor" is to resist the flow of current. Photoresistors, also known as Light Dependent Resistor (LDR), Cadmium Sulfide cells (CDS cells), Photoconductor and sometimes simply Photocells are a type of transducer which converts energy from one form to another where one of the known forms is electrical energy. To keep things simple, we will refer to it as Photoresistor.
- Resistance in a Photoresistor inversely varies with the amount of light it is exposed to. Bright light = Less resistance and Low light = more resistance.
- These sensors are used to make light sensitive devices and are more often found in street lights, cheap toys, outdoor clocks etc., if you have ever wondered how a street light turns on in the night and switches off in the day, you will be surprised to find a cheap photoresistor circuitry inside it.
- Cadmium Sulfide is often used to make these components due to its low cost.
- Other materials such as Lead sulfide Selenideare also used for high end requirements.

Advantages:

- Cheap and will not make a hole in your pocket if you spoil few
- Commonly found in most robot hobby shops
- Available in different sizes with different specifications
- Easy to design and implement them in a circuitry

Drawbacks:

- Highly inaccurate. Each one behaves differently than the other. If the first one has a resistance of 150Ω in bright light, second one can have 500Ω of resistance in the same light
- They cannot be used to determine precise light levels. Very slow for sensitive applications.
- If you put a LDR in a speeding robot and tell it to stop at an obstacle, you end up seeing your robot crash.
- Although there are other drawbacks, it is always a given choice for beginners due to its simplicity.

Photodiodes

- Photodiodes are a type of light sensor that converts light into an electric current. Basically, when light hits a photodiode, an electron-hole pair is formed. Yet, it's vital to note that the light must have at least 1.1 electron volts for this pair to form. The electrons will have a negative charge, and the hole will have a positive charge. This creates depletion regions in a photodiode. The electron-hole pair can't stay in the depleted zone, so they move towards the positive charge where the hole was first created. Photodiodes use this electron-hole pair to convert light into an electrical current. Photodiodes are used in various devices, including smoke detectors and televisions.

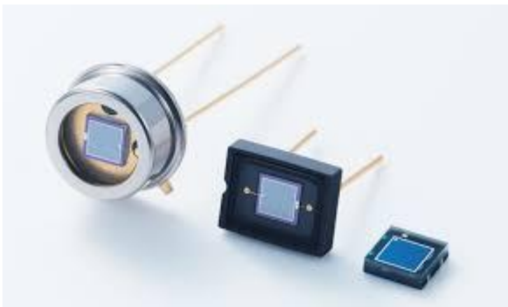
- It is a form of light-weight sensor that converts light energy into electrical voltage or current. Photodiode is a type of semi conducting device with PN junction. Between the p (positive) and n (negative) layers, an intrinsic layer is present. The photo diode accepts light energy as input to generate electric current.
- It is also called as Photodetector, photo sensor or light detector. Photo diode operates in reverse bias condition i.e. the p – side of the photodiode is connected with negative terminal of battery (or the power supply) and n – side to the positive terminal of battery.
- Typical photodiode materials are Silicon, Germanium, Indium Gallium Arsenide Phosphide and Indium gallium arsenide.
- Internally, a photodiode has optical filters, built in lens and a surface area. When surface area of photodiode increases, it results in more response time. Few photo diodes will look like Light Emitting Diode (LED). It has two terminals as shown below. The smaller terminal acts as cathode and longer terminal acts as anode.
- The symbol of the photodiode is similar to that of an LED but the arrows point inwards as opposed to outwards in the LED. The following image shows the symbol of a photodiode.

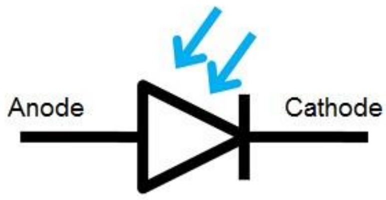
Working of a Photodiode

- Generally, when a light is made to illuminate the PN junction, covalent bonds are ionized. This generates hole and electron pairs. Photocurrents are produced due to generation of electron-hole pairs. Electron hole pairs are formed when photons of energy more than 1.1eV hits the diode.
- When the photon enters the depletion region of diode, it hits the atom with high energy. This results in release of electron from atom structure. After the electron release, free electrons and hole are produced.
- In general, an electron will have a negative charge and holes will have a positive charge. The depletion energy will have built in an electric field. Due to that electric field, electron-hole pairs move away from the junction. Hence, holes move to anode and electrons move to the cathode to produce photocurrent. The photon absorption intensity and photon energy are directly proportional to each other. When energy of photos is less, the absorption will be more. This entire process is known as Inner Photoelectric Effect.
- Intrinsic Excitations and Extrinsic Excitations are the two methods via which the photon excitation happens. The process of intrinsic excitation happens, when an electron in the valence band is excited by photon to conduction band.

Applications of Photodiode

- In a simple day to day applications, photodiodes are used. The reason for their use is their linear response of photodiode to a light illumination. When more amount of light falls on the sensor, it produces high amount of current. The increase in current will be displayed on a galvanometer connected to the circuit.
- Photodiodes helps to provide an electric isolation with help of optocouplers. When two isolated circuits are illuminated by light, optocouplers is used to couple the circuit optically. But the circuits will be isolated electrically. Compared to conventional devices, optocouplers are fast.
- Photodiodes are applied in safety electronics like fire and smoke detectors. It is also used in TV units.
- When utilized in cameras, they act as photo sensors. It is used in scintillators charge-coupled devices, photoconductors, and photomultiplier tubes.
- Photodiodes are also widely used in numerous medical applications like instruments to analyze samples, detectors for computed tomography and also used in blood gas monitors.





Modes of operation of a Photo Diode

Photodiode operates in three different modes namely Photovoltaic mode, Photoconductive mode and Avalanche diode mode.

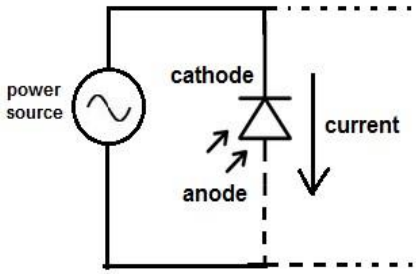
Photovoltaic Mode: This is otherwise called as Zero Bias mode. When a photodiode operates low frequency applications and ultra-level light applications, this mode is preferred. When photodiode is irradiated by flash of light, voltage is produced. The voltage produced will be in very small dynamic range and it has a non-linear characteristic. When photodiode is configured with OP-AMP in this mode, there will be a very less variation with temperature.

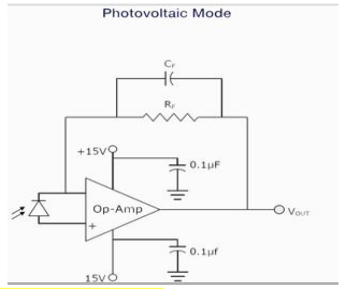
Photoconductive Mode: In this mode, photodiode will act in reverse biased condition. Cathode will be positive and anode will be negative. When the reverse voltage increases, the width of the depletion layer also increases. Due to this the response time and junction capacitance will be reduced. Comparatively this mode of operation is fast and produces electronic noise. Transimpedance amplifiers are used as preamplifiers for photodiodes. Modes of Such amplifiers keep the voltage maintains to be constant to make photo diode operate in the **photoconductive mode.**

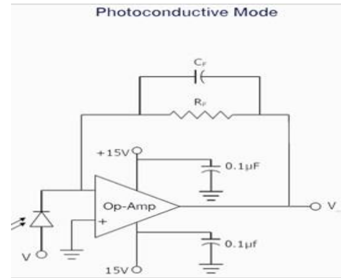
Avalanche Diode Mode: In this mode, avalanche diode operates at a high reverse bias condition. It allows multiplication of an avalanche breakdown to each photo-produced electron-hole pair. Hence, this produces internal gain within photodiode. The internal gain increases the device response.

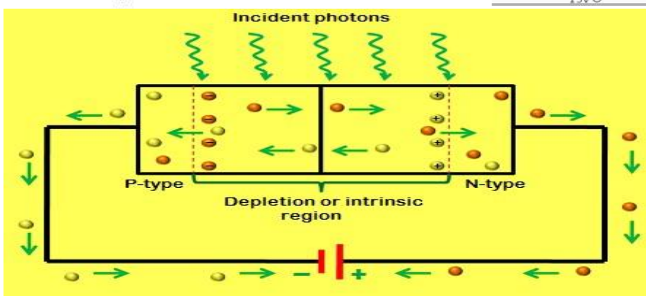
Connecting a Photodiode in an External Circuit: A photodiode operates in a circuit in reverse bias. Anode is connected to circuit ground and cathode to positive supply voltage of the circuit. When illuminated by light, current flows from cathode to anode. When photodiodes are used with external circuits, they are connected to a power source in the circuit. The amount of current produced by a photodiode will be very small. This value of current will not be enough to drive an electronic device. So when they are connected to an external power source, it delivers more current to the circuit. So, battery is used as a power source. The battery source helps to increase the current value, which helps the external devices to have a better performance

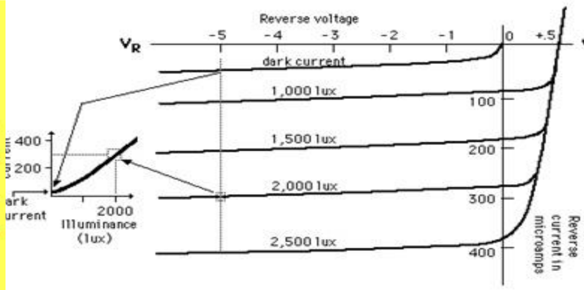
V-I Characteristics of Photodiode: Photodiode operates in reverse bias condition. Reverse voltages are plotted along X axis in volts and reverse current are plotted along Y-axis in microampere. Reverse current does not depend on reverse voltage. When there is no light illumination, reverse current will be almost zero. The minimum amount of current present is called as Dark Current. Once when the light illumination increases, reverse current also increases linearly.











Phototransistor

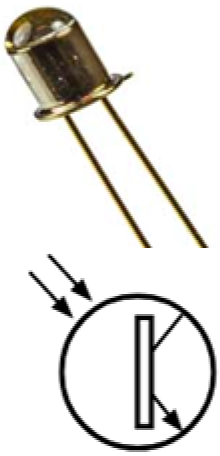
- Phototransistors are similar to photodiodes in that they both convert light energy into an electrical current.
- Yet, phototransistors are more accurate than photodiodes because they can adjust their settings based on the amount of light received.
- Phototransistors can view different intensities of light because these devices can alter the electrical current they create.
- Since phototransistors are relatively easy to use and because they're adjustable, there are various applications for them.
- Phototransistors are used in security systems and lighting control.

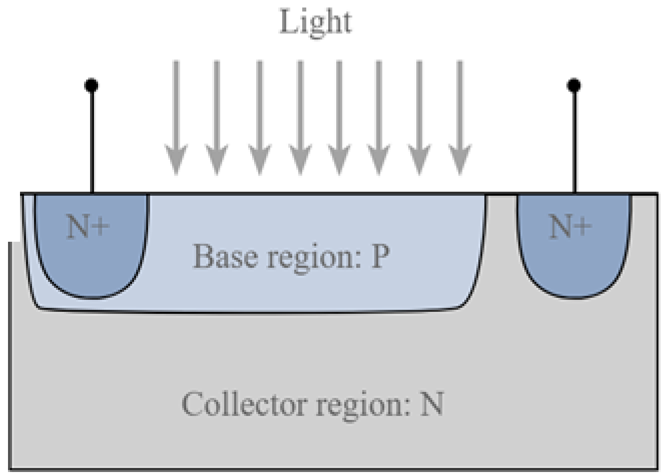
Phototransistor advantages

- Have a relatively high gain and therefore they are relatively sensitive.
- These electronic components are relatively cheap as they are effectively a transistor that is open to light.
- They can be incorporated into an integrated circuit.
- Offer a reasonable speed.

Phototransistor disadvantages

- These devices cannot handle the high voltages of other semiconductor devices like photo-thyristors and triacs.
- In applications where they are exposed to transient voltage spikes and surges, they are open to damage
- Not as fast as other light sensitive electronic components like photo-diodes.





Photoelectric sensor

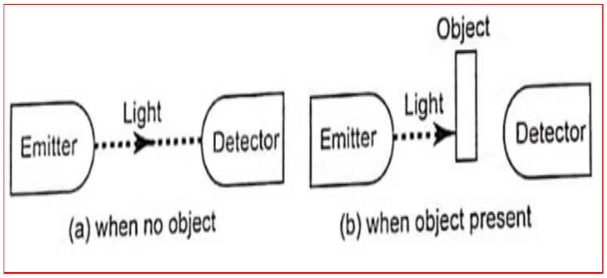
A photoelectric sensor is a device used to detect the distance, absence, or presence of an object by using a light transmitter, often infrared or LED, and a photoelectric receiver. Photoelectric sensors respond to the presence of all types of objects, be it larger, small, transparent or opaque, shiny or dull, static or motion. They can sense objects from distance of a few mm up to 100m.

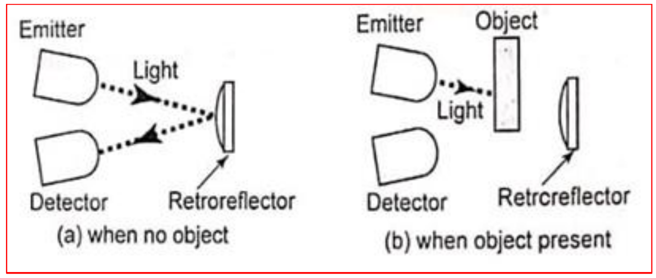
Photoelectric sensors use an emitter unit to produce a beam of light that is detected by a receiver. When the beam is broken by any external object, a presence is Mechatronics, Sensors and Transducers detected. The emitter light source is light – emitting diodes (LED) that emit light when current is applied. The photo detector receiver contains a phototransistor that or produces a current when light falls upon it.

There are two modes of detection for photoelectric sensors.

1. Through-beam

2. Retroreflective
3. A through beam arrangement consists of separate emitter and receiver elements located opposite each other as shown in image.
4. Therefore the light emitted by the emitter falls directly on the receiver. In this mode, an object is detected when the light beam is blocked from getting to the receiver from the transmitter.
5. A retroreflective arrangement places the transmitter and receiver at the same location and uses a reflector to bounce the light beam back from the transmitter to the receiver as shown in image. An object is sensed when the beam is interrupted and fails to reach the receiver.
6. The detecting range of a photoelectric sensor is its “field of view”, or the maximum distance the sensor can retrieve information from, minus the minimum distance. A minimum detectable object is the smallest object the sensor can detect. More accurate sensors can often have minimum detectable objects of minuscule size.





Sound Waves

Alternate physical compression and expansion of medium (solids, liquids, and gases) with certain frequencies are called sound waves. The medium contents oscillate in the direction of wave propagation; hence, these waves are called longitudinal mechanical waves. The name sound is associated with the hearing range of a human ear, which is approximately from 20 to 20,000 Hz. Longitudinal mechanical waves below 20 Hz are called infrasound and above 20,000 Hz (20 kHz), they are called ultrasound. If the classification were made by other animals, like dogs, the range of sound waves surely would be wider. Detection of infrasound is of interest with respect to analysis of building structures, earthquake prediction, and other geometrically large sources. When infrasound is of a relatively strong magnitude, it can be, if not heard, at least felt by humans, producing quite irritating psychological effects (panic, fear, etc.).

Audible waves are produced by vibrating strings (string music instruments), vibrating air columns (wind music instruments), and vibrating plates (some percussion instruments, vocal cords, loudspeaker). Whenever sound is produced, air is alternatively compressed and rarefied. These disturbances propagate outwardly. A spectrum of waves may be quite different—from a simple monochromatic sounds from a metronome or an organ pipe, to a reach violin music. Noise may have a very broad spectrum. It may be of a uniform distribution of density or it may be “colored” with predominant harmonics at some of its portions. When a medium is compressed, its volume changes from V to V − V . The ratio of change in pressure, p, to relative change in volume is called the bulk modulus of elasticity of medium:

Then, the speed of sound can be defined as

$$B = -\frac{\Delta p}{\Delta V / V} = \rho_0 v^2, \qquad v = \sqrt{\frac{B}{\rho_0}}.$$

where ρ0 is the density outside the compression zone and v is the speed of sound in the medium. Hence, the speed of sound depends on the elastic (B) and inertia (ρ0) properties of the medium. Because both variables are functions of temperature, the speed of sound also depends on temperature. This feature forms a basis for operation of the acoustic thermometers.

For solids, longitudinal velocity can be defined through its Young’s modulus E and Poisson ratio ν:

It should be noted that the speed depends on temperature, which always must be considered for the practical purposes. If we consider the propagation of a sound wave in an organ tube, each small volume element of air oscillates about its equilibrium position. For a pure harmonic tone, the displacement of a particle from the equilibrium position may be represented by

where x is the equilibrium position of a particle and y is a displacement from the equilibrium position, ym is the amplitude, and λ is the wavelength. In practice, it is more convenient to deal with pressure variations in sound waves rather than with displacements of the particles. It can be shown that the pressure exerted by the sound wave is

where k = 2π/λ is a wave number, ω is angular frequency, and the terms in the first parentheses represent an amplitude, pm, of the sound pressure. Therefore, a sound wave may be considered a pressure wave. It should be noted that sin and cos in Eqs. (3.100) and (3.101) indicate that the displacement wave is 90◦ out of phase with the pressure wave. Pressure at any given point in media is not constant and changes continuously, and the difference between the instantaneous and the average pressure is called the acoustic pressure P. During the wave propagation, vibrating particles oscillate near a stationary position with the instantaneous velocity ξ .

$$v = \sqrt{\frac{E(1-\nu)}{\rho_0(1+\nu)(1-2\nu)}}.$$

$$y = y_m \cos\frac{2\pi}{\lambda}(x - vt),$$

$$p = (k\rho_0 v^2 y_m)\sin(kx - \omega t),$$

The ratio of the acoustic pressure and the instantaneous velocity (do not confuse it with a wave velocity) is called the acoustic impedance:

which is a complex quantity, characterized by an amplitude and a phase.

For an idealized media (no loss), Z is real and is related to the wave velocity as

We can define the intensity I of a sound wave as the power transferred per unit area. Also, it can be expressed through the acoustic impedance:

It is common, however, to specify sound not by intensity but rather by a related parameter β, called the sound level and defined with respect to a reference intensity

The magnitude of I0 was chosen because it represents the lowest hearing ability of a human ear.

The unit of β is a decibel (dB), named after Alexander Graham Bell.

If I = I0, β = 0.

Pressure levels also may be expressed in decibels as H = 20 log10 p p0 , (3.106)

where p0 = 2 × 10−5 N/m2 (0.0002 μbar)=2.9 × 10−9 psi.

Examples of some sound levels are given in Table 3.3.

Because the response of a human ear is not the same at all frequencies, sound levels are

usually referenced to I0 at 1 kHz, at which the ear is most sensitive.

$$Z = \frac{P}{\xi}. \qquad Z = \rho_0 v.$$

$$I = P\xi = \frac{P^2}{Z}. \qquad I_0 = 10^{-12}\ \mathrm{W/m^2}$$

$$\beta = 10 \log_{10}\left(\frac{I}{I_0}\right)$$

Introduction to acoustics

Acoustics is defined as the "Science of sound", Understanding sound as a mechanical disturbance in an elastic and inertial medium. These disturbances or oscillations of air pressure are converted into mechanical waves which excite the auditory mechanism, resulting in a perception.

Perceived sound is defined by:

Frequency: It represents the number of times a particle repeats a full cycle. The spectrum is the distribution of the energy between the different component waves.

Propagation Velocity: The speed at which the wave is propagated in the medium. In the air it has a velocity of 331.5 m/s to 0 ºC.

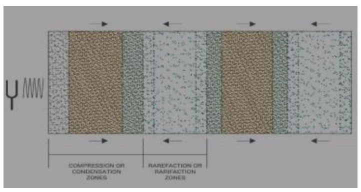
Sound Pressure Level (SPL): It represents the intensity of the sound generated by a given pressure, which corresponds to what we finally hear, measured in decibels (dB). Varies from 0 dB (hearing threshold) to 120 dB (Pain threshold).

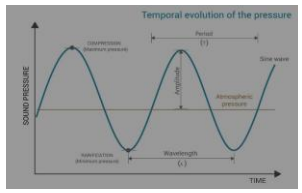
NOISE

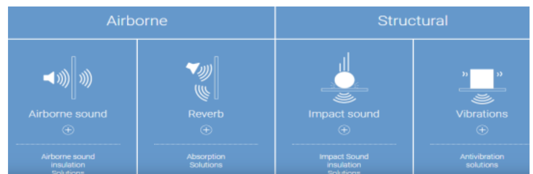
Noise is unwanted, annoying or irritating sounds, which occur when the listener is mentally or physically maladapted to the source that produces it. Any sound can be noise under certain conditions.

ACOUSTIC POLLUTION

In a society focused on achieving the well-being of people at all levels, the impact of "acoustic pollution" and the development of protection methods to reduce it is increasingly important. This pollution originates both in and outside the buildings, altering the normal conditions of the environment in a given area and generating direct consequences on our health.







In the construction industry noise is classified as:

Acoustic wave sensors

A sensor is used to measure (sense) an environment and converts this information into a digital or analogue data signal that can be interpreted by a computer or observer.

An acoustic wave sensor is an electronic device that can measure sound levels. They are called acoustic wave sensors because their detection mechanism is a mechanical (or acoustic) wave. When an acoustic wave (input) travels through a certain material or along the surface of a material, it is influenced by the different material properties and obstacles it travels through. Any changes to the characteristics of this travelling path affect the velocity and/or amplitude of the wave. These characteristics are translated into a digital signal (output) using transducers. These changes can be monitored by measuring the frequency or phase characteristics of the sensor. Then these changes can be translated to the corresponding physical differences being measured.

Ultrasonic sensors:

An ultrasonic sensor is an electronic device that measures the distance of a target object by emitting ultrasonic sound waves, and converts the reflected sound into an electrical signal. Ultrasonic waves travel faster than the speed of audible sound (i.e. the sound that humans can hear).

Ultrasonic sensors are used primarily as **proximity sensors**. They can be found in automobile self-parking technology and anti-collision safety systems. Ultrasonic sensors are also used in robotic obstacle detection systems, as well as manufacturing technology.

In comparison to infrared (IR) sensors in proximity sensing applications, ultrasonic sensors are not as susceptible to interference of smoke, gas, and other airborne particles (though the physical components are still affected by variables such as heat).

Ultrasonic sensors are also used as level sensors to detect, monitor, and regulate liquid levels in closed containers (such as vats in chemical factories). Most notably, ultrasonic technology has enabled the medical industry to produce images of internal organs, identify tumors, etc.

Ultrasonic sensors have two main components:

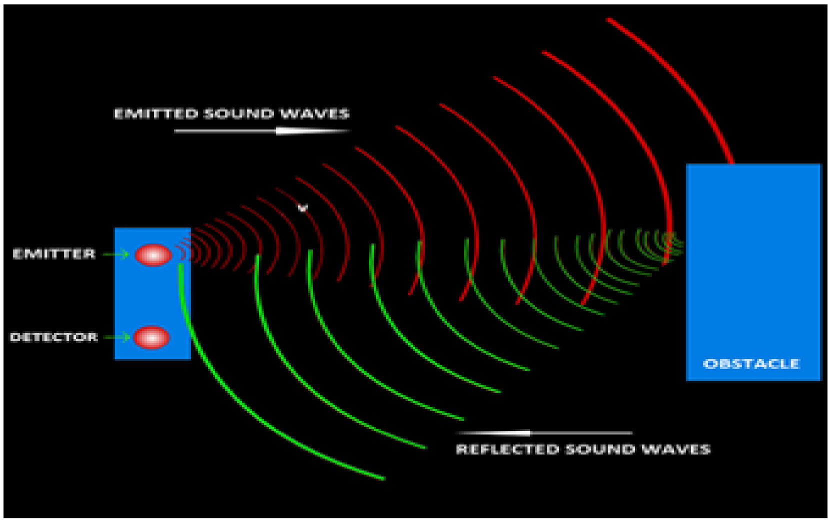
the transmitter (which emits the sound using piezoelectric crystals) and the receiver (which encounters the sound after it has travelled to and from the target).In order to calculate the distance between the sensor and the object, the sensor measuresthe time it takes between the emission of the sound by the transmitter to its contact with the receiver.

The formula for this calculation is **D = ½ T x C** (where D is the distance, T is the time, and C is the speed of sound ~ 343 meters/second).

For example, if a scientist set up an ultrasonic sensor aimed at a box and it took 0.025 seconds

for the sound to bounce back, the distance between the ultrasonic sensor and the box would be:

D = 0.5 x 0.025 x 343 or about 4.2875 meters.



Piezoelectric :

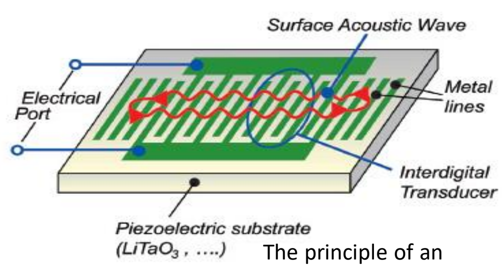
Practically all acoustic wave devices and sensors use a piezoelectric material to generate the acoustic wave. Piezoelectricity essentially means electricity resulting from pressure. It refers to the production of electrical charges as a result of mechanical stress. The sensors normally use two inter digital transducer (IDT) that can convert the incoming signal into a mechanical wave signal trough a piezoelectric substrate. The transducers are interlocked electrodes in a comb-structure. What they do is turning an electrical signal into a mechanical wave and convert it into a electrical signal again. The distance of these electrodes determines the frequency of the wave and can be used to register torque or strain (the distance changes when deformed). The performance of these sensors can be changed by varying the length, width and position of the IDT. Piezoelectric acoustic wave sensors are relatively cheap, rugged, very sensitive, reliable, and can be used passively (without a power source) and wirelessly.

Applications

All acoustic wave sensors are sensitive to changes from many different physical parameters. These sensors are often used in the **telecommunications industry**. All acoustic wave devices manufactured for the telecommunications industry **must be hermetically sealed to prevent any disturbances**. The reason for this is that these disturbances will be sensed by the device and cause an unwanted change in output. These sensors can be used as pressure, mass, thickness, torque, shock, acceleration, angular rate, viscosity, displacement, flow and force detectors under an applied stress that changes the dynamics of the object it travels through. Sensors can also detect mechanical failures or hick-ups such as grinding of components. Other applications are the monitoring of closed systems such as water pipe lines irregularities, turbulence, noise in hydraulic and pneumatic systems and pressure fluctuations. The sensors also have an acoustic electric sensitivity, allowing the detection of pH levels, ionic contaminants, and electric fields.

Examples

A good example of an acoustic sensor in nature is the ear. Every organism with ears can detect differences in sound waves and translate it to relevant information. One of the most familiar products that uses an acoustic wave sensor is the microphone. Other examples are not as well known; the Ultrasonic vibration sensor passively monitors ultrasounds produced by operating equipment. By detecting irregularities in pipes, it can be connected to alarms or recorders for data logging to ensure quick detections of malfunctions.



The principle of an acoustic wave sensor


A microphone has an acoustic sensor in it


An ultrasonic vibration sensor uses a type of acoustic sensor aiming at registering irregularities

Microphones and Hydrophones

Acoustic sensors for various frequency ranges:

The audible range sensors are generally called the microphones; however, the name is often used even for the ultrasonic and infrasonic waves. In essence, **a microphone is a pressure**

transducer adapted for the transduction of sound waves over a broad spectral range which generally excludes very low frequencies below a few hertz. The microphones differ by their sensitivity, directional characteristics, frequency bandwidth, dynamic range, sizes, and so forth. Also, their designs are quite different depending on the media from which sound waves are sensed. For example, for the perception of air waves or vibrations in solids, the sensor is called a microphone, whereas for the operation in liquids, it is called a hydrophone (even if the liquid is not water—from the Greek name of mythological water serpent Hydra). The main difference between a pressure sensor and an acoustic sensor is that latter does not need to measure constant or very slow-changing pressures. Its operating frequency range usually starts at several hertz (or as low as tens of millihertz for some applications), and the upper operating frequency limit is quite high—up to several megahertz for the ultrasonic applications and even gigahertz in the surface acoustic-wave device. Because acoustic waves are mechanical pressure waves, any microphone or hydrophone has the same basic structure as a pressure sensor: it is composed of a moving diaphragm and a displacement transducer which converts the diaphragm's deflections into an electrical signal; that is, all microphones or hydrophones differ by the design of these two essential components. Also, they may include some additional parts such as mufflers, focusing reflectors or lenses, and so forth; however, in this chapter, we will review only the sensing parts of some of the most interesting, from our point of view, acoustic sensors.

Resistive Microphones

- In the past, resistive pressure converters were used quite extensively in microphones.
- The converter consisted of a **semiconductive powder** (usually **graphite**) whose bulk resistivity was sensitive to pressure.
- Currently, we would say that **the powder possessed piezoresistive properties**.
- However, these early devices had quite a limited dynamic range, poor frequency response, and a high noise floor.

Presently, the same piezoresistive principle can be employed in the **micromachined sensors**, where stress-sensitive resistors are the integral parts of a **silicon diaphragm**

Condenser Microphones

If a parallel-plate capacitor is given an electric charge q, the voltage across its plates is

$$V = q\frac{d}{\varepsilon_0 A}, \qquad (1)$$

where $\varepsilon_0 = 8.8542 \times 10^{-12}$ C2/N m2 is the permitivity constant

Equation (1) is the basis for operation of the condenser microphones, which is another way to say "capacitive" microphones.

Thus, a capacitive microphone linearly converts a distance between the plates into electrical voltage which can be further amplified.

The device essentially requires a source of an electric charge q whose magnitude directly determines the microphone sensitivity.

The charge can be provided either from an external power supply having a voltage in the range from 20 to 200 V or from an internal source capable of producing such a charge.

This is accomplished by a built-in electret layer which is a polarized dielectric crystal.

Presently, many condenser microphones are fabricated with **silicon diaphragms**, which serve two purposes: **to convert acoustic pressure into displacement and to act as a moving plate of a capacitor.**

To achieve high sensitivity, a bias voltage should be as large as possible, resulting in a large static deflection of the diaphragm, which may result in reduced shock resistivity and lower dynamic range.

In addition, if the air gap between the diaphragm and the backplate is very small, the acoustic resistance of the air gap will reduce the mechanical sensitivity of the microphone at higher frequencies.

For instance, at an air gap of 2 μm, an upper cutoff frequency of only 2 kHz has been measured. One way to improve the characteristics of a condenser microphone is to use a mechanical feedback from the output of the amplifier to the diaphragm

The electrodes serve different purposes:

One is for the conversion of a diaphragm displacement into voltage at the input of the amplifier A1 and the other electrode is for converting feedback voltage Va into a mechanical deflection by means of electrostatic force.

The mechanical feedback clearly improves the linearity and the frequency range of the microphone; however, it significantly reduces the deflection, which results in a lower sensitivity.

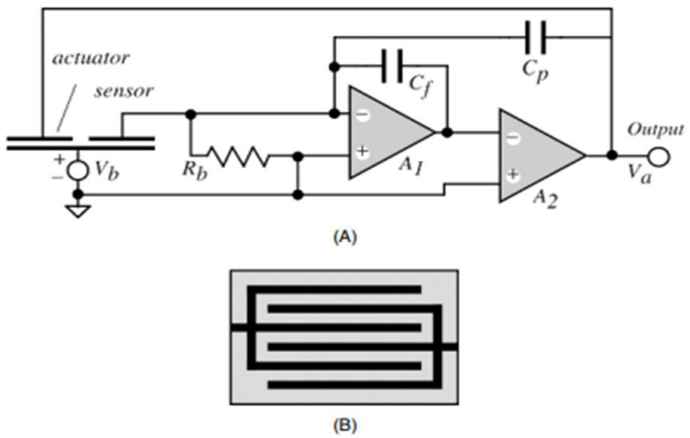


Figure-Circuit diagram and drawing of interdigitized electrodes of the microphone

Fiber-Optic Microphone

Direct acoustic measurements in hostile environments, such as in **turbojets or rocket engines, require sensors which can withstand high heat and strong vibrations.** The acoustic measurements under such hard conditions are required for computational fluid dynamics (CFD) code validation, structural acoustic tests, and jet noise abatement. For such applications, a fiber-optic interferometric microphone can be quite suitable. One such design s composed of a single-mode temperature insensitive Michelson interferometer and a reflective plate diaphragm. The interferometer monitors the plate deflection, which is directly related to the acoustic pressure. The sensor is water cooled to provide thermal protection for the optical materials and to stabilize the mechanical properties of the diaphragm. To provide an effect of interference between the incoming and outgoing light beams, two fibers are fused together and cleaved at the minimum tapered region (Fig. 12.2).

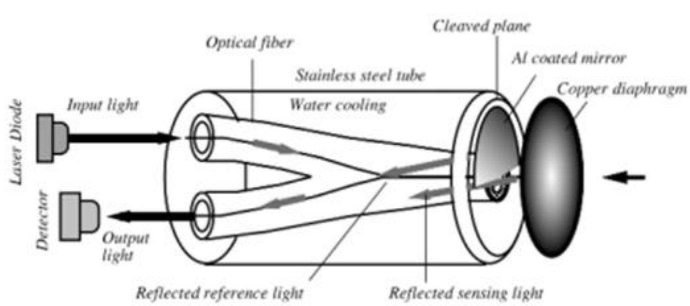


Fig. 12.2. Fiber-optic interferometric microphone. Movement of the copper diaphragm is converted into light intensity in the detector.

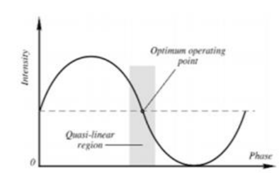


Fig. 12.3. Intensity plot as function of a reflected light phase.

To provide an effect of interference between the incoming and outgoing light beams, two fibers are fused together and cleaved at the minimum tapered region (Fig. 12.2). The fibers are incorporated into a stainless-steel tube, which is water cooled. The internal space in the tube is filled with epoxy, and the end of the tube is polished until the optical fibers are observed. Next, aluminum is selectively deposited at one of the fused fiber core ends to make its surface mirror reflective. This fiber serves as a reference arm of the microphone. The other fiber core is left open and serves as the sensing arm. Temperature insensitivity is obtained by the close proximity of the reference and sensing arms of the assembly Light from a laser source (a laser diode operating near 1.3 μm wavelength) enters one of the cores and propagates toward the fused end, where it is coupled to the other fiber core. When reaching the end of the core, light in the reference core is reflected from the aluminum mirror toward the input and output sides of the sensor. The portion of light which goes toward the input is lost and has no effect on the measurement, whereas the portion which goes to the output strikes the detector's surface.

That portion of light which travels to the right in the sensing core, exits the fiber, and strikes the copper diaphragm. Part of the light is reflected from the diaphragm back toward the sensing fiber and propagates to the output end, along with the reference light. Depending on the position of the diaphragm, the phase of the reflected light will vary, thus becoming different from the phase of the reference light. While traveling together to the output detector, the reference and sensing lights interfere with one another, resulting in the light-intensity modulation.

Therefore, the microphone converts the diaphragm displacement into a light intensity. Theoretically, the signal-to-noise ratio in such a sensor is obtainable on the order of 70–80 dB, thus resulting in an average minimum detectable diaphragm displacement of 1 Å (10−10 m). Figure 12.3 shows a typical plot of the optical intensity in the detector versus the phase for the interference patterns.

To assure a linear transfer function, the operating point should be selected near the middle of the intensity, where the slope is the highest and the linearity is the best. The slope and the operating point may be changed by adjusting the wavelength of the laser diode. It is important for the deflection to stay within one-quarter of the operating wavelength to maintain a proportional input. The diaphragm is fabricated from a 0.05-mm foil with a 1.25-mm diameter. Copper is selected for the diaphragm because of its good thermal conductivity and relatively low modulus of elasticity. The latter feature allows us to use a thicker diaphragm, which provides better heat removal while maintaining a usable natural frequency and deflection. A pressure of 1.4 kPa produces a maximum center deflection of 39 nm (390 AA), which is well within a one-quarter of the operating wavelength (1300 nm). The maximum acoustic frequency which can be transferred with the optical microphone is limited to about 100 kHz, which is well above the desired working range needed for the structural acoustic testing.

Piezoelectric Microphones

The piezoelectric effect can be used for the design of simple microphones. A piezoelectric crystal is a direct converter of a mechanical stress into an electric charge. The most frequently used material for the sensor is a piezoelectric ceramic, which can operate up to a very high frequency limit. This is the reason why piezoelectric sensors are used for the transduction of ultrasonic waves. Still, even for the audible range, the piezoelectric microphones are used quite extensively. Typical applications are voice-activated devices and blood pressure measurement apparatuses where the arterial Korotkoff sounds have to be detected.

For such acoustically non demanding applications, the piezoelectric microphone design is quite simple (Fig. 12.4). It consists of a piezoelectric ceramic disk with two electrodes deposited on each side. The electrodes are connected to wires either by electrically conductive epoxy or by soldering. Because the output impedance of such a microphone is very large, a high-input-impedance amplifier is required. Piezoelectric films [polyvinylidene fluoride (PVDF) and copolymers] were used for many years as very efficient acoustic pickups in musical instruments. One of the first applications for piezoelectric film was as an **acoustic pickup for a violin**. Later, the film was introduced for a line of acoustic guitars as a saddle-mounted bridge pickup, mounted in the bridge.The very high fidelity of the pickup led the way to a family of vibration-sensing and accelerometer applications: in one guitar pickup, a thickfilm, compressive (under the saddle) design; another is a low-cost accelerometer, and another is an after-market pickup design that is taped to the instrument. Because of the low Q of the material, these transducers do not have the self-resonance of hard ceramic pickups. Shielding can be achieved by a foldover design as shown in Fig. 12.5A. The sensing side is the slightly narrower electrode on the inside of the fold. The foldover technique provides a more sensitive pickup than alternative shielding methods because the shield is formed by one of the electrodes. For application in water, the film can be rolled in tubes, and many of such tubes can be connected in parallel (Fig. 12.5B).

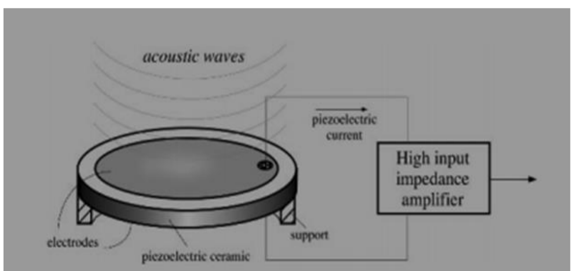


Fig. 12.4. Piezoelectric microphone.

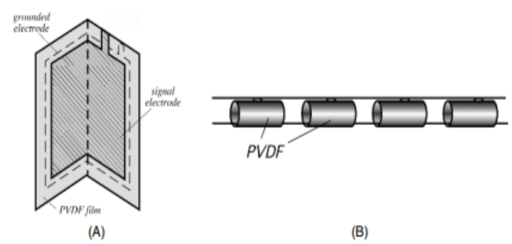


Fig. 12.5. Foldover piezoelectric acoustic pickup (A) and arrangement of a piezoelectric film hydrophone (B).

Electret Microphones

An electret is a close relative of piezoelectric and pyroelectric materials. In effect, they are all electrets with either enhanced piezoelectric or pyroelectric properties. An electret is a permanently electrically polarized crystalline dielectric material. The first application of electrets to microphones and earphones where described in 1928. An electret microphone is an electrostatic transducer consisting of a metallized electret and back plate separated from the diaphragm by an air gap (Fig. 12.6). The upper metallization and a metal back plate are connected through a resistor R's voltage V across which it can be amplified and used as an output signal. Because the electret is a permanently electrically polarized dielectric, the charge density σ1 on its surface is constant and sets an electric field E1 in the air gap. When an acoustic wave impinges on the diaphragm, the latter deflects downward, reducing the air gap thickness s1 for a value of s. Under open-circuit conditions, the amplitude of a variable portion of the output voltage becomes

Thus, the deflected diaphragm generates voltage across the electrodes. That voltage is in phase with the diaphragm deflection. If the sensor has a capacitance C, Eq. (12.2) should be written where f is the frequency of sonic waves. If the restoring forces are due to the elasticity of the air cavities behind the diaphragm (effective thickness is s0) and the tension T of the membrane, its displacement s to a sound pressure p assuming negligible losses is given by

where γ is the specific heat ratio, p0 is the atmospheric pressure, and A is the membrane area.

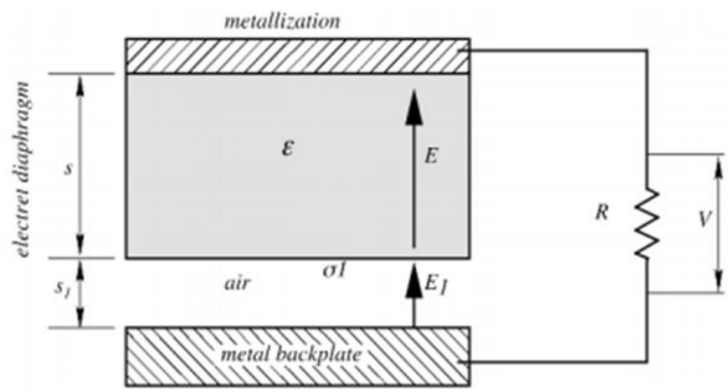


Fig. 12.6. General structure of an electret microphone. The thicknesses of layers are exaggerated for clarity.

$$V = \frac{s\Delta s}{\varepsilon_0(s+\varepsilon s_1)}.$$

$$V = \frac{s\Delta s}{\varepsilon_0(s+\varepsilon s_1)}\frac{2\pi f RC}{\sqrt{1+(2\pi f RC)^2}}, \qquad \delta_m = \frac{s s_0 \sigma_1}{\varepsilon_0(s+\varepsilon s_1)\gamma p_0}.$$

$$\Delta s = \frac{\Delta p}{(\gamma p_0/s_0)+(8\pi T/A)}, \qquad fr = \frac{1}{2\pi}\sqrt{\frac{p_0}{s_0 M}}.$$

If we define the electret microphone sensitivity as δm = V /p, then below resonance it can be expressed as

It is seen that the sensitivity does not depend on area. If the mass of the membrane is M, then the resonant frequency is defined by

This frequency should be selected well above the upper frequency of the microphone's operating range. The electret microphone differs from other similar detectors in the sense that it does not require a dc bias voltage. For comparable design dimensions and sensitivity, a condenser microphone would require well over 100 V bias. The mechanical tension 388 12 Acoustic Sensors of the membrane is generally kept at a relatively low value (about 10 N m−1), so that the restoring force is determined by the air-gap compressibility.

A membrane may be fabricated of Teflon FEP (Fluorinated Ethylene Propylene), which is permanently charged by an electron beam to give it electret properties.

The temperature coefficient of sensitivity of the electret microphones are in the range of 0.03 dB/◦C in the temperature range from −10 to +50◦C. Foil-electret (diaphragm) microphones have more desirable features than any other microphone type. Among them is very wide frequency range from 10−3Hz and up to hundreds of megahertz. They also feature a flat frequency response (within ±1 dB), low harmonic distortion, low vibration sensitivity, good impulse response, and insensitivity to magnetic fields. Sensitivities of electret microphones are in the range of few millivolts per microbar. For operation in the infrasonic range, an electret microphone requires a miniature pressure equalization hole on the backplate. When used in the ultrasonic range, the electret is often given an additional bias (like a condenser microphone) in addition to its own polarization. Electret microphones are high-impedance sensors and thus require high-inputimpedance interface electronics. A JFET transistor has been the input of choice for many years. However, recently monolithic amplifiers gained popularity. An example is the LMV1014 (National Semiconductors), which is an audio amplifier with very low current consumption (38 μA) that may operate from a small battery power supply ranging from 1.7 to 5 V.

Hydrophone

A **hydrophone** is a microphone designed to be used underwater for recording or listening to underwater sound.

A typical hydrophone works by converting a sound wave into an electrical voltage by detecting changes in pressure in the surrounding environment. The speed and distance at which a sound wave travels through water will be proportional to the pressure changes, which will determine the nature of the electrical output that is transmitted. Most hydrophones are based on a piezoelectric transducer that generates an electric potential when subjected to a pressure change, such as a sound wave. Some piezoelectric transducers can also serve as a sound projector, but not all have this capability, and some may be destroyed if used in such a manner. A hydrophone can detect airborne sounds, but will be insensitive because it is designed to match the acoustic impedance of water, a denser fluid than air. Sound travels 4.3 times faster in water than in air, and a sound wave in water exerts a pressure 60 times that exerted by a wave of the same amplitude in air. Similarly, a standard microphone can be buried in the ground, or immersed in water if it is put in a waterproof container, but will give poor performance due to the similarly bad acoustic impedance match. Piezoelectric material is ideal for making hydrophones. They can change their form and help generate an electrical potential in response to mechanical or external pressure changes. When an electrical voltage is applied to the crystalline ceramic material, the crystalline structure aligns, becomes anisotropic, and carries an electrical charge. A typical hydrophone has a transducer. This transducer is crucial for converting the incoming sound waves into an electrical voltage. Use of a piezoelectric transducer as an alternative to crystal material is now a popular option in modern-day hydrophone technology. A hydrophone with a single transducer has a circular conical shape that reflects incoming sound waves which in turn allows the hydrophone to be positioned at varying locations and depth. Figure 1 illustrates how a typical hydrophone is applied underwater to track sound waves from varying sources. The only problem with a single transducer is that signals from other directions interfering with the main signal cannot be subtracted and this can obscure data about the location of the desired signal. While a hydrophone can detect sound waves in the air, it is not as sensitive with airborne sounds because of its acoustic impedance is designed specifically for sound detection in water.

Array Hydrophones

Array hydrophones (streamers - built of multiple transducers) are all wired to receive a large sound signal collectively. The transducers are packed together in a tube with oil, which aids the collection of pressure waves entering the hydrophone. Pre-amplifiers are often used to enhance the electrical signal and limit the potential of noise contamination from additional components to the hydrophone.

Temperature Change and Hydrophone Sensitivity

It is important to remember that sound in water is affected by the temperature of the water. Warm surface water is less dense and so sound traveling through the water to the surface will refract and becomes trapped, a phenomenon referred to as a surface duct.

As most hydrophones are used in an open-water environment, they are typically exposed to temperature and pressure variations, and hence, the technology needs to be wired to account for variations and so to provide an accurate picture of sound location.

The sensitivity of hydrophones can be determined by the voltage produced by a hydrostatic pressure wave. A useful parameter in choosing piezoelectric materials to be used in hydrophones is the voltage coefficient, which links the electric field and the applied hydrostatic strain. Another widely used parameter is the hydrostatic strain coefficient, which refers to polarization resulting from changes in stress.

Calibration methods such as comparison or substitution can also be applied; however, this method does require calibrating the transducers over a full range of environmental conditions.

Applications of Hydrophones

The applications of hydrophones typically involve positioning the hydrophone on the seafloor or parallel to a boat under water. Sound waves traveling in from various distances will reach the hydrophone at different times, and this time difference helps locate the source of a signal wave. Marine environmental research often deploys array hydrophones to track underwater marine life and their behavioral patterns. Underwater surveillance can also be managed using array hydrophones. For example, the US Navy's sound surveillance system consisting of a series of hydrophone arrays were placed in the Atlantic Ocean in the 1950s to monitor submarine activity during the cold war.

The video below demonstrates the different sounds that are traced by a hydrophone array. The video illustrates SOFAR channeling of the sound wave to the hydrophone array.

Use of a marine hydrophone array to record sound waves.

Submarines also use hydrophones to track the position of an incoming, underwater remotely operated vehicle (ROV) to avoid collisions. The hydrophone is placed on top of a submarine, facing down at a 25 to 30-degree angle to allow for accurate tracking of sound. By tracking the location of an incoming boat, the submarine crew can remain in a safe position underwater until the surrounding area is safe enough for the crew to resume to the surface without colliding with an ROV.

Additional applications of a hydrophone include the following:

- Environmental monitoring
- Navigation/positioning systems
- Underwater exploration
- Towed arrays
- Deep ocean operation

Hydrophones are becoming highly useful for tracking patterns of micro-earthquakes and underground volcanic activity. A recent publication by Dziak R.P. et al. (2012) has revealed how the application of ocean-bottom hydrophones helped measure an increase in seismic activity over several years to the point at which a volcanic eruption was observed in April 2011.

Studies have also hinted on the development of an autonomous hydrophone called the Quasi-Eulerian hydrophone, or QUEphone. It is a tether-free floating hydrophone that can maintain an almost fixed position in ocean water and detect acoustic events in near-real time. It can continuously monitor sound and transmit data by repeatedly traveling between the seafloor and the sea surface.

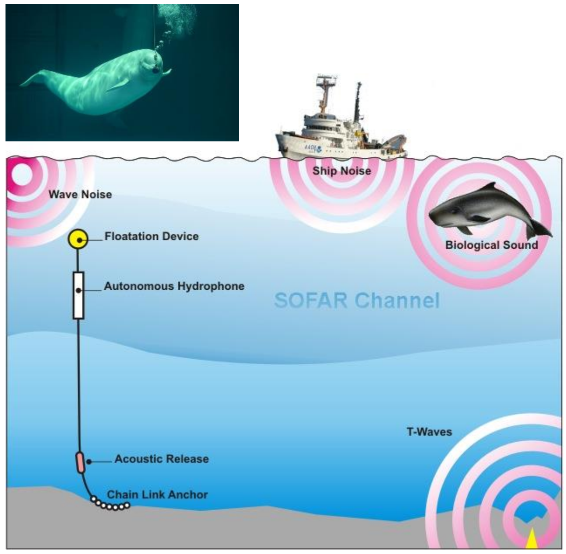


Figure 1. *Open-water monitoring using a hydrophone.*

Nuclear Radiation Detector

- A radiation Detector or particle detector is a device that measures this ionization of many types of radiation, like- beta radiation, gamma radiations, and alpha radiation with the matter. Thus, creating electrons and positively charged ions.

What is radiation detector?

- Radiation Detector is an instrument **used to detect or identify high-energy particles**, such as those produced by **nuclear decay, cosmic radiation, or reactions in a particle accelerator.**

Evolution of radiation detector

- Earlier, photographic plates were used to identify tracks left by nuclear interactions. Sub-nuclear particles are discovered by using cloud chambers which needed photographic recordings and a tedious measurement of tracks from the photographs.
- Electronic detectors developed with the invention of the transistor. Modern detectors use calorimeters to measure the energy of the detected radiation. They may also be used to measure other attributes such as momentum, spin, charge, etc. of the particles.

Type of Detectors

Scintillator

- When excited by ionizing radiation, a scintillator exhibits scintillation which is nothing but the property of luminescence. When a scintillator is coupled to an electronic light sensor such as a photomultiplier tube (PMT), photodiode, or silicon photomultiplier, a scintillator detector. Scintillator-type detectors first convert light into electrical pulses. They use vacuum tubes to perform so.

Gaseous Ionization Detectors

- A radiation detection instrument used in particle physics to detect the presence of ionizing particles, and in radiation protection applications to measure ionizing radiation is called Gaseous ionization detectors.

Geiger Counter

- Geiger-Mueller counter, commonly called the Geiger counter is the most commonly used detector. A central wire in between a gas-filled tube at high voltage is used to collect the ionization produced by incident radiation. Although it cannot distinguish between them, it can detect alpha, beta, and gamma radiation.

Types of radiations

Alpha radiation

- Alpha particles or double ionized helium nuclei are the fast-moving helium atoms. They have high energy ranging in MeV.
- They have low penetration depth; typically a few cms of air or skin due to their large mass.

Beta radiation

- They are fast-moving electrons. Their energy ranges from hundreds of KeV to several MeV.
- They have better penetration depth due to their comparatively lighter mass. Typically, several feet of air, several millimeters of lighter materials.

Gamma radiation

- They are the stream of photons. Typical energy ranges from Several KeV to Several MeV.
- They have comparatively very low mass. Thus, possess good penetration depth. Typically, a few inches of lead

Solid-State Acoustic Detectors

Currently, use of the acoustic sensors is broader than detecting sound. In particular, they became increasingly popular for detecting mechanical vibrations in a solid for the fabrication of such sensors as microbalances and surface acoustic-wave (SAW) devices.

Applications range over measuring displacement, concentration of compounds, stress, force, temperature, and so forth. All such sensors are based on elastic motions in solid parts of the sensor and their major use is serving as parts in other, more complex sensors, (e.g., in chemical detectors, accelerometers, pressure sensors, etc.). In chemical and biological sensors, the acoustic path, where mechanical waves propagate, may be coated with chemically selective compound which interact only with the stimulus of interest. An excitation device (usually of a piezoelectric nature) forces atoms of the solid into vibratory motions about their equilibrium position. The neighboring atoms then produce a restoring force tending to bring the displaced atoms back to their original positions. In the acoustic sensors, vibratory characteristics, such as phase velocity and/or the attenuation coefficient, are affected by the stimulus. Thus, in acoustic sensors, external stimuli, such as mechanical strain in the sensor's solid, increase the propagating speed of sound. In other sensors, which are called gravimetric, sorption of molecules or attachment of bacteria cause a reduction of acoustic-wave velocity. In another detector, called the acoustic viscosity sensors, viscous liquid contacts the active region of an elastic-wave sensor and the wave is attenuated. Acoustic waves propagating in solids have been used quite extensively in electronic devices such as electric filters, delay lines, microactuators, and so forth. The major advantage of the acoustic waves as compared with electromagnetic waves is their low velocity. Typical velocities in solids range from 1.5 × 103 to 12 × 103 m/s, and the practical SAWs utilize the range between 3.8 × 103 and 4.2 × 103 m/s, that is, acoustic velocities are five orders of magnitude smaller than those of electromagnetic waves. This allows for the fabrication of miniature sensors operating with frequencies up to 5 GHz. When the solid-state acoustic sensor is fabricated, it is essential to couple the electronic circuit to its mechanical structure where the waves propagate. The most convenient effect to employ is the piezoelectric effect. The effect is reversible, which means that it works in both directions: The mechanical stress induces electrical polarization charge, and the applied electric field stresses the piezoelectric crystal. Thus, the sensor generally has two piezoelectric transducers at each end: one at the transmitting end, for the generation of acoustic waves, and the other at the receiving end, for conversion of acoustic waves into an electrical signal. Because silicon does not possess piezoelectric effect, additional piezoelectric material must be deposited on the silicon waver in the form of a thin film.

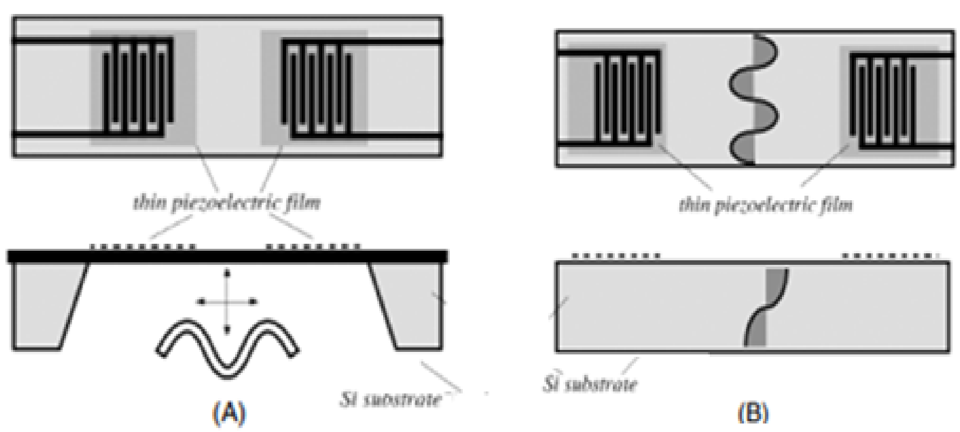


Figure 12.7 shows a sensor with a flextural and with the acoustic plate mode

- Typical piezoelectric materials used for this purpose are zinc oxide (ZnO), aluminum nitride (AlN), and the so-called solid-solution system of lead–zirconite–titanium oxides Pb(Zr,Ti)O3 known as PZT ceramic.
- When depositing thin films on the semiconductor material, several major properties must be taken into account:

1. Quality of the adhesion to the substrate
2. Resistance to the external factors (such as fluids which interact with the sensing surface during its operations)
3. Environmental stability (humidity, temperature, mechanical shock, and vibration)
4. Value of electromechanical coupling with the substrate
5. Ease of processing by the available technologies
6. Cost

The strength of the piezoelectric effect in elastic-wave devices depends on the configuration of the transducting electrodes. Depending on the sensor design, for the bulk excitation (when the waves must propagate through the cross-sectional thickness of the sensor), the electrodes are positioned on the opposite sides and their area is quite large. For the SAW, the excitation electrodes are interdigitized. Several configurations for the solid-state acoustic sensors are known. They differ by the mode the waves propagate through the material. In the former case, a very thin membrane is flexed by the left pair of the interdigitized electrodes and its vertical deflection induces response in the right pair of the electrodes. As a rule, the membrane thickness is substantially less than the wavelength of the oscillation. In the latter case, the waves are formed on the surface of a relatively thick plate. In either case, the space between the left and right pairs of the electrodes is used for interaction with the external stimulus, such as pressure, viscous fluid, gaseous molecules, or microscopic particles. A typical application circuit for a SAW includes a SAW plate as a time-keeping device of a frequency oscillator.Because many internal and external factors may contribute to the propagation of an acoustic wave and, subsequently, to change in frequency of oscillation, the determination of change in stimulus may be ambiguous and contain errors. An obvious solution is to use a differential technique, where two identical SAW devices are employed: One device is for sensing the stimulus and the other is reference (Fig. 12.8). The reference device is shielded from stimulus, but subjected to common factors, such as temperature, aging, and so forth. The difference of the frequency changes of both oscillators is sensitive only to variations in the stimulus, thus canceling the effects of spurious factors.

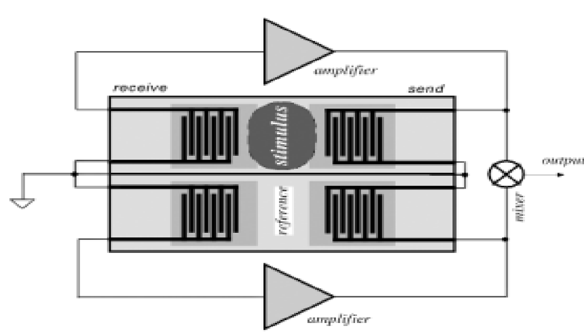
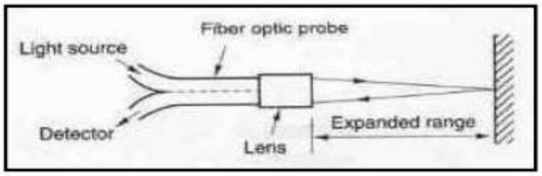


Fig. 12.8. Differential SAW sensor.

Fiber Optic Sensors

Basic Components:

- source of light
- a length of sensing (and transmission) fiber
- a photo-detector
- demodulator
- processing and display optics
- required electronics

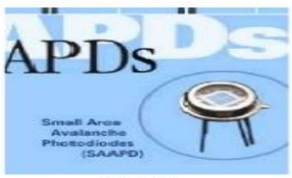


Detectors

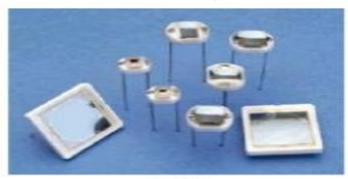
- Detector is the receiving end of a fiber optic link.

There are two kinds of Detectors

1. PIN (Positive Intrinsic Negative)
2. APD (Avalanche photo diodes)



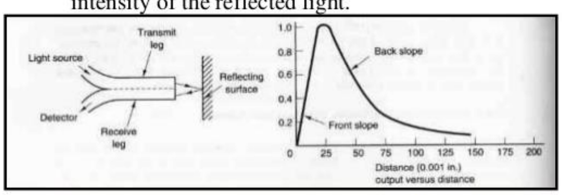
APD



PIN

A. Intensity Modulated Strain Gages

- **Reflective sensors**
  - One bundle is used to transmit the light to a reflecting target
  - Other collects the reflected light and transmits to a detector
  - Any movement of the target will effect the intensity of the reflected light.

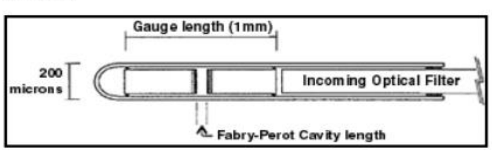


Rustle of leaves

Threshold of hearing

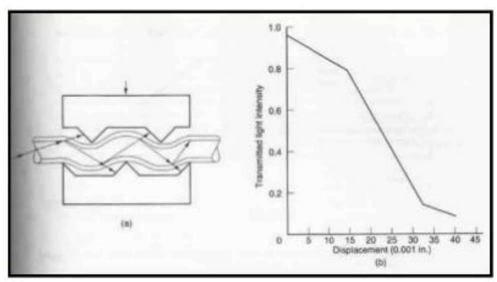
B. Phase Modulated Strain Gages

- **Fabry-Perot Interferometers (FPI)**
  - light source is conveyed via an optical fiber to two mirrors (reflectors).
  - When the displacement between the mirrors has changed due to strain, optical spectrum changes
  - absolute distance between the mirrors gives the strain.

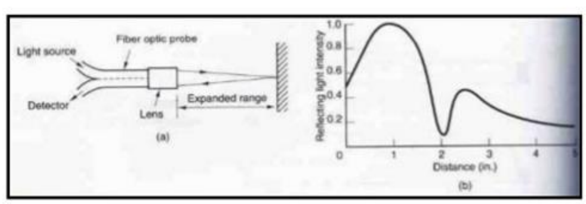


A. Intensity Modulated Strain Gages

- **Micro-bend Sensors**
  - If a fiber is bent, a portion of the trapped light is lost through the wall.



- Plain reflective displacement sensors have a limited dynamic range of about 0.2 in.
- Can be improved by a lens system to 5 in.
- sensitive to the orientation and contamination of the reflective surface



Model Questions

1. Discuss about Wheatstone bridge circuit, strain gauges and load cells with suitable examples
2. Explain Fiber optic strain gauge and Semiconductor strain gauges with neat diagrams
3. Explain Bourdon and McLeod Gauge with their applications in measurement system.
4. Discuss the suitability of Thermal Conductivity Gauge and Ionization Gauge in measuring vacuum.
5. Explain different types of Anemometers used for the measurement of air flow, wind speed, etc.
6. Explain different types of Ultrasonic and hot wire anemometers used for the measurement of air flow.
7. Explain the principle of light emitter and detector with neat diagrams
8. Discuss about acoustics and acoustic sensors and Ultrasonic sensors with neat diagrams.
9. Explain various types of Microphones and Hydrophones with neat diagrams
10. Explain in detail about (a) Sound level meters and (b) Nuclear radiation sensors.

SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHATRONICS ENGINEERING

UNIT IV - Measurement of Electrical Parameters - SMR1302

SMR1302 SENSORS AND INSTRUMENTATION

UNIT IV MEASUREMENT OF ELECTRICAL PARAMETERS

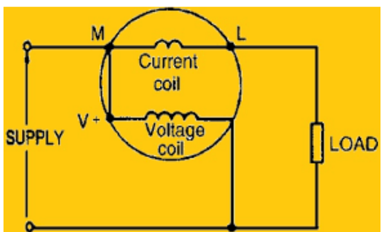
TOPICS:

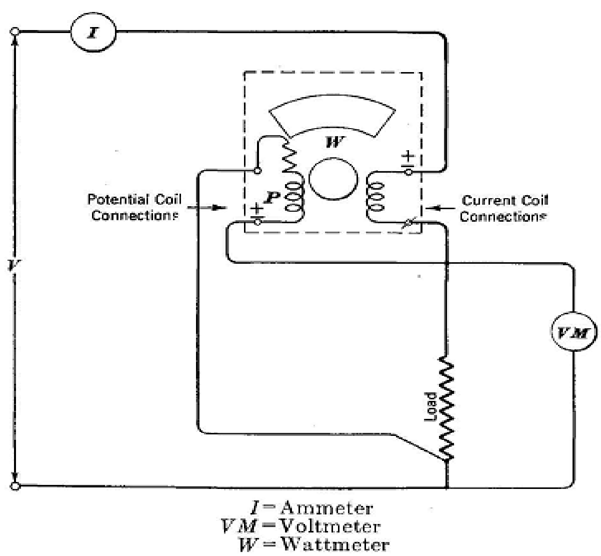
Three phase & Single phase watt meter and power factor, Resistive, capacitive and inductive measurements, Instrument Transformers: CT and PT and their errors, Applications of CT and PT in the extension of instrument range

Wattmeter

The wattmeter is an instrument for measuring the electric power (or the supply rate of electrical **energy**) in **watts** of any given circuit.

- Electromagnetic wattmeters are used for measurement of **Utility frequency and Audio frequency power**; other types are required for **radio frequency measurements**.





Electrodynamometer Type Wattmeter

Dynamometer type wattmeter works on very simple principle and this principle can be stated as when any current carrying conductor is placed inside a magnetic field, it experiences a mechanical force and due to this mechanical force deflection of conductor takes place.

Construction and Working Principle of Electrodynamometer Type Wattmeter

Now let us look at constructional details of electrodynamometer. It consists of following parts.

Moving Coil

Moving coil moves the pointer with the help of **spring control instrument**. Limited of current flows through the moving coil so as to avoid heating. So in order **to limit the current**

we have connected the **high value resistor in series with the moving coil**. The moving is air cored and is **mounted on a pivoted spindle** and **can move freely**. In **electrodynamometer type wattmeter**, moving coil works as **pressure coil**. Hence moving coil is connected across the voltage and thus **the current flowing through this coil is always proportional to the voltage**

Fixed Coil

The fixed coil is divided into two equal parts and these **are connected in series with the load**, therefore the **load current will flow through these coils.** Now the reason is very obvious of using two fixed coils instead of one, so that it can be constructed to carry considerable amount of electric current. **These coils are called the current coils** of **electrodynamometer type wattmeter**. Earlier these fixed coils are designed to carry the current of **about 100 amperes** but now the modern wattmeter are designed to carry current of about **20 amperes in order to save power.**

Control System Out of two controlling systems i.e.

1. Gravity control

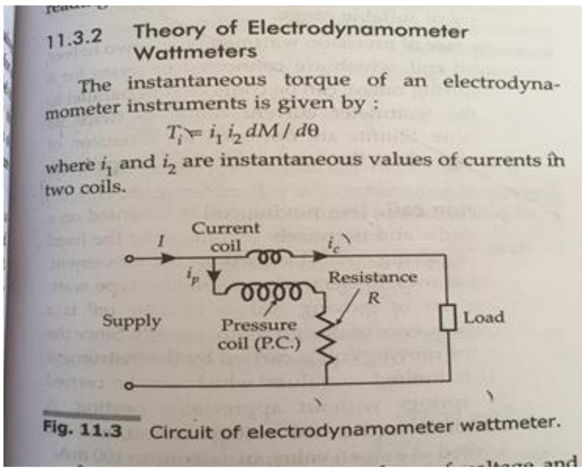
2. Spring control, only spring controlled systems are used in these types of wattmeter. Gravity controlled system cannot be employed because they will be appreciable amount of errors.

Damping System: Air friction damping is used, as eddy current damping will distort the weak operating magnetic field and thus it may leads to error.

Scale

- There is uniform scale which is used in these types of instrument as moving coil moves linearly over a range of 40 degrees to 50 degrees on either side. Now let us derive the expressions for the controlling torque and deflecting torques. In order to derive these expressions let us consider the circuit diagram given below:
- We know that instantaneous torque in electrodynamic type instruments is directly proportional to product of instantaneous values of currents flowing through both the coils and the rate of change of flux linked with the circuit. Let I1 and I2 be the instantaneous values of currents in pressure and current coils respectively. So the expression for the torque can be written as:
- Where, x is the angle. Now let the applied value of voltage across the pressure coil be
- Assuming the electrical resistance to the pressure coil be very high hence we can neglect reactance with respect to its resistance. In this the impedance is equal to its electrical resistance therefore it is purely resistive. The expression for instantaneous current can be written as I2 = v / Rp where Rp is the resistance of pressure coil
- If there is phase difference between voltage and electric current, then expression for instantaneous current through current coil can be written as

- As current through the pressure coil is very very small compared to the current through current coil hence current through the current coil can be considered as equal to total load current. Hence the instantaneous value of torque can be written as
- Average value of deflecting torque can be obtained by integrating the instantaneous torque from limit 0 to T, where T is the time period of the cycle.
- Controlling torque is given by Tc = Kx where K is spring constant and x is final steady state value of deflection.



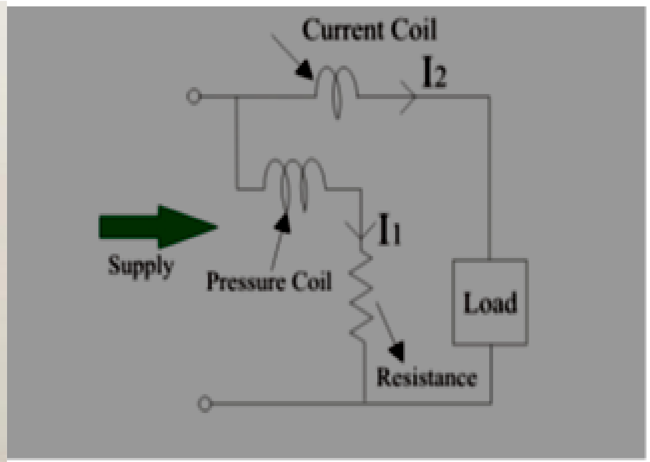
11.3.2 Theory of Electrodynamometer Wattmeters

The instantaneous torque of an electrodynamometer instruments is given by :

$$T_i = i_1 i_2 \, dM / d\theta$$

where i_1 and i_2 are instantaneous values of currents in two coils.

Fig. 11.3 Circuit of electrodynamometer wattmeter.



$$T = I_1 \times I_2 \times \frac{dM}{dx}$$

$$v = \sqrt{2}V sin\omega t$$

$$I_2 = \sqrt{2} \times \frac{V sin\omega t}{R_p}$$

$$I_1 = I(t) = \sqrt{2}I sin(\omega t - \phi)$$

$$\sqrt{2} \times \frac{V sin\omega t}{R_p} \times \sqrt{2} \times I \times sin(\omega t - \phi) \times \frac{dM}{dx}$$

$$T_d = deflecting\ torque = \frac{VI}{R_p} cos\phi \times \frac{dM}{dx}$$

Advantages of Electrodynamometer Type Wattmeter

Following are the **advantages of electrodynamometer type wattmeter** and they are written as follows:

Scale is uniform upto a certain limit. They can be used for both to measure AC as well DC quantities as scale is calibrated for both.

Errors in Electrodynamometer Type Wattmeter

Following are the errors in the electrodynamometer type watt meters:

Errors in the pressure coil inductance. Errors may be due to pressure coil capacitance.

Errors may be due to mutual inductance effects. Errors may be due connections. (i.e. pressure coil is connected after current coil). Error due to Eddy currents. Errors caused by vibration of moving system. Temperature error. Errors due to stray magnetic field.

Low Power Factor Wattmeter

As the name suggests the low power factor meter are the instruments that measures lower values of power factor accurately. There are two main reasons that would suggests us that we should not use ordinary wattmeter in measuring the low value of power factor.

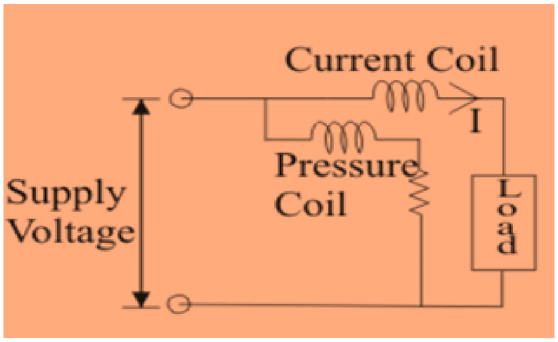
1. The value of deflecting torque is very low even though we fully excite the current and pressure coils. 2. Errors due to pressure coil inductance.

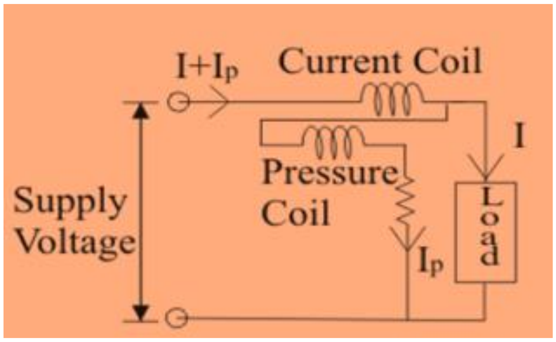
some modification or adding some new features we can use modified electrodynamic wattmeter or low power factor to measure the low power factor accurately.

(1) The electrical resistance of the ordinary wattmeter's pressure coil is reduced to low value such that current in the pressure coil circuit is increased, thus it leads to.

In this category two cases diagrams arises and these are shown below:

- Both the ends of the pressure coil is connected to supply side (i.e. current coil is in series with the load). The supply voltage is equal to the voltage across the pressure coil. Thus in this case we have power shown by the first wattmeter is equal to the power loss in the load plus power loss in the current coil.
- In the second category, the current coil is not in series with the load and the voltage across the pressure coil is not equal to the applied voltage. The voltage across pressure coil is equal to the voltage across the load. In this power shown by the second watt meter is equal to the power loss in the load plus the power loss in the pressure coil.
- From the above discussion we conclude that in both cases we have some amount of errors hence there is need to do some modification in above circuits to have minimum error.





$$Mathematically\ P_1 = power\ consumed\ by\ load + I^2 R_1$$

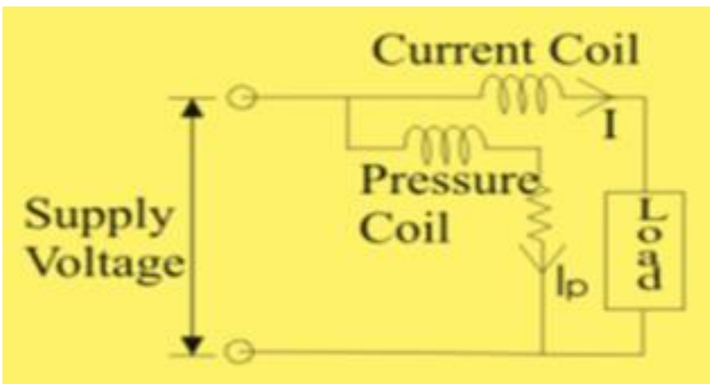
$$Mathematically\ P_2 = power\ consumed\ by\ load + I^2 R_2$$

The modified circuit is shown below:

We have used here a special coil called compensating coil, **it carries current equal to the sum of two currents** i.e load current plus pressure coil current. The pressure coil is placed such that the field produced by the compensating coil is opposed by the field produced by pressure coil as shown in the above circuit diagram. Thus the net field is due to the current I only. Hence by this way error caused by pressure coil can be neutralised.

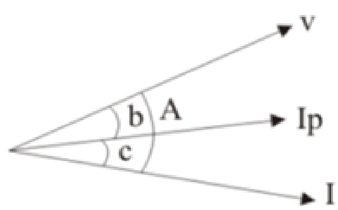
(2) We require compensating coil in the circuit in order to make the low power factor meter. It is the second modification that we have discussed in detail above.

(3) Now the third point deals with the compensation of the inductance of pressure coil, which can be achieved by doing modification in above circuit.



Now let us derive an expression for the correction factor for pressure coil inductance. And from this correction factor we are going to derive an an expression for error due to inductance of pressure coil. If we consider the inductance of pressure coil we don't have voltage across pressure in phase with the applied voltage. Hence it that case it lag by an angle

$$\frac{cos(A)}{cos(b)cos(A-b)}$$



$$\frac{VIcos(C)\frac{dM}{dx}}{K+R_p}\cdots\cdots\cdots(1) \qquad b = tan^{-1}\frac{W_l}{R+r_p}$$

$$Error = \{1-(correction\ factor)\} \times (actual\ reading\ of\ the\ voltmeter)$$

Where, R is electrical resistance in series with pressure coil, rp is pressure coil resistance, here we also conclude that the current in the current coil is also lagging by some angle with the current in pressure coil. And this angle is given by C = A - b. At this time reading of the voltmeter is given by

Where, Rp is (rp+R) and x is angle. If we ignore the effect of inductance of pressure i.e putting b = 0 we have expression for true power as

On taking ratio of equations (2) and (1) we have expression for correction factor as written below:

And from this correction factor error can be calculated as

On substituting the value of correction factor and taking suitable approximation we have expression for error as

$$e = VI\sin(A)*\tan(b).$$

Now we know that the error caused by pressure coil inductance is given by the expression

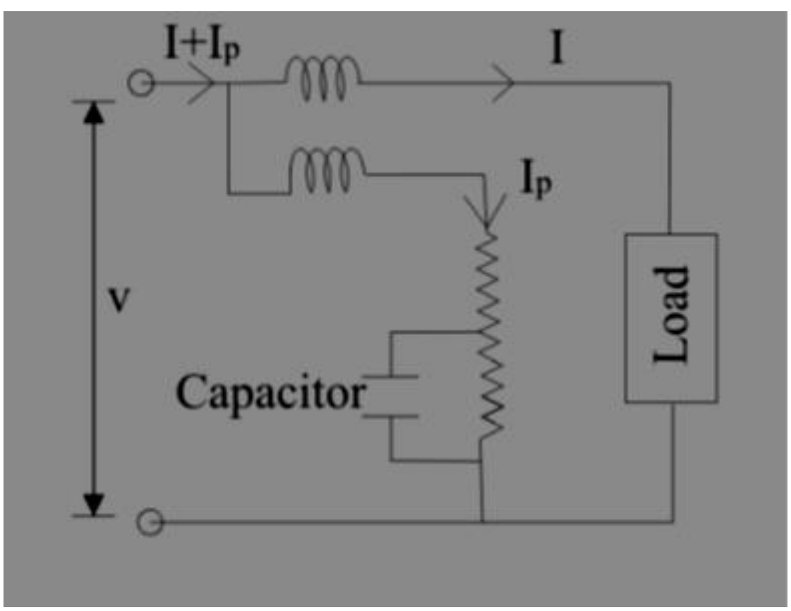
$$e = VI\sin(A)\tan(b),$$

if power factor is low (i.e in our case the value of φ is large hence we have large error).

Thus in order to avoid this situation we have connect the variable series resistance with a

capacitor as shown in the figure. This final modified circuit so obtained is called

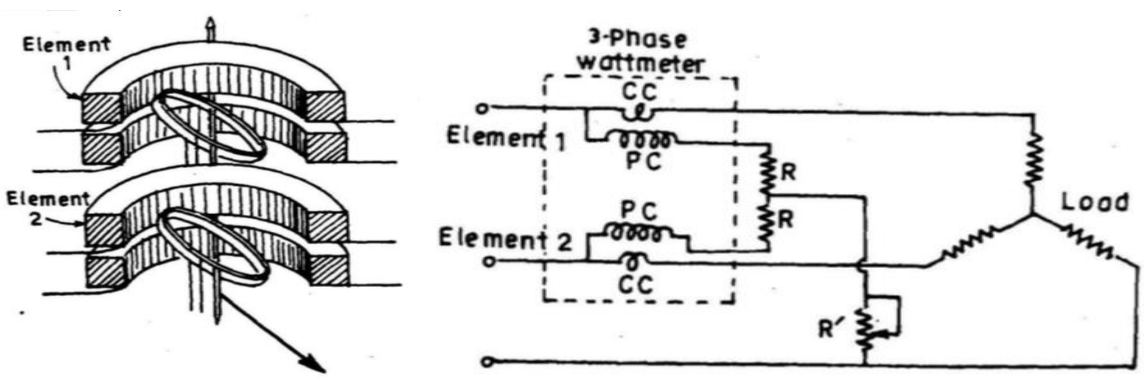
low power factor meter. A modern low power factor meter is designed such that it gives high accuracy while measuring power factors even lower than 0.1.



Two-Element Wattmeter for Three-Phase System

Two single-phase wattmeters were used to measure the power in a three-phase, three-wire system. The two single-phase wattmeters can be combined into a single instrument.

The scale of this instrument indicates the **sum or difference of the power values indicated by the separate meters**. To make the single wattmeter, **two sets of potential coils are mounted on a single shaft**. Also, **two sets of field coils are mounted on the instrument frame so that they have the proper relationship to the armature coils**. In this way, each of two power measuring mechanisms **develops a torque that is proportional to the power in the circuit to which it is connected.** These torque values are added to obtain the **total power in the three-phase, three-wire circuit.** If the power factor of the system is less than 0.5, the torque of one mechanism opposes that of the second mechanism. **The difference between the torque values is the power indication.** A wattmeter containing two dynamometer mechanisms is called a ***two-element wattmeter.***



Three phase & Single phase watt meter and power factor Power Factor Meters

Now there are two types of power factor meters-

1. **Electrodynamometer type**

2**. Moving iron type.**

Let us study electrodynamometer type first.

Electrodynamometer Type Power Factor Meter

In **electrodynamometer type power factor meters are**

1. **Single phase 2. Three phase.**

The general circuit diagram of single phase electrodynamometer power factor

meter is given below.

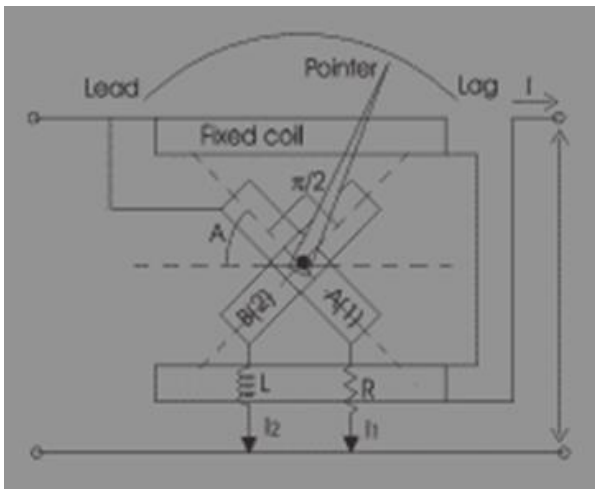
Now the pressure coil is split into two parts one is purely inductive another is purely resistive as shown in the diagram by resistor and inductor. At present the reference plane is making an angle A with coil 1.

And the angle between both the coils 1 and 2 is 90o. Thus the coil 2 is making an angle (90o + A) with the reference plane. Scale of the meter is properly calibrated as shown the value values of cosine of angle A.

Let us mark the electrical resistance connected to coil 1 be R and inductor connected to coil 2 be L. Now during measurement of power factor the values of R and L are adjusted such that R = wL so that both coils carry equal magnitude of current.

Therefore the current passing through the coil 2 is lags by 90o with reference to current in coil 1 as coil 2 path is highly inductive in nature. Let us derive an expression for deflecting torque for this **power factor meter**.

Now there are two deflecting torques one is acting on the coil 1 and another is acting on the coil 2. The coil winding are arranged such that the two torques produced, are opposite to each other and therefore pointer will take a position where the two torques are equal. Let us write a mathematical expression for the deflecting torque for coil 1-



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Where M is the maximum value of mutual inductance between the two coils, B is the angular deflection of the plane of reference.

- Now the mathematical expression for the deflecting torque for coil 2 is-
- At equilibrium we have both the torque as equal thus on equating T1=T2 we have A = B. From here we can see that the deflection angle is the measure of phase angle of the given circuit. The phasor diagram is also shown for the circuit such that the current in the coil 1 is approximately at an angle of 90o to current in the coil 2 .

Advantages of Electrodynamic Type Power Factor Meters

1. Losses are less because of minimum use of iron parts and also give less error over a small range of frequency as compared to moving iron type instruments.

2. They high torque is to weight ratio.

Disadvantages of Electrodynamic Type Power Factor Meters

1. Working forces are small as compared to moving iron type instruments.

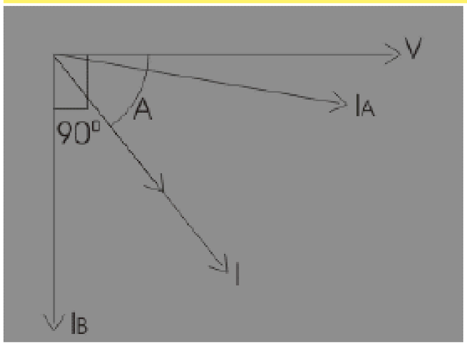
2. The scale is not extended over 360o.

3. Calibration of electrodynamometer type instruments are highly affected by the changing the supply voltage frequency.

4. They are quite costly as compared to other instruments.

$$T_1 = KVIM\cos A\sin B$$

$$T_2 = KVIM\cos(90 - A)\sin(90 + B) = KVIM\sin A\cos B$$



Watt-hour meter

Watt-hour meter is in fact a measuring device which can evaluate and records the electrical power passing through a circuit in a certain time. By implementing the Watt-hour meter, **we can know how much amount of electrical energy is used by a consumer** or **a residence or an electrically powered device or a business.** Electrical utilities install these meters at their consumer's place to evaluate the electrical usage for the purpose of billing. The reading is taken in each one billing period. Usually, the billing unit is Kilowatt-hour (kWh).

This is equal to the total usage of electrical energy by a consumer of one kilowatt during a period of one hour and it is also equal to 3600000 joules. **The Watt-Hour Meter is often referred as energy meter or electric meter or electricity meter or electrical meter. Mainly the watt-hour meter comprises of a tiny motor and a counter.** The motor will operate by diverting exact fraction of current which is flowing in the circuit to be measured.

Electromechanical Type Induction Meter

In this type of meter, a non-magnetic and electrically conductive aluminium metal disc is made to revolve in a magnetic field.

The rotation is made possible with the power passing through it. The rotation speed is proportional to the power flow through the meter.

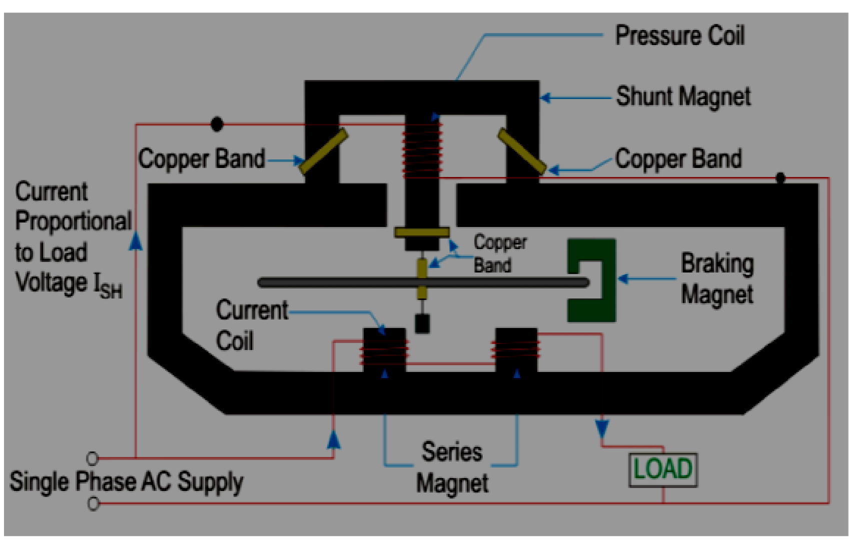
Gear trains and counter mechanisms are incorporated to integrate this power. This meter works by counting the total number of revolutions and it is relative to the usage of energy.

A series magnet is connected in series with the line and that comprises of a coil of few turns with thick wire. A shunt magnet is connected in shunt with the supply and comprises of a coil of large number of turns with thin wire. A braking magnet which is a permanent magnet is included for stopping the disc at the time of power failure and to place the disc in position. This is done by applying a force opposite to the rotation of the disc.

A flux is produced by the series magnet that is directly proportional to the current flow and another flux is produced by the shunt magnet corresponding to the voltage. Because of the inductive nature, these two fluxes lag each other by 90o. An eddy current is developed in the disc which is the interface of the two fields. This current is produced by a force that is corresponding to the product of instantaneous current, voltage and the phase angle among them. A break torque is developed on the disc by the braking magnet positioned over one side of the disc. The speed of the disc becomes constant when the following condition is achieved, Braking torque = Driving torque.

The gear arrangement linked with the shaft of the disc is implemented for recording the number of revolution. This is for single phase AC measurement. Additional number of coils can be implemented for different phase configuration.

$$Power = \frac{3600.Kh}{time\ in\ sec\ for\ one\ revolution\ of\ the\ disc}$$



ERRORS IN ENERGY METERS

The energy measurements by energy meters involve errors owing to many sources and reasons as follows:

Errors in driving system include errors due to incorrect magnitude of flux values, phase angles, etc. and lack of symmetry in magnetic circuit.

Errors in braking system such as changes in the strength of brake magnet, changes in disc resistance, self braking effect of series magnet flux and abnormal friction of the moving parts.

Errors in registering system are also expected to be present since they involve mechanical parts. They are taken care of by calibration of the meter.

Errors caused due to friction, overloads, phase angle variations, temperature effects, creeping of the meter, etc. These errors are avoided by correct adjustments made using the various compensator facility provided on the meter.

Adjustments Full Load UPF Adjustment:

The potential coil is connected across rated supply voltage and rated full load current at unity power factor is passed through the current coil. The brake magnet position is adjusted to vary the braking torque so that the moving system moves at correct speed.

Lag or LPF adjustment:

It is clear from equation (8.10) that the energy meter will register correct value only if the angle between the shunt magnet flux, f Pand the supply voltage, V is 900 (D = 900).

Hence the pressure coil should be designed to be highly inductive.

Also, various lag adjustment devices are made use of for this purpose. For LPF adjustments, the pressure coil is connected across the rated supply voltage and rated full load current at 0.5 lagging power factor is passed through the current coil. The lag device is adjusted until the meter runs at true speed.

Light Load UPF Adjustment:

Firstly, full load UPF and LPF adjustments are made on the meter until it runs at correct speed. Then rated supply voltage is applied across the pressure coil and a very low current of 5-10 % of full load value is passed through the meter at unity power factor. The light load adjustment is done so that the meter runs at proper speed.

Creep Adjustment:

Firstly, full load UPF and light load adjustments are made for correct speeds at both the loads and the performance is rechecked at0.5 power factor. Then, as a final check on all the above adjustments, the pressure coil is excited by 110 % of the rated voltage with zero load current. If the light load adjustment is proper, the meter should not creep under these conditions. If the error still persists, then all the above adjustments are carried out once again.

INDUCTION TYPE METERS

The principle of working and construction of ***induction type meter*** is very simple and easy to understand that's why these are widely used in measuring energy in domestic as well as industrial world. In all induction meters we have two fluxes which are produced by two different alternating currents on a metallic disc. Due to alternating fluxes there is an induced emf, the emf produced at one point (as shown in the figure given below) interacts with the alternating current of the other side resulting in the production of torque. Similarly, the emf produced at the point two interacts with the alternating current at point one, resulting in the production of torque again but in opposite direction. Hence due to these two torques which are in different directions, the metallic disc moves. This is basic principle of working of an **induction type meters**. Now let us derive the mathematical expression for deflecting torque. Let us take flux produced at point one be equal to F1 and the flux and at point two be equal to F2. Now the instantaneous values of these two flux can written as:

Where, Fm1 and Fm2 are respectively the maximum values of fluxes F1 and F2, B is phase difference between two fluxes. We can also write the expression for induced emf's at point one be at point two. Thus we have the expression for eddy currents at point one is

Where, K is some constant and f is frequency. Let us draw phasor diagram clearly showing F1, F2, E1, E2, I1 and I2. From phasor diagram, it clear that I1 and I2 are respectively lagging behind E1 and E2 by angle A

The angle between F1 and F2 is B. From the phasor diagram the angle between F2 and I1 is (90-B+A) and the angle between F1 and I2 is (90 + B + A).

Thus we write the expression for deflecting torque as

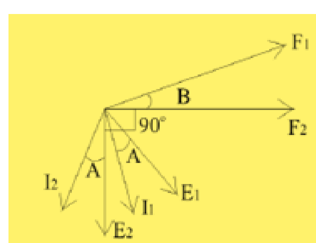
Similarly the expression for Td2 is

- The total torque is Td1 - Td2, on substituting the the value of Td1 and Td2 and simplying the expression we get
- Which is known as the general expression for the deflecting torque in the **induction type meters**.

$$F_1 = F_{m1} sin\omega t, \quad F_2 = F_{m2} sin(\omega t - B)$$

$$E_1 = -\frac{d(F_1)}{dt} \quad and \quad E_2 = -\frac{d(F_2)}{dt}$$

$$I_1 = \frac{E_1}{Z} = K \times f \times F_1$$



$$T_{d1} = K \times F_2 \times I_1 \times cos(90 - B + A) = K \times F_1 \times F_2 \times \frac{f}{Z} cos(90 - B + A),$$

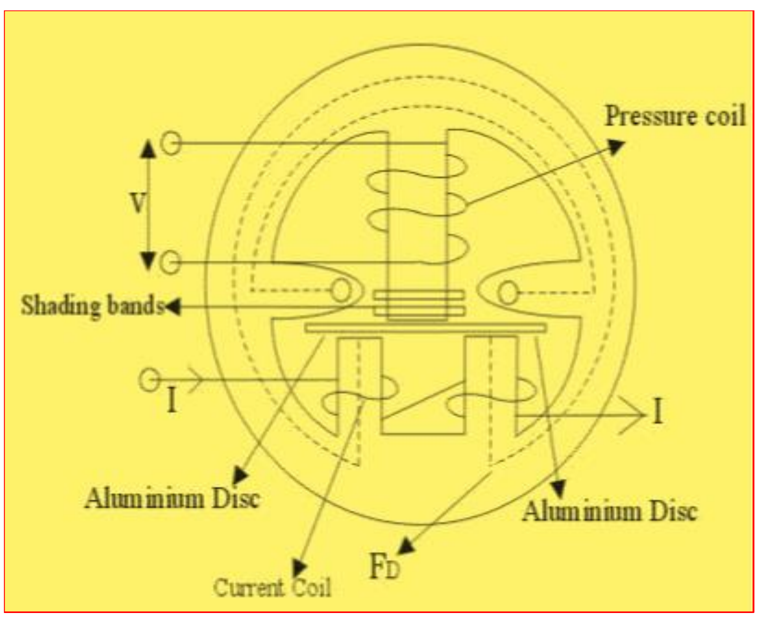
$$T_{d2} = K \times F_1 \times F_2 \times \frac{f}{Z} cos(90 + A + B)$$

Types of induction meters

- Single phase type and Three phase type induction meters.

Single phase induction type energy meter consists of four important systems which are written as follows:

- **Driving System**: Driving system consists of two electromagnets on which pressure coil and current coils are wounded, as shown above in the diagram. The coil which consisted of load current is called current coil while coil which is in parallel with the supply voltage (i.e. voltage across the coil is same as the supply voltage) is called pressure coil. Shading bands are wounded on as shown above in the diagram so as to make angle between the flux and applied voltage equal to 90 degrees.
- **Moving System**: In order to reduce friction to greater extent floating shaft energy meter is used, the friction is reduced to greater extinct because the rotating disc which is made up of very light material like aluminium is not in contact with any of the surface. It floats in the air. One question must be arise in our mind is that how the aluminium disc float in the air? To answer this question we need to see the constructional details of this special disc, actually it consists of small magnets on both upper and lower surfaces. The upper magnet is attracted to an electromagnet in upper bearing while the lower surface magnet also attracts towards the lower bearing magnet, hence due to these opposite forces the light rotating aluminium disc floats.
- **Braking System**: A permanent magnet is used to produce breaking torque in single phase induction energy meters which are positioned near the corner of the aluminium disc.
- **Counting System**: Numbers marked on the meter are proportion to the revolutions made by the aluminium disc, the main function of this system is to record the number of revolutions made by the aluminium disc.



Single phase type

Now let us look at the working operation of the single phase induction meter. In order to understand the working of this meter let us consider the diagram given below:

Here we have assumed that the pressure coil is highly inductive in nature and consists of very large number of turns. The current flowing in the pressure coil is Ip which lags behind voltage by an angle of 90 degrees.This current produces flux F. F is divided into two parts Fg and Fp.

Fg which moves on the small reluctance part across the side gaps. Fp: It is responsible for the production of driving torque in the aluminium disc.It moves from high reluctance path and is in phase with the current in the pressure coil.Fp is alternating in nature and thus emf Ep and current Ip.

The load current which is shown in the above diagram is flowing through the current coil produces flux in the aluminium disc, and due this alternating flux there on the metallic disc, an eddy current is produced which interacts with the flux Fp which results in production of torque.

As we have two poles, thus two torques are produced which are opposite to each other. Hence from the theory of induction meter that we have discussed already above the net torque is the difference of the two torques.

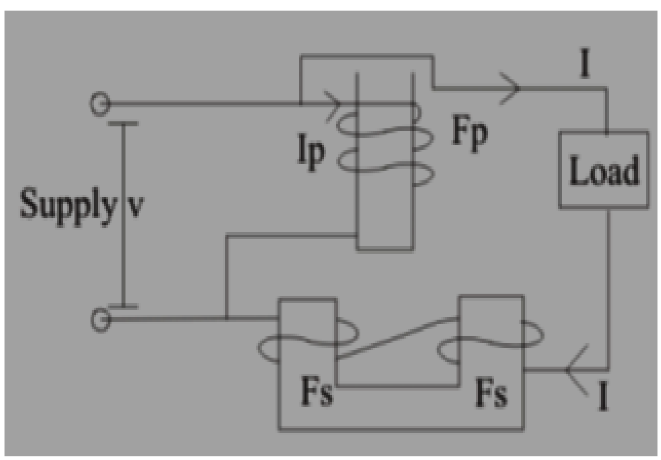
Advantages of Induction Type Meters

Following are the advantages of induction type meters:

1. They are inexpensive as compared to moving iron type instruments.

2. They have high torque is to weight ratio as compared to other instruments.

3. They retain their accuracy over wide range of temperature as well as loads.



THREE PHASE ENERGY METER

It is well established that for measurement of total power or energy in a n- conductor system, it is required to use a meter with (n-1) elements. The principle of single phase energy meter can as well be extended to obtain a poly-phase energy meter, in particular a three phase energy meter. Usually, a three phase energy meter is available as a 2-element meter or 3-element meter, each element being similar in construction to the single phase meter and all elements mounted on a common shaft. The torque developed by each element is summed up mechanically and the total number of revolutions made by the shaft is proportional to the total three phase energy consumption.

Construction, Operation and Testing

In a two-element, three phase energy meter the two discs are mounted on a common spindle and each disc has its own brake magnet. The moving system drives a single gear train. Each unit is provided with its own copper shading ring, shading band, friction compensator, etc., for adjustments to be made to obtain the correct reading.

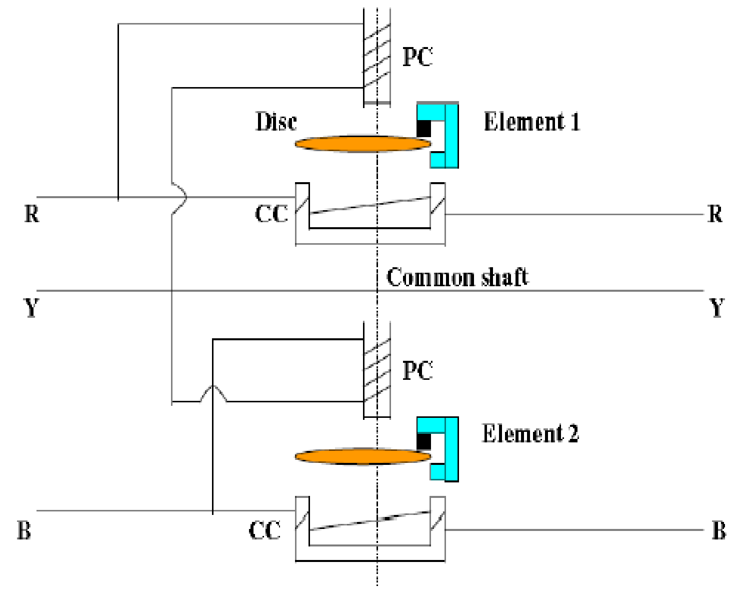


Figure Three Phase Energy Meter

A two element energy meter used for three phase energy measurements in three phase three wire systems, is schematically shown in figure. It is needful that for the same power/ energy, the driving torque should be equal in the two elements. This is checked by torque adjustment.

For torque adjustment, the two current coils are connected in series opposition and the two potential coils are connected in parallel. Full load current is allowed to pass through the current coil. This set up causes the two torques to be in opposition and so, if the torques are equal, then the disc should not move. If there is any slight motion indicating inequality of the two torques, then the magnetic shunt is adjusted until the disc stalls. Thus the torque balancing is obtained before testing the meter.

The friction compensator and brake magnet positions are adjusted to each of the two/three elements separately, treating each of them as a single phase element on single phase AC supply. The calibration of three phase meter can also be performed in a similar manner, as that described earlier, for single phase energy meters

MEASUREMENT OF RESISTANCE

Resistance is one of the most basic elements encountered in electrical and electronics engineering. The value of resistance in engineering varies from very small value like, resistance of a transformer winding, to very high values like, insulation resistance of that same transformer winding. Although a multimeter works quite well if we need a rough value of resistance, but for accurate values and that too at very low and very high values we need specific methods. In this article we will discuss various methods of resistance measurement. For this purpose we categories the resistance into three classes-

MEASUREMENT OF LOW RESISTANCE (<1Ω)

The major problem in **measurement of low resistance** values is the contact resistance or lead resistance of the measuring instruments, though being small in value is comparable to the resistance being measured and hence causes serious error

The methods employed for measurement of low resistances are:-

1. Kelvin's Double Bridge Method 2. Potentiometer Method 3. Ducter Ohmmeter.

KELVIN'S DOUBLE BRIDGE

Kelvin's double bridge is a modification of simple Wheatstone bridge. Figure below shows the circuit diagram of Kelvin's double bridge. As we can see in the above figure there are two sets of arms, one with resistances P and Q and other with resistances p and q. R is the unknown low resistance and S is a standard resistance. Here r represents the contact resistance between the unknown resistance and the standard resistance, whose effect we need to eliminate. For measurement we make the ratio P/Q equal to p/q and hence a balanced Wheatstone bridge is formed leading to null deflection in the galvanometer.

Hence for a balanced bridge we can write

Putting eqn 2 in 1 and solving and using P/Q = p/q, we get-

Hence we see that by using balanced double arms we can eliminate the contact resistance completely and hence error due to it. To eliminate another error caused due to thermo-electric emf, we take another reading with battery connection reversed and finally take average of the two readings. This bridge is useful for resistances in range of 0.1μΩ to 1.0 Ω.

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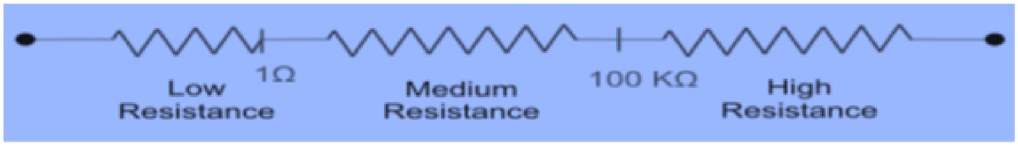

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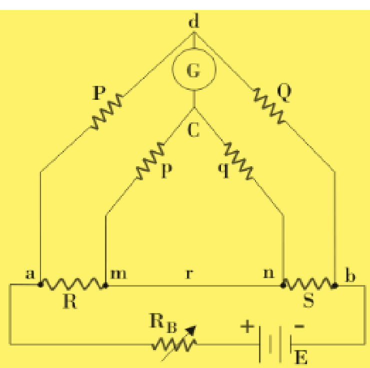
$$E_{ad} = E_{amc}$$

$$Or, \left\{\frac{P}{P+Q}\right\} E_{ab} = I\left[R + \frac{p}{p+q}\left\{\frac{r(p+q)}{p+q+r}\right\}\right] \text{.....(1)}$$

$$Where, E_{ab} = I\left[R + S + \frac{p}{p+q}\left\{\frac{r(p+q)}{p+q+r}\right\}\right] \text{.....(2)}$$

Putting eqn 2 in 1 and solving and using P/Q = p/q, we get-

$$R = \frac{P}{Q} S$$



Kelvin Double Bridge

2) MEASUREMENT OF MEDIUM RESISTANCE (1Ω - 100KΩ)

Following are the methods employed for measuring a resistance whose value is in the range 1Ω - 100kΩ -

1. Ammeter-Voltmeter Method 2. Wheatstone Bridge Method 3. Substitution Method

4. Carey- Foster Bridge Method 5. Ohmmeter Method

WHEATSTONE BRIDGE METHOD

This is the simplest and the most basic bridge circuit used in measurement studies. It mainly consists of four arms of resistance P, Q; R and S. R is the unknown resistance under experiment, while S is a standard resistance. P and Q are known as the ratio arms. An EMF source is connected between points a and b while a galvanometer is connected between points c and d. A bridge circuit always works on the principle of null detection, i.e. we vary a parameter until the detector shows zero and then use a mathematical relation to determine the unknown in terms of varying parameter and other constants.

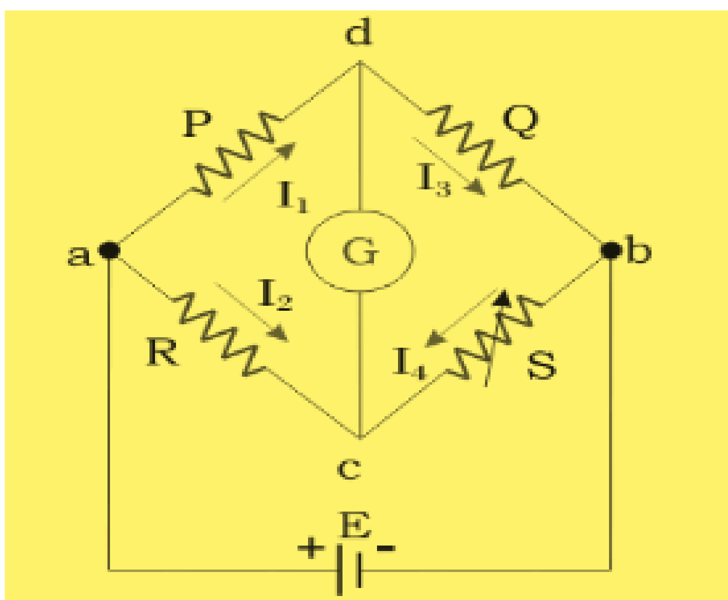
Here also the standard resistance, S is varied in order to obtain null deflection in the galvanometer. This null deflection implies no current from point c to d, which implies that potential of point c and d is same.

Hence Combining the above two equations we get the famous equation –

$$I_1 P = I_2 R \ldots\ldots (4)$$

$$Also,\ I_1 = I_3 = \frac{E}{(P+Q)} \text{ and } I_2 = I_4 = \frac{E}{(R+S)} \ldots\ldots (5)$$

$$R = \frac{P}{Q} S$$



Wheatstone Bridge

3) MEASUREMENT OF HIGH RESISTANCE (>100KΩ)

Following are few methods used for measurement of high resistance values-

Loss of Charge, Megger, Megohm bridge and Direct Deflection Method

LOSS OF CHARGE METHOD

In this method we utilize the equation of voltage across a discharging capacitor to find the value of unknown resistance R. Figure below shows the circuit diagram and the equations involved are-

However the above case assumes no leakage resistance of the capacitor. Hence to account for it we use the circuit shown in the figure below. R1 is the leakage resistance of C and R is the unknown resistance. We follow the same procedure but first with switch S1 closed and next with switch S1 open. For the first case we get

For second case with switch open we get

Using R1 from above equation in equation for R' we can find R.

MAXWELL BRIDGE

A Maxwell bridge is a modification to a Wheatstone bridge used to measure an unknown inductance (usually of low Q value) in terms of calibrated resistance and inductance or resistance and capacitance. When the calibrated components are a parallel resistor and capacitor, the bridge is known as a Maxwell-Wien bridge. It is named for James C. Maxwell, who first described it in 1873.

It uses the principle that the positive phase angle of an inductive impedance can be compensated by the negative phase angle of a capacitive impedance when put in the opposite arm and the circuit is at resonance; i.e., no potential difference across the detector (an AC voltmeter or ammeter)) and hence no current flowing through it. The unknown inductance then becomes known in terms of this capacitance.

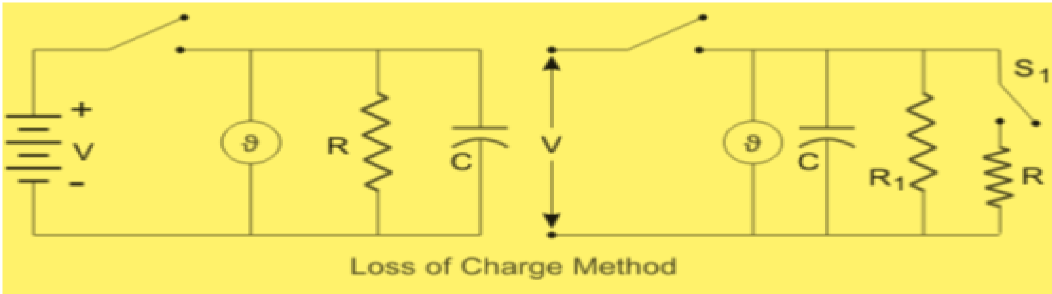
With reference to the picture, R1 R4 are known fixed resistances. R2, C2 are known variable resistance, capacitances variable entities. R2 and C2 are adjusted until the bridge is balanced.

R3 and L3 can then be calculated based on the values of the other components

$$v = V e^{\frac{-t}{RC}}$$
$$R = \frac{0.4343t}{C\ log_{10} V/v}$$

$$R' = \frac{0.4343t}{C\ log_{10} V/v}$$
$$Where,\ R' = \frac{RR_1}{R+R_1}$$

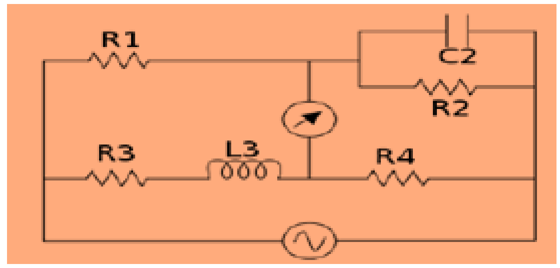
$$R_1 = \frac{0.4343t}{C\ log_{10} V/v}$$



Loss of Charge Method

$$R_3 = \frac{R_1 \cdot R_4}{R_2}$$

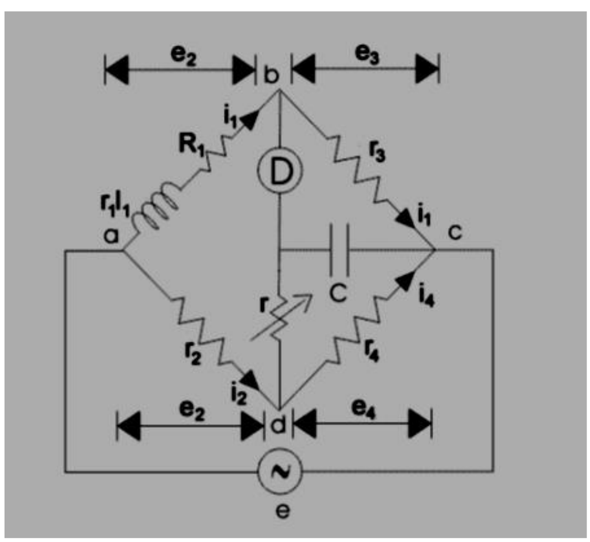
$$L_3 = R_1 \cdot R_4 \cdot C_2$$



MEASUREMENT OF RESISTANCE - Anderson's Bridge

Anderson's Bridge

The main disadvantage of using Hay's bridge and Maxwell bridge is that, they are unsuitable of measuring the low quality factor. However Hay's bridge and Maxwell bridge are suitable for measuring accurately high and medium quality factor respectively. So, there is need of bridge which can measure low quality factor and this bridge is modified Maxwell's bridge and known as **Anderson's bridge**. Actually this bridge is the modified Maxwell inductor capacitance bridge. In this bridge double balance can obtained by fixing the value of capacitance and changing the value of electrical resistance only. In this circuit the unknown inductor is connected between the point a and b with electrical resistance r1 (which is pure resistive). The arms bc, cd and da consist of resistances r3, r4 and r2 respectively which are purely resistive. A standard capacitor is connected in series with variable electrical resistance r and this combination is connected in parallel with cd. A supply is connected between b and e.



Now let us derive the expression for l_1 and r_1:

At balance point, we have the following relations that holds good and they are:

$$i_1 = i_3 \ and \ i_2 = i_c + i_4$$

Now equating voltages drops we get,

$$i_1 . r_3 = \frac{i_c}{j\omega C} \ldots\ldots\ldots (1)$$

$$i_1 . (R_1 + r_1 + j\omega l_1) = i_2 . r_2 + i_c . r \ldots\ldots\ldots (2)$$

$$i_c \left(r + \frac{1}{j\omega C} \right) = (i_2 - i_c) r_4 \ldots\ldots\ldots (3)$$

Putting the value of i_c in above equations, we get

$$i_1(r_1 + R_1 + j\omega l_1) = i_2 r_2 + j i_1 \omega C r_3 r$$

$$\Rightarrow i_1(r + r_1 + j\omega l_1 - j\omega C r_3 r) = i_2 r_2 \ldots . (4)$$

$$or \ we \ have \ i_1(j\omega C r_3 r + j\omega C r_3 r_4 + r_3) = i_2 r_4 r_2 \ldots . (5)$$

$On \ equating \ (4) \ and \ (5) \ and \ separating \ the \ real \ andimaginary \ parts \ are \ have,$

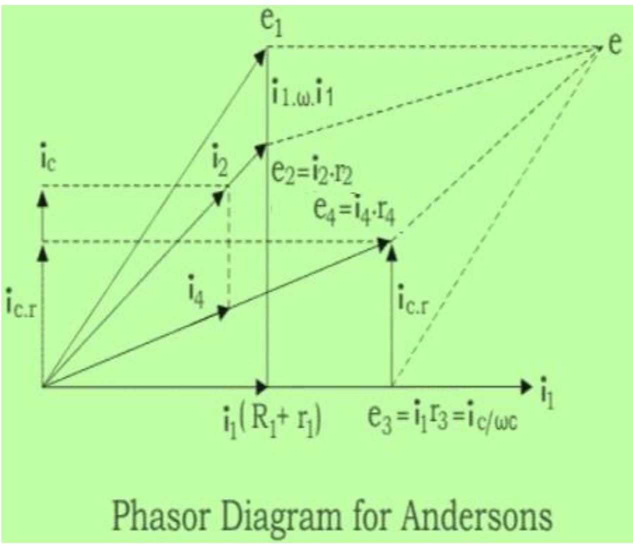
$$r_1 = \frac{r_2 r_3}{r_4} - R_1 r_2 \ldots . (6)$$

$$and \ l_1 = \frac{C . r_3}{r_4} [r(r_4 + r_2) + r_2 r_4] r_2 \ldots . (7)$$

Working

At first set the signal generator frequency at audible range. Now adjust r1 and r such that phones gives a minimum sound. Measure the values of r1 and r (obtained after these adjustments) with the help of multimeter. Use the formula that we have derived above in order to find out the value of unknown inductance. The experiment can be repeated with the different value of standard capacitor.

Phasor Diagram of Anderson's Bridge



Let us mark the voltage drops across ab, bc, cd and ad as e1, e2, e3 and e4 as shown in figure above. Here in the **phasor diagram of Anderson's bridge**, we have taken i1 as reference axis. Now ic is perpendicular to i1 as capacitive load is connected at ec, i4 and i2 are lead by some angle as shown in figure. Now the sum of all the resultant voltage drops i.e. e1, e2, e3 and e4 is equal to e, which is shown in phasor diagram. As shown in the **phasor diagram of Anderson's bridge .** the resultant of voltages drop i1 (R1 + r1) and i1.ω.l1 (which is shown perpendicular to i1) is e1. e2 is given by i2.r2 which makes angle 'A' with the reference axis. Similarly, e4 can be obtained by voltage drop i4.r4 which is making angle 'B' with reference axis.

Advantages of Anderson's Bridge

- It is very easy to obtain the balance point in Anderson's bridge as compared to Maxwell bridge in case of low quality factor coils.
- There is no need of variable standard capacitor is required instead of thin a fixed value capacitor is used.
- This bridge also gives accurate result for determination of capacitance in terms of inductance.

Disadvantages of Anderson's Bridge

- The equations obtained for inductor in this bridge is more complex as complex as compared to Maxwell's bridge.
- The addition of capacitor junction increases complexity as well as difficulty of shielding the bridge.

Measurement of Capacitance using Schering Bridge

This bridge is used to measure to the capacitance of the capacitor, dissipation factor and measurement of relative permittivity. Let us consider the circuit of Schering bridge as shown below: Here, c1 is the unknown capacitance whose value is to be determined with series electrical resistance r1. c2 is a standard capacitor. c4 is a variable capacitor. r3 is a pure resistor (i.e. non inductive in nature). And r4 is a variable non inductive resistor connected in parallel with variable capacitor c4. Now the supply is given to the bridge between the points a and c. The detector is connected between b and d. From the theory of ac bridges we have at balance condition, Substituting the values of z1, z2, z3 and z4 in the above equation, we get

Equating the real and imaginary parts and the separating we get

Let us consider the phasor diagram of the above Shering bridge circuit and mark the voltage drops across ab,bc,cd and ad as e1, e3,e4 and e2 respectively. From the above Schering bridge phasor diagram, we can calculate the value of tanδ which is also called the dissipation factor.

$$\left(r_1 + \frac{1}{j\omega c_1}\right)\left(\frac{r_4}{1 + j\omega c_4 r_4}\right) = \frac{r_3}{j\omega c_2}$$

$$\left(r_1 + \frac{1}{j\omega c_1}\right) r_4 = \frac{r_3}{j\omega c_2}(1 + j\omega c_4 r_4)$$

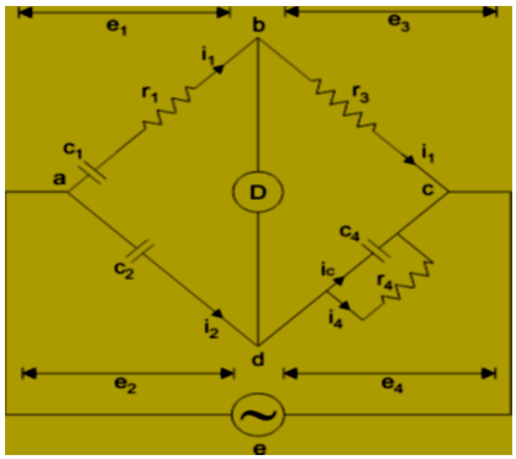
$$r_1 r_4 - \frac{j r_4}{\omega c_1} = -\frac{j r_3}{\omega c_2} + \frac{r_3 r_4 c_4}{c_2}$$

$$l_1 \frac{1}{N^2 A}$$

$$r_1 = \frac{r_3 c_4}{c_2}$$

$$c_1 = c_2 \frac{r_4}{r_3}$$

$$\tan\delta = \omega c_1 r_1 = \omega \frac{c_2 r_4}{r3} \times \frac{r_3 c_4}{c_2} = \omega c_4 r_4$$



Measurement of Capacitance using De Seauty Bridge

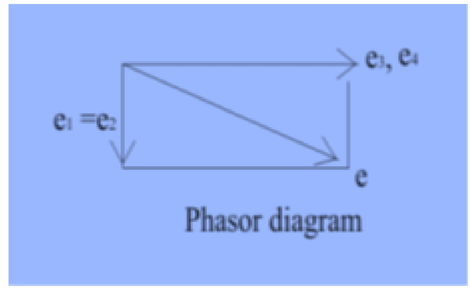
This bridge provide us the most suitable method for comparing the two values of capacitor if we neglect dielectric losses in the bridge circuit. The circuit of **De Sauty's bridge** is shown below. Battery is applied between terminals marked as 1 and 4. The arm 1-2 consists of capacitor c1 (whose value is unknown) which carries current i1 as shown, arm 2-4 consists of pure resistor (here pure resistor means we assuming it non inductive in nature), arm 3-4 also consists of pure resistor and arm 4-1 consists of standard capacitor whose value is already known to us. Let us derive the expression for capacitor c1 in terms of standard capacitor and resistors. At balance condition we have,

It implies that the value of capacitor is given by the expression

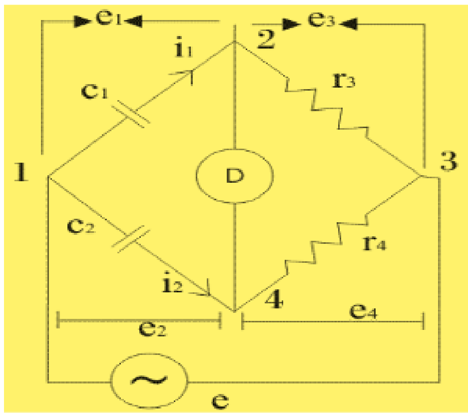
In order to obtain the balance point we must adjust the values of either r3 or r4 without disturbing any other element of the bridge. This is the most efficient method of comparing the two values of capacitor if all the dielectric losses are neglected from the circuit. Now let us draw and study the phasor diagram of this bridge.

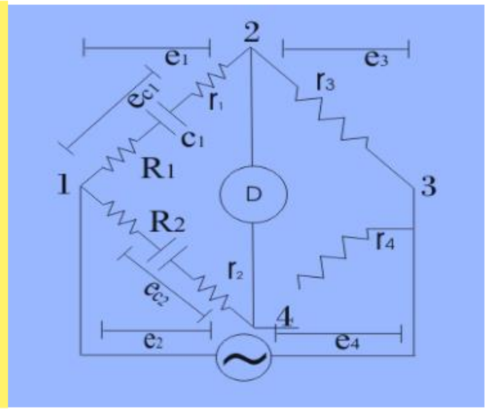
Phasor diagram of **De Sauty bridge** is shown below:

$$\frac{1}{j\omega c_1} \times r_1 = \frac{1}{j\omega c_2} \times r_3$$



$$c_1 = c_2 \times \frac{r_4}{r_3}$$





Let us mark the current drop across unknown capacitor as e1, voltage drop across the resistor r3 be e3, voltage drop across arm 3-4 be e4 and voltage drop across arm 4-1 be e2. At balance condition the current flows through 2-4 path will be zero and also voltage drops e1 and e3 be equal to voltage drops e2 and e4 respectively. In order to draw the phasor diagram we have taken e3 (or e4) reference axis, e1 and e2 are shown at right angle to e1 (or e2). Why they are at right angle to each other? Answer to this question is very simple as capacitor is connected there, therefore phase difference angle obtained is 90o. Now instead of some advantages like bridge is quite simple and provides easy calculations, there are some disadvantages of this bridge because this bridge give inaccurate results for imperfect capacitor (here imperfect means capacitors which not free from dielectric losses). Hence we can use this bridge only for comparing perfect capacitors. Here we interested in modify the **De Sauty's bridge**, we want to have such a kind of bridge that will gives us accurate results for imperfect capacitors also. This modification is done by Grover. The modified circuit diagram is shown below:

Here Grover has introduced electrical resistances r1 and r2 as shown in above on arms 1-2 and 4-1 respectively, in order to include the dielectric losses. Also he has connected resistances R1 and R2 respectively in the arms 1-2 and 4-1. Let us derive the expression capacitor c1 whose value is unknown to us. Again we connected standard capacitor on the same arm 1-4 as we have done in **De Sauty's bridge**. At balance point on equating the voltage drops we have: On solving above equation we get: This the required equation.

$$\left(R_1 + r_1 + \frac{1}{j\omega c_1}\right) r_4 = \left(R_2 + r_2 + \frac{1}{j\omega c_2}\right) r_3 \cdots\cdots\cdots (1)$$

$$\frac{c_1}{c_2} = \frac{R_2 + r_2}{R_1 + r_1} = r_4 r_3$$

By making the phasor diagram we can calculate dissipation factor. Phasor diagram for the above circuit is shown below

Let us mark δ1 and δ2 be phase angles of the capacitors c1 and c2 capacitors respectively.

From the phasor diagram we have tan(δ1) = dissipation factor = ωc1r1 and similarly we have tan(δ2) = ωc2r2.

From equation (1) we have

on multiplying ω both sides we have

Therefore the final expression for the dissipation factor is written as

Hence if dissipation factor for one capacitor is known.

However this method is gives quite inaccurate results for dissipation factor.

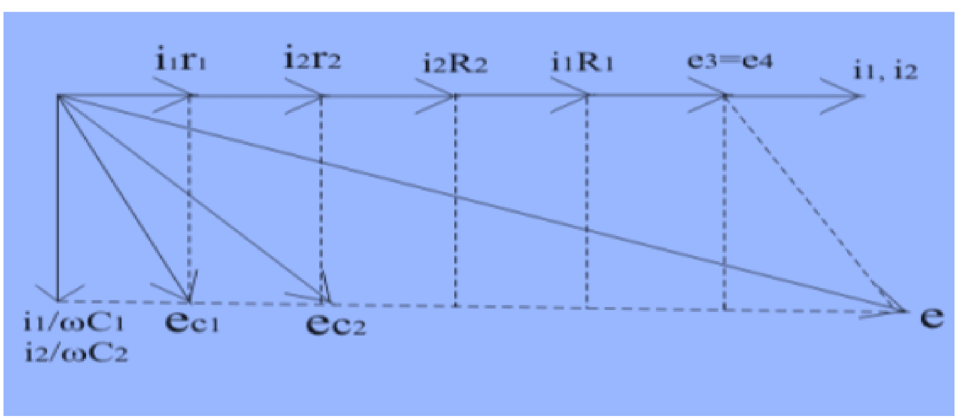
$$c_2 r_2 - c_1 r_1 = c_1 R_1 - c_2 R_2$$

on multiplying ω both sides we have

$$\omega c_2 r_2 - \omega c_1 r_1 = \omega(c_1 R_1 - c_2 R_2)$$

$$But\ \frac{c_1}{c_2} = \frac{r_4}{r_3}$$

$$tan(\delta_1) - tan(\delta_2) = \omega c_2 \left(R_1 \frac{r_4}{r_3} - R_2 \right)$$



INSTRUMENT TRANSFORMERS

Introduction of Instrument Transformers

Instrument Transformers are used in AC system for measurement of electrical quantities i.e. voltage, current, power, energy, power factor, frequency. **Instrument transformers are also used with protective relays for protection of power system.** Basic function of Instrument transformers is to step down the AC System voltage and current. The voltage and current level of power system is very high. It is very difficult and costly to design the measuring instruments for measurement of such high level voltage and current. Generally measuring instruments are designed for 5 A and 110 V.

The measurement of such very large electrical quantities, can be made possible by using the Instrument transformers

Definitions and Functions

The name instrument transformer is a general classification applied to current and voltage devices used to change currents and voltages from one magnitude to another or to perform an isolating function, that is, to isolate the utilization current or voltage from the supply voltage for safety to both the operator and the end device in use.

Instrument transformers are designed specifically for use with electrical equipment falling into the broad category of devices commonly called instruments such as voltmeters, ammeters, wattmeters, watt-hour meters, protection relays, etc.

Figure 1 shows some of the most basic uses for instrument transformers. Voltage transformers are most commonly used to lower the high line voltages down to typically 120 volts on the secondary to be connected to a voltmeter, watthour meter, or protection relay.

Similarly, current transformers take a high current and reduce it to typically 5 amps on the secondary winding so that it can be used with a watthour meter, ammeter, or protection relay.

Advantages of Instrument Transformers

The large voltage and current of AC Power system can be measured by using small rating measuring instrument i.e. 5 A, 110 – 120 V.

By using the instrument transformers, measuring instruments can be standardized. Which results in reduction of cost of measuring instruments. More ever the damaged measuring instruments can be replaced easy with healthy standardized measuring instruments.

Instrument transformers provide electrical isolation between high voltage power circuit and measuring instruments. Which reduces the electrical insulation requirement for measuring instruments and protective circuits and also assures the safety of operators.

Several measuring instruments can be connected through a single transformer to power system.

Due to low voltage and current level in measuring and protective circuit, there is low power consumption in measuring and protective circuits.

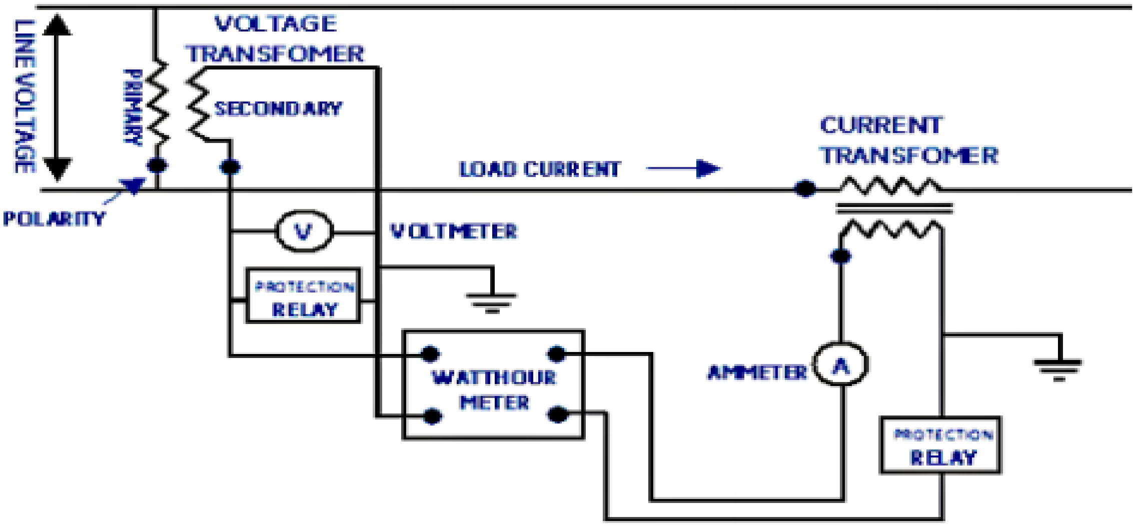


Figure 1 – Common uses of instrument transformers

Instrument Transformers

How will you measure AC currents and voltages of very high magnitude? You will need the measuring instruments having higher range, which literally mean huge instruments. Or there's another way, using the transformation property of AC currents and voltages. You can transform the voltage or current down with a transformer whose turns ratio is accurately known, then measuring the stepped down magnitude with a normal range instrument. The original magnitude can be determined by just multiplying the result with the transformation ratio. Such specially constructed transformers with accurate turns ratio are called as **Instrument transformers**.

These instruments transformers are of two types –

(i) **Current Transformers (CT)** and (ii) **Potential Transformers (PT)**.

Current Transformers (CT)

Current transformer is used to step down the current of power system to a lower level to make it feasible to be measured by small rating Ammeter (i.e. 5A ammeter). Current transformers are generally used to **measure currents of high magnitude**. These transformers step down the current to be measured, so that it can be measured with a normal range ammeter. A Current transformer has only one or very few number of primary turns. The primary winding may be just a conductor or a bus bar placed in a hollow core (as shown in the figure). The secondary winding has large number turns accurately wound for a specific turns ratio. Thus the current transformer steps up (increases) the voltage while stepping down (lowering) the current.

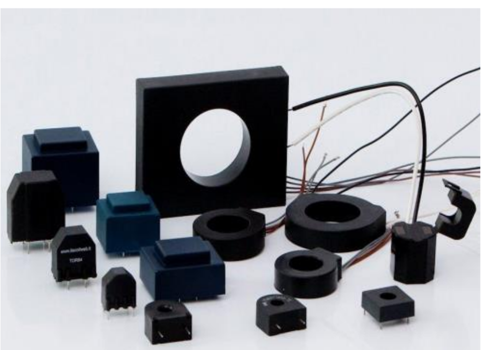
Now, the secondary current is measured with the help of an AC ammeter. The turns ratio of a transformer is

$N_P / N_S = I_S / I_P$

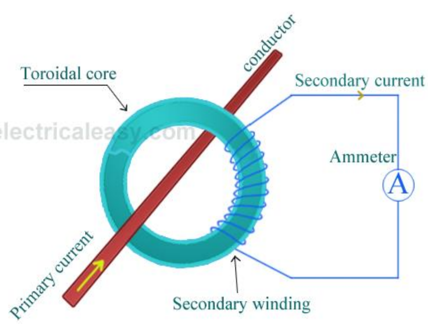
Applications

One of the common **application of a current transformer** is in a 'Digital Clamp Meter'. Generally, **current transformers** are expressed in their primary to secondary current ratio. A 100:5 CT would mean the secondary current of 5 amperes when primary current is 100 amperes. The secondary current rating is generally 5 amperes or 1 ampere, which is compatible with standard measuring instruments.

Primary of C.T. is having very few turns. Sometimes bar primary is also used. Primary is connected in series with the power circuit. Therefore, sometimes it also called series transformer**.** The secondary is having large no. of turns. Secondary is connected directly to an ammeter. As the ammeter is having very small resistance. Hence, the secondary of current transformer operates almost in short circuited condition. One terminal of secondary is earthed to avoid the large voltage on secondary with respect to earth. Which in turns reduce the chances of insulation breakdown and also protect the operator against high voltage. More ever before disconnecting the ammeter, secondary is short circuited through a switch ‘S’ as shown in figure above to avoid the high voltage build up across the secondary.

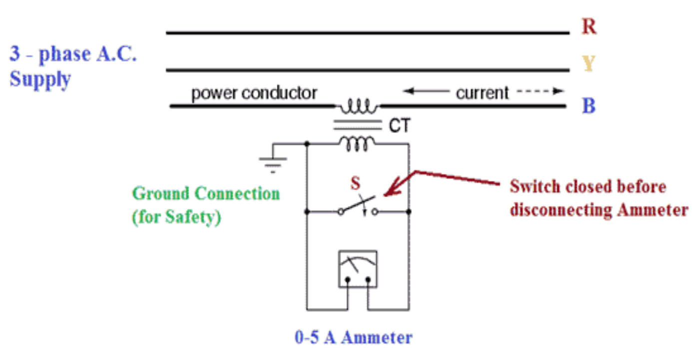


current Transformers



Current Transformer

Digital Clamp Meter



Current Transformer (C.T.)

Construction of Current Transformer:

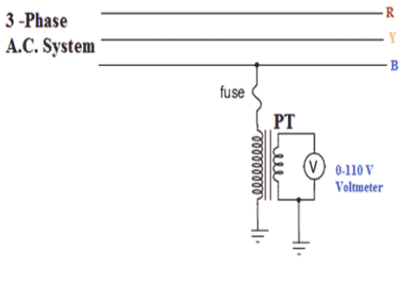
- Wound type: Current transformers are constructed in various ways. In one method there are two separate windings on a magnetic steel core. The primary winding consists of a few turns of heavy wire capable of carrying the full load current while the secondary winding consist of many turns of smaller wire with a current carrying capacity of between 5/20 amperes, dependent on the design. This is called the wound type due to its wound primary coil.
- Window type: Another very common type of construction is the so-called "window," "through" or donut type current transformer in which the core has an opening through which the conductor carrying the primary load current is passed. This primary conductor constitutes the primary winding of the CT (one pass through the "window" represents a one turn primary), and must be large enough in cross section to carry the maximum current of the load.
- Indoor Type: indoor units are protected due to their being mounted in an enclosure of some kind. The indoor types must be compatible for connection to bus type electrical construction.
- Outdoor Type: The outdoor unit must be protected for possible contaminated environments. Outdoor units will have larger spacing between line and ground, which is achieved by the addition of skirts on the design. For outdoor types the hardware must be of the non-corrosive type and the insulation must be of the non-arc-tracking type and outdoor types are normally on the pole top installations

Potential Transformer (PT)

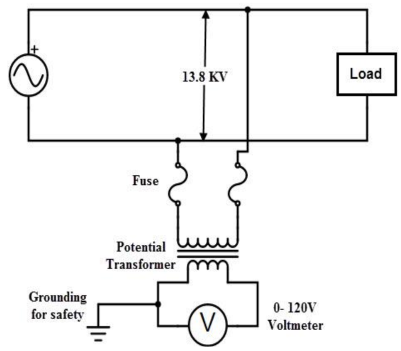
Potential transformers are also known as **voltage transformers** and they are basically step down transformers with extremely accurate turns ratio. Potential transformers step down the voltage of high magnitude to a lower voltage which can be measured with standard measuring instrument. These transformers have large number of primary turns and smaller number of secondary turns. A potential transformer is typically expressed in primary to secondary voltage ratio. For example, a 600:120 PT would mean the voltage across secondary is 120 volts when primary voltage is 600 volts.

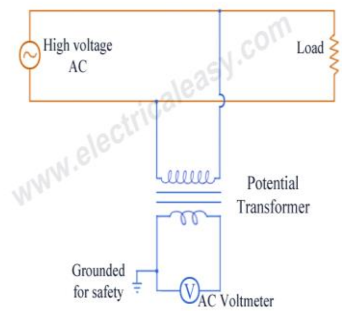
Working Principle of Potentiometer

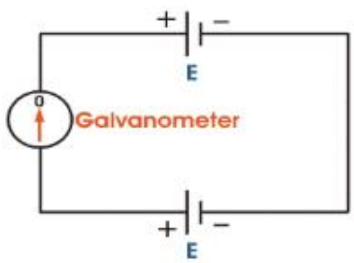
This is a very basic instrument used for comparing emf two cells and for calibrating ammeter, voltmeter and watt-meter. The basic **working principle of potentiometer** is very very simple.Suppose we have connected two battery in head to head and tale to tale through a galvanometer. That means the positive terminals of both battery are connected together and negative terminals are also connected together through a galvanometer as shown in the figure below. It is clear that if the voltage of both battery cells is exactly equal, there will be no circulating current in the circuit and hence the galvanometer shows null deflection. The **working principle of potentiometer** depends upon this phenomenon.

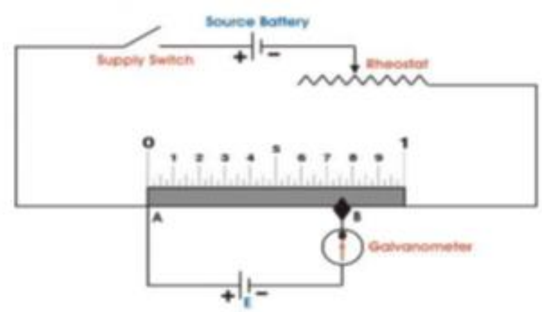


Potential Transformer (P.T.)









Now let's think about another circuit, where a battery is connected across a resistor via a switch and a rheostat as shown in the figure below voltage-drop-calculation/ across the resistor. As there is a voltage drop across the resistor, this portion of the circuit can be considered as a voltage source for other external circuits. That means anything connected across the resistor will get voltage. If the resistor has uniform cross section throughout its length, the electrical resistance per unit length of the resistor is also uniform throughout its length.

Voltage drop per unit length of the resistor is also uniform. Suppose the current through the resistor is i A and resistance per unit length of the resistor is r Ω. Then the voltage appears per unit length across the resistor would be 'ir' ans say it is v volt. Positive terminal of a standard cell is connected to point A on the sliding resistor and negative terminal of the same is connected with a galvanometer. Other end of the galvanometer is in contact with the resistor via a sliding contact as shown in the figure above. By adjusting this sliding end, a point like B is found where, there is no current through the galvanometer, hence no deflection of galvanometer. That means emf of the standard cell is just balanced by the voltage-drop-calculation/ appears across AB.

Now if the distance between point A and B is L, then it can be written emf of standard cell E = Lv volt.

As v (voltage drop per unit length of the sliding resistor) is known and L is measured from the scale attached to the resistor

The value of E i.e. emf of standard cell can also be calculated from the above simple equation very easily. Potential transformers consist of two separate windings on a common magnetic steel core. One winding consists of fewer turns of heavier wire on the steel core and is called the secondary winding. The other winding consists of a relatively large number of turns of fine wire, wound on top of the secondary, and is called the primary winding. Current transformers are constructed in various ways. One method is quite similar to that of the potential transformer in that there are two separate windings on a magnetic steel core. But it differs in that the primary winding consists of a few turns of heavy wire capable of carrying the full load current while the secondary winding consist of many turns of smaller wire with a current carrying capacity of between 5/20 amperes, dependent on the design. This is called the wound type due to its wound primary coil. Another very common type of construction is the so-called “window,” “through” or donut type current transformer in which the core has an opening through which the conductor carrying the primary load current is passed.

This primary conductor constitutes the primary winding of the CT (one pass through the “window” represents a one turn primary), and must be large enough in cross section to carry the maximum current of the load. Another distinguishing feature is the difference between indoor and outdoor construction. The performance characteristics of the two constructions are essentially the same, but the physical appearance and hardware are different. The outdoor unit must be protected for possible contaminated environments while indoor units are protected due to their being mounted in an enclosure of some kind. Thus most outdoor units will have larger spacing between line and ground, which is achieved by the addition of skirts on the design. This provides larger surface creepage distances from the primary the secondary ampere-turns.

Thus 110 amperes X 2 turns is 220 ampere turns on the primary. To equalize this on the secondary of a standard 200:5 ampere unit which has 40 turns (40 X 5 amperes = 200NI), we would have to add 4 secondary turns through the window of the CT thus giving us a total of 44 secondary turns X 5 amperes = 220 ampere turns. Thus we have modified a standard 200:5 ampere CT to be a 110:5 ampere unit by adding 2 external primary turns and 4 external secondary turns to it. Had we chosen to back off the 4 secondary turns instead of adding, we would have had a 90:5 ampere CT. Refer to instruction for using a variable-ratio current transformer. terminals (at line potentials) to the secondary terminals and the base plate (at ground potentials). For outdoor types the hardware must be of the non-corrosive type and the insulation must be of the non-arc-tracking type. One other feature that differentiates the indoor from the outdoor is the orientation of the primary terminals. The indoor types must be compatible for connection to bus type electrical construction as opposed to the outdoor types that are normally on the pole-top installations. The secondary consists of a larger number of turns of smaller wire. The number is dependent on the primary to secondary current transformation desired. If a lower current rating than is available is required due to a low load density, this can be achieved by looping the primary cable through the window of the CT.

An example would be the need for a 100 ampere to 5 unit when the lowest current rating made by the manufacturer was 200 to 5 amperes. By looping the cable through the window so that the cable passes through the window twice, we can make an effective 100:5 ampere unit out of a 200:5 ampere unit. Smaller increments of current change can be achieved by adding or backing off secondary turns as well as primary turns, i.e., we can make a 110:5 ampere unit out of a standard 200:5 ampere unit by adding 2 primary turns and adding 4 secondary turns. The primary amperes turns must equal. Another distinguishing feature is the difference between indoor and outdoor construction.

The performance characteristics of the two constructions are essentially the same, but the physical appearance and hardware are different. The outdoor unit must be protected for possible contaminated environments while indoor units are protected due to their being mounted in an enclosure of some kind. Thus most outdoor units will have larger spacing between line and ground, which is achieved by the addition of skirts on the design. This provides larger surface creepage distances from the primary the secondary ampere-turns. Thus 110 amperes X 2 turns is 220 ampere turns on the primary.

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Thus we have modified a standard 200:5 ampere CT to be a 110:5 ampere unit by adding 2 external primary turns and 4 external secondary turns to it. Had we chosen to back off the 4 secondary turns instead of adding, we would have had a 90:5 ampere CT.

Magnetic Circuits

Instrument transformers can be simplified with basic magnetic circuits. Figure 2 depicts the most basic magnetic circuit of an ideal instrument transformer. As a current passes through the primary winding it induces a magnetic flux in the steel core.

The flux flows through the core and induces a current on the secondary winding proportional to the ratio of turns on the primary to the secondary. Instrument transformers are not a perfect device and incur losses from resistance and stray inductance of the copper winding and core.

The two biggest losses are due to the copper windings that carry the current and the magnetic core that carries the flux. Figure 3 below shows the electric circuit and associated losses of an actual transformer. Figure 4 shows the equivalent circuit for a current transformer.

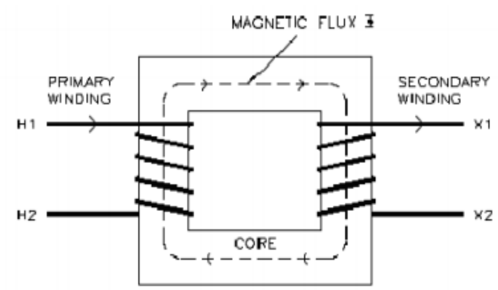


Figure 2 – Basic Magnetic Circuit

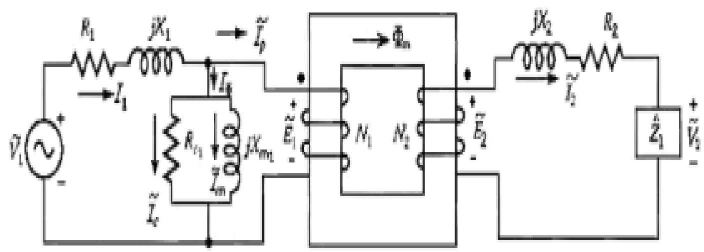


Figure 3 – Non-Ideal Magnetic Circuit

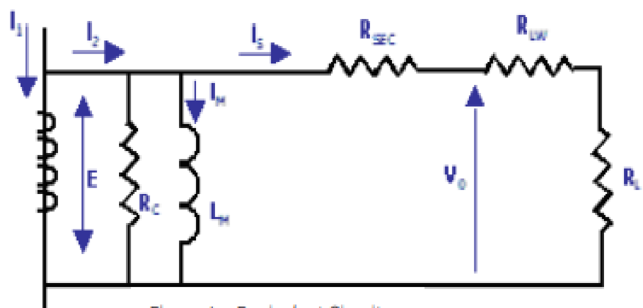


Figure 4 – Equivalent Circuit

$I_2 = I_s + I_M$
I_1 = Primary Current
I_2 = Secondary Current for ideal transformer
I_s = Secondary Current seen on secondary
I_M = Magnetization Current

E = Induced Electromotive Force
V_0 = Secondary Voltage
L_M = Magnetizing Inductance
R_C = Core Loss
R_{SEC} = Resistance of secondary
R_{LW} = Resistance of leadwire
R_L = Resistance of load

Rating and Ratio

The rating of an instrument transfer is expressed by two groups of numbers representing the nominal current or voltage which may be applied to its primary winding and the current or voltage which would then be induced in its secondary winding. For example, the designation 480:120 volt expresses the rating of the potential transformer. This means that when 480 volts is applied to the primary winding, 120 volts will be induced on the secondary.

Likewise a designation of 400:5 amperes expresses the rating of a current transformer and means that when 400 amperes flow through the primary, 5 amperes will flow through the secondary. Industry standards have established 120 volts as the secondary rating of potential transformers having primary ratings up to 24,000 volts and 115 volts as the secondary rating of PT's having ratings above 24,000 volts.

Similarly, industry standards have established 5 amperes as the secondary rating of current transformers.

The ratio of an instrument transformer is the relationship of its primary rating to its secondary rating.

For example, the potential transformer mentioned above having a rating of 480:120 volts will have a ratio of 4:1 and the current transformer having a rating of 400:5 amperes will have a ratio of 80:1. Magnetic Circuits R.

Potential Transformer -Thermal Rating

Potential transformers have a thermal rating rather than a rating factor as with the CT and it designates the maximum volt-ampere burden, which may be connected to its secondary at specified ambient temperatures of either 30 or 55°C.

Potential Transformer Overvoltage Requirements

The IEEE standards allow two levels of operation. One is a continuous operation level and one is for emergency conditions.

A potential transformer must be capable of operating at 110% above rating voltage continuously provided the secondary burden in volt amperes at this voltage does not exceed the thermal rating.

The emergency rating of potential transformers is defined at one minute of operation, thus enough time for protective equipment to operate

Voltage Transformer Ratings and Characteristics			
GROUP	BUSHINGS	RATING	RVF
1	2	L-G	1.25/8hr
2	2	L-L	-
3	1	L-G	(25-161kV, 1.74/1min) (230-750kV, 1.40/1min)
4A	1	L-G	1.25/8hr
4B	1	L-L	-
5	1	L-G	1.40/1min

IEEE C57.13-2008 defines five distinct groups of voltage transformers and provides ratings and characteristics of each grouping. This table summarizes each grouping.

Current Transformer – Thermal rating factor

Rating factor (RF) is a term, which applies to a current transformer.

In its application to a current transformer, it is the number representing the amount by which the primary load current may be increased over its nameplate rating without exceeding the allowable temperature rise.

In other words, it is a designation of the transformer’s overload capability. In order to be completely meaningful, the ambient temperature at which the rating factor applies should be stated.

The standard ambient reference levels are at 30°C or 55°C.

In the manufacturer’s literature, a typical statement would be: RF 2.0 at 30°C ambient with RF 1.5 at 55°C ambient.

These statements mean that in a 30°C ambient, the CT will safely carry on a continuous basis 2 times the nameplate rating and at 55°C ambient, it will carry 1.5 times the nameplate rating. It is very important that the ambient temperature be considered when applying CT’s above the rating.

Typical rating factors of CT's are 1.0, 1.25, 1.33, 1.5, 2.0, 3.0, and 4.0. Many times the manufacturer will only list the CT rating factor at 30°C ambient (room temperature).
If you wish to know what the rating factor is at some other ambient temperature, you will have to convert the value by use of a rather simple proportional equation.
Following is a typical example:
The manufacturer states his 400:5 ampere CT has a rating factor of 4.0 at a 30°C ambient and you wish to know how much you must derate it when it is put in an enclosure where the highest ambient temperature might be 55°C. The basic formula for a 55°C rise CT is:

The basic formula for a 55°C rise CT is:

$$\frac{(\text{New RF at New AMB})^2}{(\text{Stated RF at 30 }^{\circ}\text{C})^2} = \frac{85 - \text{New AMB }^{\circ}\text{C}}{55^{\circ}\text{C}}$$

And for our particular example:

$$\frac{(X)^2}{(4.0)^2} = \frac{30}{55}$$

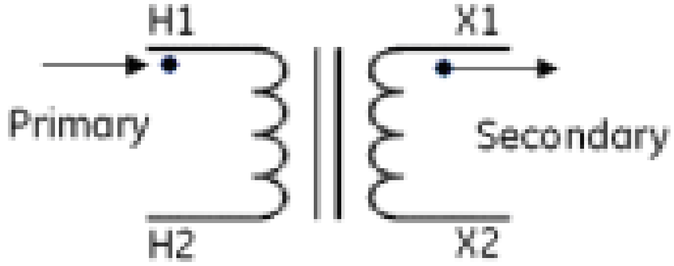
$$X^2 = 8.73$$

$$X = \text{RF @ } 55\,^{\circ}\text{C} = 2.95$$

Thus where the 400 ampere unit could carry (400 X 4.0) 1600 amperes primary at 30°C ambient without exceeding the manufacturer's recommended transformer thermal rating, it can safely carry only 2.95 x 400 at 55°C. The IEEE standard C57.13 provides a graph depicting the change in thermal rating to ambient temperature as well.

Insulation/Voltage Class

- The insulation class indicates the magnitude of voltage, which an instrument transformer can safely withstand between its primary and secondary winding and between its primary or secondary winding and ground (core, case or tank) without a breakdown in the insulation.
- Industry standards have established insulation classes ranging from 600 volts up through 545 KV. System voltages presently extend up to 765 KV with 1100 and 1500 KV being investigated for future transmission expansions.
- Industry recommendations are that the insulation class of an instrument transformer should be at least equal to the maximum line-to-line voltage existing on the system at the point of connection.
- For example, the insulation class of a potential transformer used on a 7200/12470 volt system should be 15 KV even though the PT has a primary rating of 7200 volts and is connected phase-to-ground.
- Similarly, any current transformer used on a 7200/12470Y volt system should be of the 15 KV insulation class.
- Under fault conditions these units could be subjected to line-to-line voltage.

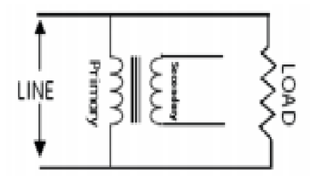


Polarity

- In the application of instrument transformers it is necessary to understand the meaning of polarity and to observe certain rules when connecting watthour meters, relays, etc. If you will accept the fact, without proof, that the flow of current in the secondary winding is in a direction opposite to in the primary winding, that is, 180° out of phase with it, it will be relatively simple to understand the meaning of polarity. At any instant, when the current is flowing into one of the primary terminals it will be flowing out of one of the secondary terminals. The polarity of a transformer therefore is simply an identification of the primary terminal and the secondary terminal, which satisfies the previously stated conditions. All instrument transformers, whether current or potential will have polarity marks associated with at least one primary terminal and one secondary terminal. These markings usually appear as white dots or letter and number combinations. When number and letter combinations are used IEEE refers to H1 as the primary terminal marking and to X1 for the secondary polarity mark. In applications which depend on the interaction of two currents, such as a watthour meter or protective relay, it is essential that the polarity of both current and potential transformers be known and that definite relationships are maintained. While all instrument transformers should be clearly marked as to their polarity, it is sometimes necessary to verify existing markings or to determine the polarity of an old or unmarked transformer. One simple method of determining polarity on a potential transformer is to connect a suitable DC permanent magnet voltmeter, preferably one with a 150 volt range, across the high voltage terminals, with the marked primary terminal of the transformer connected to the plus (+) terminal of the voltmeter. Then connect a battery and connect the plus (+) terminal of the battery to the marked secondary terminal. Make an instantaneous contact between the negative (-) terminal of the battery and the unmarked or (X2) secondary terminal of the transformer. A deflection or "kick" will be indicated on the voltmeter. If the initial "kick" (the one resulting from making, not breaking the circuit) is in an upscale direction, the potential terminals are marked correctly. Similarly, a polarity check may be made on a current transformer. Connect a DC permanent magnet ammeter of 5 ampere capacity or less (depending on the transformer ratio) across the current transformer secondary. Connect the plus connect a battery in series and connect the negative (-) terminal of the battery to the unmarked of (H2) marked terminal of the transformer, make an instantaneous contact between the marked or (H1) primary terminal of the transformer and the plus (+) terminal of the battery. If the initial kick (the one resulting from making not breaking the circuit) is upscale, the current transformer terminals are marked correctly. Precautions should be taken when making this test on current transformers to prevent core magnetization from occurring due to the direct current. Window or bar type units with low current ratings (400 ampere and down) are particularly susceptible to this residual magnetism. It is a best practice to demagnetize the CT after using DC. This can be accomplished by connecting at least 50 ohms variable across the secondary terminals and bring the primary current up to full load. Reduce the series resistance until it reaches zero without opening the secondary circuit. For best results, gradually reduce the primary circuit to zero before disconnecting the resistance circuit.

Connections - Potential Transformers

Potential transformers are normally connected across two lines of the circuit in which the voltage is to be measured. Normally they will be connected L-L (line-to-line) or L-G (line-to-ground). A typical connection is as follows:

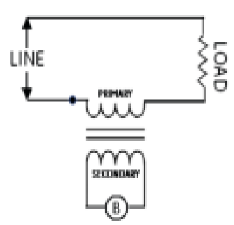


When a phase relationship of "direction of flow" is of no consequence, such as in a voltmeter which operates only according to the magnitude of the voltage, there is no need to observe the polarity of the transformer. However, in watthour meter applications, polarity must always be observed.

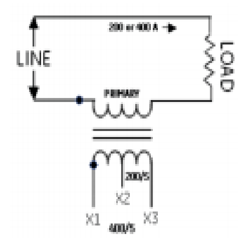
Most potential transformers have a single winding secondary as previously shown, however, they may have tapped secondary windings, or dual secondary windings.

Connections - Current Transformers

CT's with wound primaries always have their primary windings connected in series with the line and the load and their secondary windings connected to the burden (the watthour meter current coil) as show below:



Current transformers having a center tapped secondary are referred to as a dual ratio CT. They are used in applications where it is necessary to have available two ratios of primary to secondary current from the same secondary winding of the CT. This may be accomplished by adding a tap in the secondary winding to get a second ratio. The ratio obtained by the tap is usually one-half the ratio obtained by the full secondary winding. A schematic example is shown below. With 200 amperes flowing in the primary,



- Potential transformers are normally connected across two lines of the circuit in which the voltage is to be measured.
- Normally they will be connected L-L (line-to-line) or L-G (line-to-ground).
- A typical connection is as follows:
- CT's with wound primaries always have their primary windings connected in series with the line and the load and their secondary windings connected to the burden (the watthour meter current coil) as show below:
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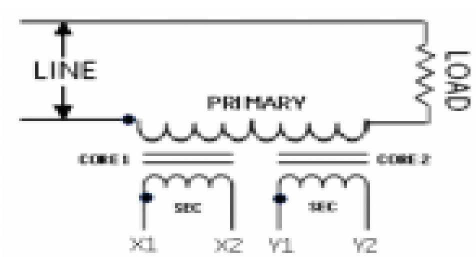
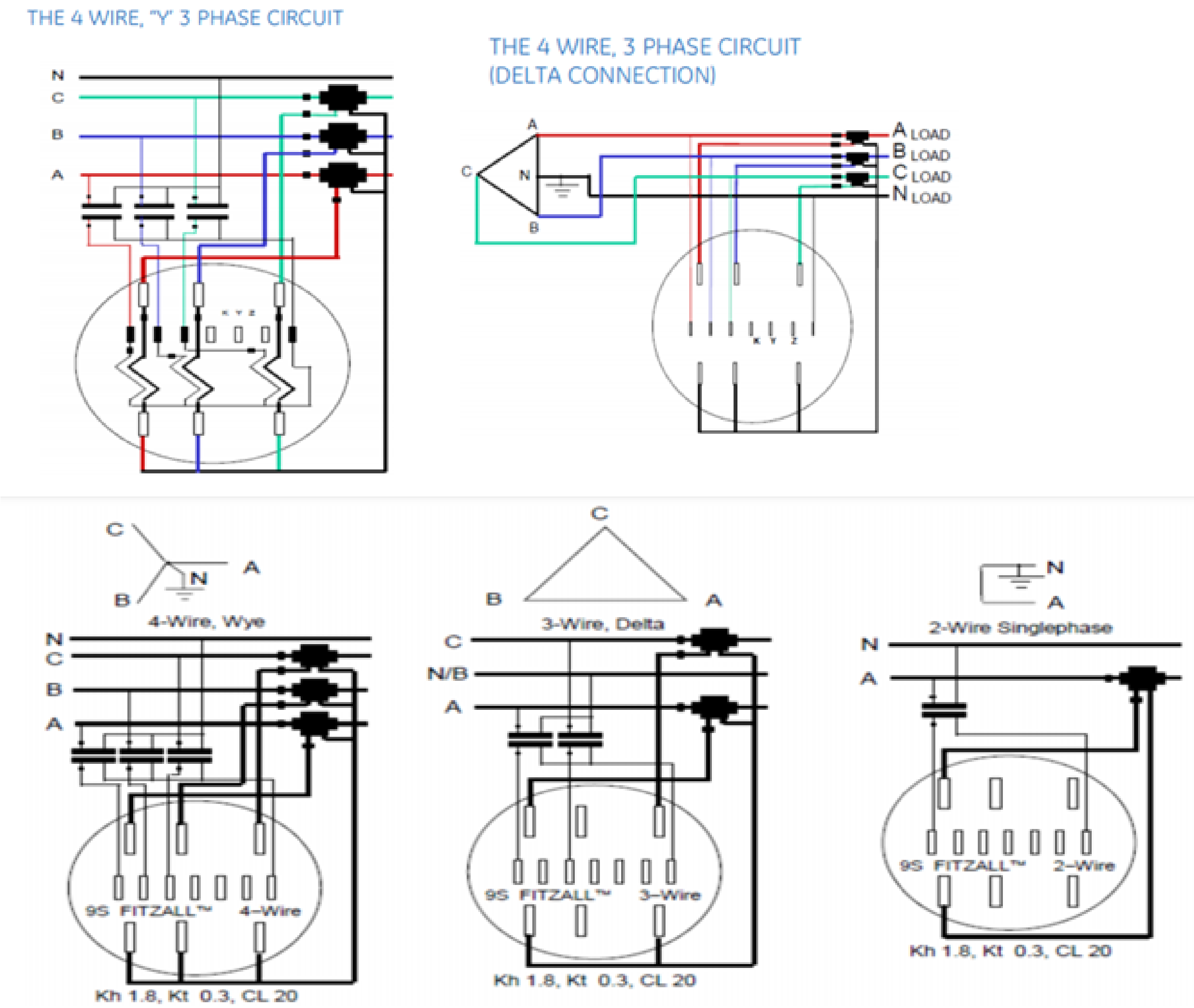
watthour meter applications, polarity must always be observed. Most potential transformers have a single winding secondary as previously shown, however, they may have tapped secondary windings, or dual secondary windings. it is necessary to have available two ratios of primary to secondary current from the same secondary winding of the CT. This may be accomplished by adding a tap in the secondary winding to get a second ratio. The ratio obtained by the tap is usually one-half the ratio obtained by the full secondary winding.

- A schematic example is shown below. With 200 amperes flowing in the primary, a connection X2 – X3 will produce 5 amperes out of the secondary. Then as the load grows to 400 amperes, the secondary circuit will be reconnected to X1 – X3 to produce 5 amperes in the secondary. It is not recommended to reconnect while the unit is energized, the secondary terminals must be short circuited so as not to induce high voltage in the secondary circuit when the circuit is opened to make the connection. Voltage from a few hundred volts to several thousand volts, dependent on the design, can be developed in the secondary circuit when it is open circuited with current flowing in the primary winding. On a dual ratio tapped secondary CT, both the full winding and the tapped winding cannot be operated simultaneously. The unused terminal must be left open to avoid short circuiting a portion of the secondary winding. Another design of CT quite commonly used is the double secondary CT. In this configuration the CT has two cores, two secondary windings and one common primary winding. Its application would be for using one CT to both meter and relay a common circuit where the metering circuit must be isolated from the relaying circuit. A schematic of this would like this: In this design, if both the circuits are not going to be used simultaneously, then the unused circuit must be short circuited while the other is energized or you will develop an induced high voltage on the open circuited unused CT.



Connections - Standard Metering

- Typical current transformer connections on three common circuits will illustrate the principles involved in making CT installations.



Typical Examples

Metering Accuracy

There are two sources of error in instrument transformers, namely ratio error and phase angle error. In a given transformer, the metering error is the combination of the two separate errors. This combination is called Transformer Correction Factor (TCF), IEEE has established accuracy classes for both current and potential transformers. The limit of permissible error in a potential transformer for a given accuracy class remains constant over a range of voltage from 10% below to 10% above rated voltage. In the figure to the right is a standard test card provided by the manufacturer showing the performance of the CT at 10% and 100% of rated current. The limit of permissible error in a current transformer accuracy class has one value at 100% rated current and allows twice that amount of error at 10% rated current. Typically 0.3% error is acceptable for watthour metering, 0.6% to 1.2% error for indicating instruments. The figure to the right shows the performance limits of a standard metering 0.3% accuracy CT with a rating factor of 4.0.

High Accuracy Instrument Transformers

Two new accuracy classes have been developed by IEEE C57.13.6 to accommodate the shift towards electronic relays and meters from the traditional induction devices. Consequently, manufacturers have begun to improve accuracy of instrument transformers to take advantage of the lower impedance of the devices. Included in the new high accuracy standard are new testing points and burdens to verify performance. New burdens of E.04, (1.0 Volt-Ampere at 5Amp, unity power factor), E0.2, (5.0 Volt-Ampere at 5Amp, unity power factor), and low current test point of 5% versus the traditional 10% rated current, are now required.

0.15 Accuracy Instrument Transformers

Current transformers must maintain 0.15% accuracy from rated current through rating factor at rated burden.

At 5% rated current through 100%, the current transformer must maintain 0.3% accuracy. No accuracy is guaranteed at levels below 5%. Voltage transformers are 0.15% accuracy from 90%-110% of rated voltage.

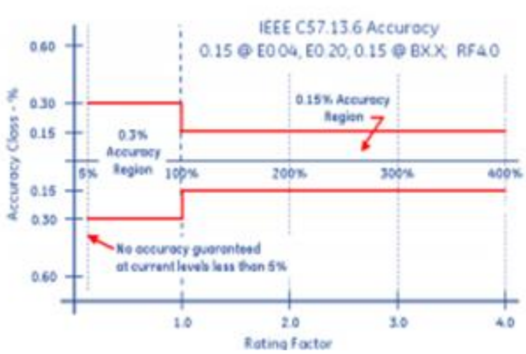
0.15S Accuracy Instrument Transformers

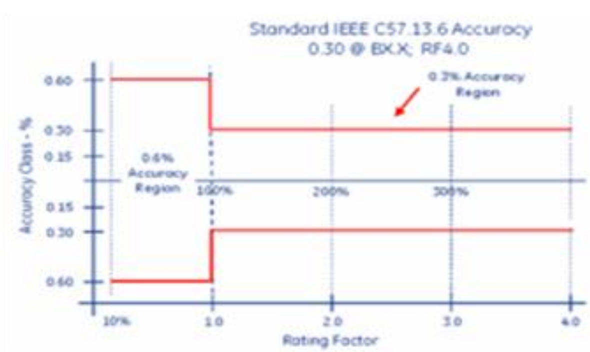
Current transformers must maintain 0.15% accuracy from 5% rated current through rating factor at rated burden. No accuracy is guaranteed at levels below 5%. Voltage transformers are 0.15% accuracy from 90%-110% of rated voltage.

Relay Accuracy of a Current Transformer

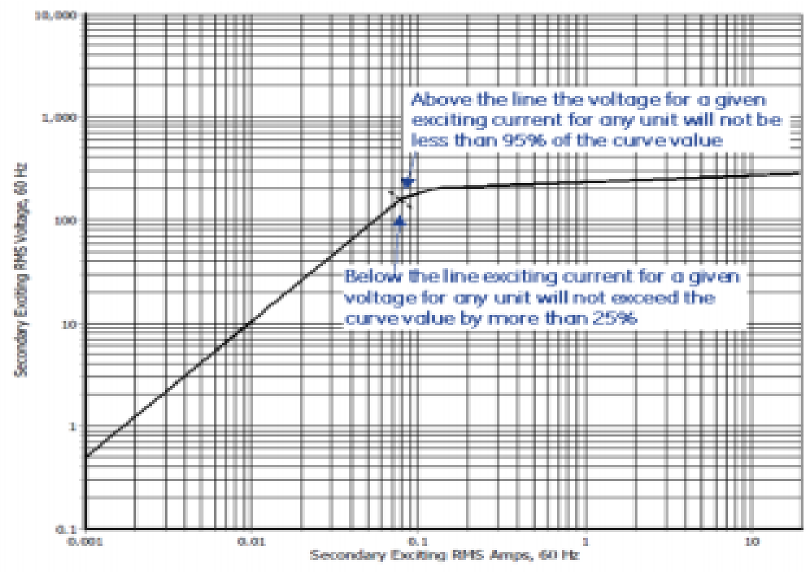
Current transformers that are used to operate relays for control and system protection must have certain accuracy during over-current conditions. The transformer must be able to not only withstand the high currents involved, but must also transform current to a lower value suitable for application to the relay terminals, and do this with a reasonable accuracy. A typical relay accuracy classification might be C200 or T200. The “C” stands for calculated and means that the window and bar type units which have a fully distributed secondary winding on a low leakage flux core thus leading itself to calculated values. The “T” stands for tested because wound type units do not have fully distributed windings, they must be tested because the leakage reactance is not predictable. The last number is the secondary voltage that can be developed at the secondary terminals without saturation.

Thus the meaning of the relay classification! C200 would be (10% accuracy inferred at 20 X normal current X secondary impedance OR V = IR 200 volt = (20 X 5 amps) X B2.0 ohms Thus, this CT would have an error of no larger than 10% at 20 times normal secondary current with a secondary burden of 2.0 ohms. Manufacturers will often offer a graph of the excitation performance of a particular CT. The graph allows the end user to determine the performance of the CT over the entire range of secondary current and ensure that the CT will function as required. The figure to the right shows a typical excitation curve of a relay class CT.





Sl. No.	Current Transformer (C.T.)	Potential Transformer (P.T.)
1	Connected in series with power circuit.	Connected in Parallel with Power circuit.
2	Secondary is connected to Ammeter.	Secondary is connected to Voltmeter.
3	Secondary works almost in short circuited condition.	Secondary works almost in open circuited condition.
4	Primary current depends on power circuit current.	Primary current depends on secondary burden.
5	Primary current and excitation vary over wide range with change of power circuit current	Primary current and excitation variation are restricted to a small range.
6	One terminal of secondary is earthed to avoid the insulation break down.	One terminal of secondary can be earthed for Safety.
7	Secondary is never be open circuited.	Secondary can be used in open circuit condition



CTs Applications

- ➢ UPS systems
- ➢ Transfer switches
- ➢ Motor-generator sets
- ➢ Commercial sub-metering,
- ➢ CT 's in one package for 3-phase metering
- ➢ Accurate measuring for metering/WATT/VAR
- ➢ Current sensing, recording, monitoring & control
- ➢ Control panels and drives
- ➢ Standard CT used as measuring standard for comparison
- ➢ Winding temperature indicator (WTI) for power transformers
- ➢ Summation current transformers.

PTs Applications

- ❖ Electrical Metering systems
- ❖ Electrical protection systems
- ❖ Distance protection of feeders
- ❖ Synchronizing generators with grid
- ❖ Impedance protection of generators

Types of Voltage or Potential Transformers

Majorly these are classified into outdoor and indoor potential transformers.

1. Outdoor Potential Transformers

These can be single or three phase voltage transformers available for different range of operating voltages that are used for outdoor relaying and metering applications. Up to 33KV, these are of electromagnetic type single and three phase voltage transformers. Above 33KV single phase outdoor potential transformers can be two types electromagnetic type and capacitive voltage transformer (CVT).

Electromagnetic or Wound Type Conventional Potential Transformer

These are similar to the conventional oil filled wire wound transformers. The figure below shows the electromagnetic type of PT wherein tap tank is connected to the line terminal. A plug is provided on the tank to fill the oil and this tank is mounted on an insulator support.

At the base, ground terminal and oil drain plug is provided. In this, primary is connected between the two phases or between one phase and ground. So one end of the primary is connected to main line at the top and the other end is brought out at the bottom and is grounded with other ground terminals.

The secondary terminals including earth terminal are located in the terminal box at the bottom, further these are connected to the metering and relay circuits. These are used up to or below 132 KV operating voltages due to insulation aspects.

Capacitive Voltage Transformers (CVTs)

It is a capacitive potential divider connected between the phase of main line and ground. These can be coupling capacitor or bushing type CVTs. These two types are electrically less or more similar, but the difference is that the formation of capacitance which further decides their rated burden (or load).

A coupling capacitor type consists of a stack of series connected capacitors which are made up of oil-impregnated paper and aluminium foil. For desired primary and secondary voltages, primary and secondary terminals are connected across the capacitors.

The bushing type CVT uses condenser type bushings provided with tapping. CVTs are also used for power line carrier communication and hence more economical.

2.Indoor Potential Transformers

These are also available as single or three phase PTs which are of moulded, magnetic type. The mounting mechanism can be fixed or drawout type. In this type of PTs, all parts of primary winding are insulated from earth at its rated insulation capacity. These are designed to operate relays, measuring instruments, and other control devices in indoor service with high accuracy.

Based on the function, PT or voltage transformers are classified into metering voltage transformers and protection voltage transformers.

Errors in Voltage Transformer

For an ideal voltage transformer, the voltage produced in the secondary winding is an exact proportion to the primary voltage and are exactly in phase opposition. But in actual PTs this is not so because of the presence of voltage drops in primary and secondary resistance and also due the power factor of the burden on secondary. This causes to occurrence of ratio and phase angle errors in voltage transformers. Let us know in detail.

Consider the phasor diagram of potential transformer shown above,

where

Io = No load current

Im = magnetizing component of no load current

Iu = Wattful component of no load current

Es and Ep = Induced voltages in secondary and primary windings respectively

Np and Ns = Number of turns in primary and secondary windings respectively

Ip and Is = Primary current and secondary current

Rp and Rs = Resistances of primary and secondary windings respectively

Xp and Xs = Reactances of primary and secondary windings respectively

β = Phase angle error

The primary induced voltage or EMF Ep is derived by subtracting the primary resistive (IpRp) and reactive drop (IpXp) from the primary voltage Vp. And also, secondary terminal voltage Vs is derived by subtracting secondary winding resistance drop (IsRs) and reactance drop (IsXs) vectorially from secondary induced EMF Es. Due to these drops nominal ratio of the potential transformer is not equal to the actual ratio of the PT, hence introduces a ratio error.

Ratio Error

The ratio error of the potential transformer is defined as the variation in actual ratio of transformation from nominal ratio.

Percentage Ratio Error = (Kn – R) / R × 100

Where

Kn is the nominal or rated transformation ratio and is

Kn = Rated primary voltage / Rated secondary voltage

Phase Angle Error

In ideal PT, there should not exist any phase angle between the primary voltage and reversed secondary voltage. But in practice, there exist a phase difference between Vp and Vs reversed (as we can observe in above figure), thereby, introduces phase angle error. It is defined as the phase difference between the primary voltage and reversed secondary voltage.

In order to reduce these errors such that the accuracy is improved by designing the transformers in such a way that they windings have appropriate magnitudes of internal resistance and reactances. In addition to this, the core should require minimum magnetizing and core loss components of exciting current.

Applications of Voltage Transformers

- Electrical Metering systems
- Electrical protection systems
- Distance protection of feeders
- Synchronizing generators with grid
- Impedance protection of generators

The class of potential transformers used for metering is called as measurement voltage or potential transformers. On other hand PTs used for protection called as protection voltage transformers. In some cases PTs are used for both metering and protection purposes, in such cases, one secondary winding is connected to metering and other secondary winding is used for protection.

Instrument Transformer

Instrument transformers are used to protect or isolate the metering equipment, relays, instruments, and other control devices from the circuit which is operating at high voltage and currents and in which electrical quantities are to be measured. These are specially designed for the use of electrical instruments such as ammeters, voltmeters, watt meters, protective relays, energy meters, etc. to increase their range of measurement. These serve as voltage and current level conversion equipments from a high voltage circuitry to the levels suitable for measurement. The classification of instrument transformers includes both voltage and current transformers

Current Transformers

These are used to step-down the current levels so that ammeters, current coils of other instruments and relays are need not be connected directly to the high power operating circuit. Hence, all these instruments are isolated from high power circuit. A current transformer consists of separate primary and secondary windings. The primary consists of one or a few turns of heavy wire wound on a laminated core. This winding is connected in series with one of the power lines. In some CT's, line conductor or wire itself serves as primary which is passing through the core. The secondary winding consists of a large number of turns of a small size wire which is wounded on the core. This winding is connected to instruments or relays. The usual standard rating of secondary current of a CT is 5A. And the primary winding current is determined by the maximum value of the load current.

Potential Transformers

These transformers operate as similar to the standard power transformer, but only difference is that these are small capacity transformers. These are used to step-down the voltage levels in the high power circuit to levels suitable for measuring range. PT's are connected parallel across the line in which electrical parameters to be measured or protective system is to be connected. The primary or high voltage side winding is connected between one of the power lines to ground or between phase to phase lines. The secondary or low voltage side winding is connected to the load or potential coils of the various instruments and relays or other control equipments. Most commonly, the secondary winding is wounded for 115 or 120 volts.

Combined Instrument Transformer

This type of transformers can accommodate both current and voltage transformers in a single free standing unit. This type of transformers converts voltages and currents to the standardized low and measurable values which are useful for metering, protection and other high voltage control systems. This results to the optimum use of space and less supporting structures and mounting pads. These are mainly used in protective relaying and revenue metering applications.

combined Instrument Transformer

Extension of Range

There is no fundamental difference in the operating principles of ammeters and voltmeters.

Both are current operated devices (except electrostatic type voltmeters) i.e. deflecting torque is produced when current flows through their operating coils.

In an ammeter, the deflecting torque is produced by the current to be measured or by a definite fraction of it whereas in a voltmeter torque is produced by the current proportional to the voltage to be measured.

Thus, the real difference between the two instruments is in the magnitude of the currents producing the deflecting torque.

The essential requirements of a measuring instrument are that its introduction into the circuit, where measurements are to be made, does not alter the circuit conditions and the power consumed by them for their operation is small.

An ammeter is connected in series with the circuit whose current is to be measured.

Therefore, it should have a low resistance.

On the other hand, a voltmeter is connected in parallel with the circuit whose voltage is to be measured; therefore, it must have high resistance.

Thus we conclude that the difference is only in the resistance of the instrument, in fact, an ammeter can be converted into voltmeter by connecting a high resistance in series with it.

In practice, heavy currents and voltages are required to be measured. Therefore, it becomes necessary that the current and voltage being measured be reduced and brought within the range of the instrument.
There are four common devices used for the range extension of ammeter and voltmeter namely;

- **shunts, multipliers and current and potential transformers**.

The ranges of electrical measuring instruments (whether ammeter, voltmeter or any other type of meters) are limited by the currents, which be carried by the coils of the instruments safely.

Shunts: The range of an ammeters can be extended by connecting a low resistance, called shunts, connected in parallel with ammeter**.** The shunt by passes **the extra current and allows only safe current to flow through the ammeter**.

It is possible to extend the range of an ammeter by using a shunt. A shunt is a low-value resistance having minimum temperature co-efficient and is connected in parallel with the ammeter whose range is to be extended. The combination is connected in series with the circuit whose current is to be measured. This shunt provides a bypath for extra current because it is connected across (i.e. in parallel with) the instrument. These shunted instruments can be used to measure currents many times greater than their normal full-scale deflection currents. The ratio of maximum current (with shunt) to the full-scale deflection current (without shunt) is known as the 'multiplying power' or 'multiplying factor' of the shunt. **Properties of Shunts**:

1. Temperature coefficient should be low. 2. Its resistance should not be vary with time.

3. Should carry the current without excessive temperature rise. 4. Should have low thermal e.m.f with copper.

Multipliers: The range of voltmeter can be extended by connecting a high resistance, called multiplier in series with the voltmeter coil. The multiplier limits the current through the meter so that it does not exceed the value of full scale deflection and thus prevents the movement from being damaged. Note: Materials used for multipliers are manganin and constantan.

Multipliers are used for the range extension of voltmeters. The multiplier is a non-inductive high-value resistance connected in series with the instrument whose range is to be extended. The combination is connected across the circuit whose voltage is to be measured.

Properties of Multipliers:

Their resistance should not change with time. 2. The change in their resistance with temperature should be small i.e. TVR should be small. 3.They should be non-inductively wound for A.C meters. In practice, heavy currents and voltages are required to be measured. Therefore, it becomes necessary that the current and voltage being measured be reduced and brought within the range of the instrument. The moving coil instruments can carry the maximum current of about 50 mA safely and the potential drop across the moving coil instrument is about 50 mV. The shunts and multipliers are used to extend the range of moving coil ammeters and voltmeters respectively. Whereas in the case of moving iron ammeters, for the ranges up to 0 – 250 A, shunts are used and for the ranges higher than that, Current Transformers CTs are used. And also, in the case of moving iron voltmeters, for the ranges up to 0 – 750 V, multipliers are used and for the ranges higher than that, PTs are used.

Range Extension of Ammeter by Current Transformer

For ranges above 0 – 250 A, a current transformer is used in conjunction with 0 – 5 A moving iron AC ammeter as shown in the figure. The current transformer is a step up transformer i.e. number of secondary turns is more than the primary turns.

Usually, the primary winding of the transformer contains a single turn or at the most a few turns. The primary of this transformer is connected in series with the load and carries the load current. The AC ammeter is connected across the secondary of the transformer. Since in figure, the current transformer ratio is 10:1, it means that line (or load) current is equal to 10 times the reading on the AC meter. Therefore, load current, I_L = 3 x 10 = 30 A.

Range Extension of Voltmeter by Potential Transformer

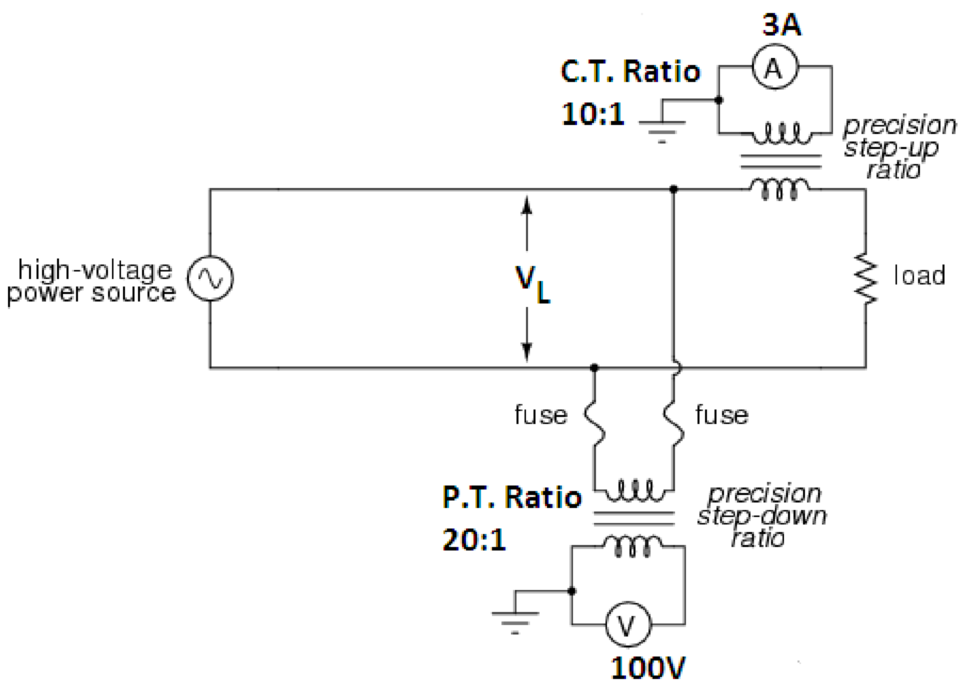
The range of a moving-iron AC voltmeter is extended by connecting a high resistance (multiplier) in series with it.

For ranges higher than 0 – 750 V, where power wasted in the multiplier would be excessive,

a 0 – 110 V moving-iron AC voltmeter is used in conjunction with a potential transformer as shown in the figure. The potential transformer is a step-down transformer i.e. number of primary turns is more than the secondary turns.

The primary of the transformer is connected across the load across which voltage is to be measured. The AC voltmeter is connected across the secondary.

Since in figure, the potential transformer ratio is 20:1, the load voltage is equal to 20 times the reading on the AC voltmeter.
Load voltage, V_L = 100 x 20 = 2000 V
Note that both secondaries of the instrument transformers are grounded as a safety measure.



Extension of Range of Ammeter by Shunt

It is possible to extend the range of an ammeter by using a shunt. A shunt is a low-value resistance having minimum temperature co-efficient and is connected in parallel with the ammeter whose range is to be extended. The combination is connected in series with the circuit whose current is to be measured.
This shunt provides a bypath for extra current because it is connected across (i.e. in parallel with) the instrument.
These shunted instruments can be used to measure currents many times greater than their

normal full-scale deflection currents.
The ratio of maximum current (with shunt) to the full-scale deflection current (without shunt) is known as the 'multiplying power' or 'multiplying factor' of the shunt.
Emample: A moving coil ammeter reading up to 1 ampere has a resistance of 0.02 ohm. How could this instrument be adopted to read current up to 100 amperes.
Solution: In this case,
Full-scale deflection current of the ammeter, $I_m = 1$ A Line current to be measured, $I = 100$ A Resistance of ammeter, $R_m = 0.02$ ohm
Let, the required shunt resistance = S

As seen from Figure, the voltage across the instrument coil and the shunt resistance is the same since both are joined in parallel.
$\therefore$ $I_m*R_m = S*I_s = S(I - I_m)$ or $\mathbf{S = I_m*R_m/(I - I_m)}$ = 1*0.02/(100 – 1) = 0.02/99 = 0.000202 **Ans**.

Extension of Range of Voltmeter by Multipliers

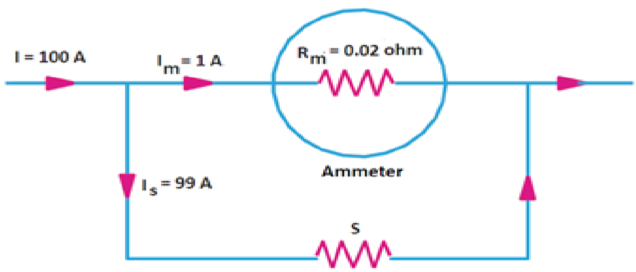
Multipliers are used for the **range extension of voltmeters**. The multiplier is a non-inductive high-value resistance connected in series with the instrument whose range is to be extended. The combination is connected across the circuit whose voltage is to be measured.
Example: A moving coil voltmeter reading up to 20 mV has a resistance of 2 ohms. How this instrument can be adopted to read voltage up to 300 volts.
Solution: In this case, Voltmeter resistance, $R_m = 2$ ohm Full-scale voltage of the voltmeter, $\nu = R_m I_m = 20$ mV = 0.02 V
Full-scale deflection current, $I_m = v/R_m = 0.02/2 = 0.01$ A Voltage to be measured, V = 300 V
Let the series resistance required = R
Then as seen from figure, the voltage drop across R is $V - \nu$
$R * I_m = V - \nu$ or $\mathbf{R = (V - v)/I_m}$ or R = (300 – 0.02)/0.01 = 299.98/0.01 = 29998 ohms **Ans.**

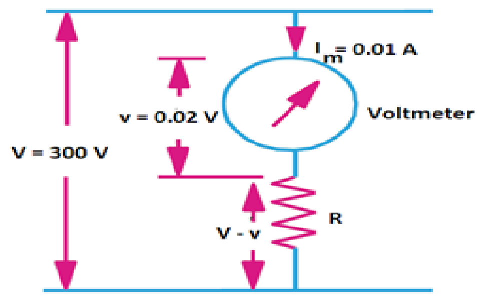
Shunts can not be used to **extend the range of moving-iron AC ammeters** accurately. It is because the division of current between the operating coil and the shunt varies with frequency (since reactance of the coil depends upon frequency). In practice, the *range of moving-iron AC ammeters are extended by one of following methods:*

Range Extension of Ammeter by Coil Turns

By changing the number of turns of the operating coil. For example, suppose that full-scale deflection is obtained with 400 ampere-turns. For full-scale reading with 100A, the number of turns required would be = 400 / 100 = 4. Similarly, for full-scale reading with 50A, the number of turns required in = 400/50 = 8.

Thus the ammeter can be arranged to have different ranges by merely having a different number of turns on the coil. Since the coil carries the whole of the current to be measured, it has a few turns of thick wire. The usual ranges obtained by this method are from 0 -250 A.





Extension of Range

Shunts are used for the extension of range of Ammeters.

So a good shunt should have the following properties:-

1- The temperature coefficient of shunt should be low

2- Resistance of shunt should not vary with time

3- They should carry current without excessive temperature rise

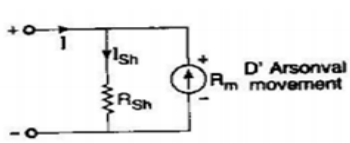
4- They should have thermal electromotive force with copper

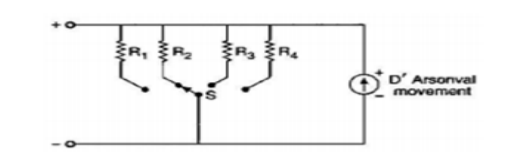
- ‘Manganin’ is used for DC shunt and ‘Constantan’ as AC shunt.

Ammeter:- PMMC is used as indicating device. The current capacity of PMMC is small. It is impractical to construct a PMMC coil, which can carry a current greater than 100 mA. Therefore a shunt is required for measurement of large currents.

- Rm = Internal resistance of movement (coil) in Ω
- Rsh = Resistance of shunt in Ω
- Im = Ifs = Full scale deflection current of movement in Amperes
- Ish = Shunt current in Amperes
- I = Current to be measured in Amperes

Since the shunt resistance is in parallel with the meter movement, the voltage drop across shunt and movement must be same.





$$I_{sh}R_{sh} = I_m R_m$$

$$R_{sh} = {I_m R_m}/{I_{sh}}$$

$$I_{sh} = I - I_m$$

$\therefore$ We can write $R_{sh} = {I_m R_m}/{(I - I_m)}$

$$\frac{I}{I_m} - 1 = \frac{R_m}{R_{sh}}$$

$$\frac{I}{I_m} = 1 + \frac{R_m}{R_{sh}}$$

$\frac{I}{I_m} = m$ is known as 'multiplying power' of shunt

Resistance of shunt $R_{sh} = {R_m}/{(m-1)}$

Or $R_{sh} = {R_m}/{\left(\frac{I}{I_m} - 1\right)}$

Multi Range Ammeter:- Let m_1, m_2, m_3, m_4 be the shunt multiplying powers for current I_1, I_2, I_3, I_4.

$$R_{sh1} = {R_m}/{(m_1 - 1)}$$

$$R_{sh2} = {R_m}/{(m_2 - 1)}$$

$$R_{sh3} = {R_m}/{(m_3 - 1)}$$

$$R_{sh4} = {R_m}/{(m_4 - 1)}$$

<u>Voltmeter</u>:-

For measurement of voltage a series resistor or a multiplier is required for extension of range.

I_m = Deflection current of movement
R_m = Internal resistance of movement
R_s = Multiplier resistance
V = Full range voltage of instrument

$$V = I_m(R_s + R_m)$$

$$R_s = \frac{V - I_m R_m}{I_m} = \frac{V}{I_m} - R_m$$

* For more than 500 V multiplier is mounted outside the case.

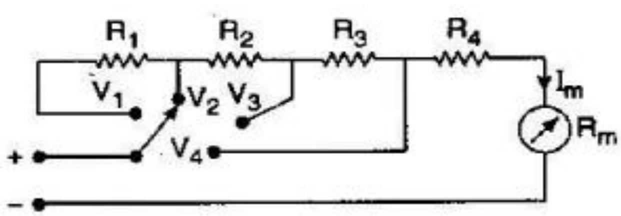
<u>Multi Range Voltmeter:</u>

$$R_{s1} = \frac{V_1}{I_m} - R_m$$

$$R_{s2} = \frac{V_2}{I_m} - R_m$$

$$R_{s3} = \frac{V_3}{I_m} - R_m$$

$$R_{s4} = \frac{V_4}{I_m} - R_m$$



**** For average value divide the reading by 1.11. For peak value multiply the voltage by 1.414. To get peak-to-peak ratio multiply the reading by 2.828.***
***** Thermocouple and hot wire instruments are used for measurement of true power and rms value of voltage & current.***

Model Questions

1. Explain electrodynamic wattmeter and induction type meters.
2. Explain Low power factor meter and their types with neat diagrams
3. Explain single and three phase wattmeter and their applications with neat diagrams
4. Explain in detail about De Seauty Bridge and Schering bridge method used for measurement of capacitance.
5. Explain two-element wattmeter used for three-phase system with diagrams
6. Explain in detail about instrument transformers and their applications.
7. Explain the construction and working of current transformer with diagrams
8. Explain the working and advantages of potential transformer with diagrams
9. Explain how extension of range of instruments are achieved using CT and PT.
10. Differentiate between current and potential transformers and list their applications

SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHATRONICS ENGINEERING

UNIT V - Signal Conditioning And Data Acquisition - SMR1302

SMR1302 SENSORS AND INSTRUMENTATION

UNIT V SIGNAL CONDITIONING AND DATA ACQUISITION

Amplification, Filtering – Level conversion – Linearization - Buffering – Sample and Hold circuit – Quantization – Multiplexer / De multiplexer – Analog to Digital converter – Digital to Analog converter- I/P and P/I converter - Instrumentation Amplifier-V/F and F/V converter Data Acquisition -Data Logging – Data conversion – Introduction to Digital Transmission system

Signal Conditioning

Analog signals need to be correctly *"prepared"* before they can be converted into digital form for further processing. Signal conditioning is an electronic circuit that manipulates a signal in a way that prepares it for the next stage of processing. Many data acquisition applications involve environmental or mechanical measurement from sensors, such as temperature and vibration. These sensors require signal conditioning before a data acquisition device can effectively and accurately measure the signal. For example, thermocouple signals have very small voltage levels that must be amplified before they can be digitized. Other sensors, such as resistance temperature detectors (RTDs), accelerometers, and strain gauges require excitation to operate. All of these preparation technologies are forms of signal conditioning. Signal conditioning is one of the fundamental building blocks of modern Data acquisition (DAS or DAQ system). The basic purpose of a data acquisition system is to make physical measurements. They are comprised of the following basic components:

(1) Sensors (2) Signal Conditioning (3) Analog-to-Digital Converter (ADC) and (4) Some sort of computer with DAQ software for signal logging and analysis.

Data acquisition systems need to connect to a wide variety of sensors and signals in order to do their job. Signal conditioners take the analog signal from the sensor, manipulate it, and send it to the ADC (analog-to-digital converter) subsystem to be digitized for further processing (usually by computer software). As the name implies, they are in the business of conditioning signals so that they can be converted into the digital domain by the A/D subsystem, and then displayed, stored, and analyzed. After all, you cannot directly connect 500V to one of the inputs of an A/D card - and thermocouples, RTDs, LVDTs, and other sensors require conditioning to operate and to provide a normalized voltage output that can be input into the A/D card.

Top Requirements of Signal Conditioners

Today signal conditioners include some of the required elements that make them useful for modern data acquisition systems. These elements are: (1) Electrical isolation (2) The right connectors for sensor connections (3) Measurement range selection (4) Signal filtering (e.g. anti-aliasing filtering) (5) Conformance with sensor requirements.

Signal conditioning is the operation performed on the signal to convert it to a form suitable for interfacing with other elements in the system.

Signal conditioning can be categorized into:

1. **Signal-range and offset changes:** Amplification and zero adjustment
2. **Linearization:** Certain signal conditioners can perform linearization when the signals produced by a sensor do not have a straight-line relationship with the physical measurement.
3. **Conversions:** e.g. current to voltage and voltage to current
4. **Filtering :** removing unwanted frequencies

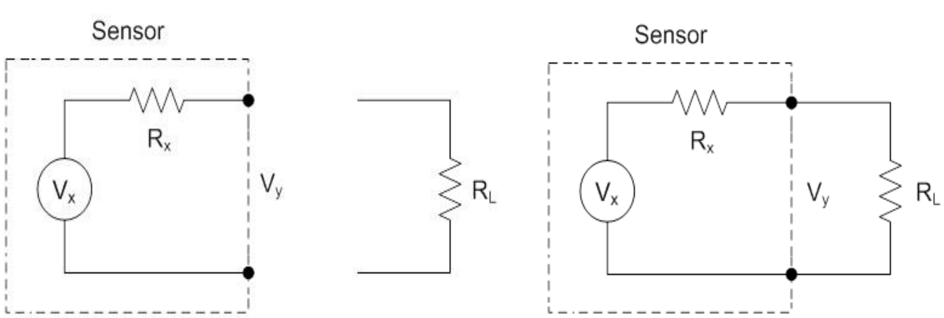
Before discussing signal conditioning, it is important to understand:

- the loading effect.
- the buffer circuit.
- the difference amplifier.
- the instrumentation amplifier.

- **The loading effect :**Connecting a sensor or circuit to a load introduces uncertainty in the measurement (i.e. in the amplitude of the output voltage) as shown below.
- The output voltage is calculated using voltage division as

$$V_y = \frac{R_L}{R_L + R_x} V_x$$

- The output voltage is reduced by the voltage drop over the internal resistance of the sensor R_X.
- To reduce the uncertainty (i.e. to keep $V_y \approx V_x$), $R_L \gg R_X$



without load: $V_y = V_x$ **with load:** $V_y < V_x$

Buffering

The buffer circuit :

To minimize the loading effect, we must look for an amplifier that has infinite (very large) input impedance to obtain the whole sensor output voltage.

Furthermore, as this amplifier is probably going to drive other circuits, it should have zero (very small) output impedance.

A device having these two properties is called a buffer such as the voltage follower circuit shown.

Buffer amplifier:

Buffer amplifier is a circuit which transforms electrical impedance from one circuit to another.

The main purpose of a buffer is to prevent the loading of a preceding circuit by the succeeding one. For example, a sensor may have the capability to produce a voltage or current corresponding to a particular physical quantity it sense but it may not have the power to drive circuitry it is connected to. In such situations a buffer can be used.

A buffer when connected between the sensor and the succeeding circuitry easily drives the circuitry in terms of current or voltage according to the sensor output.

Buffers are classified into voltage buffers and current buffers. The symbols of ideal voltage buffer and current buffer are shown in Fig 1 and Fig 2 respectively.

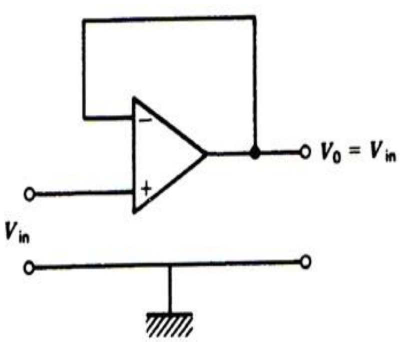
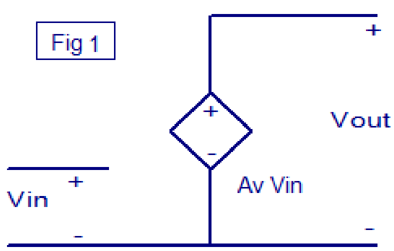
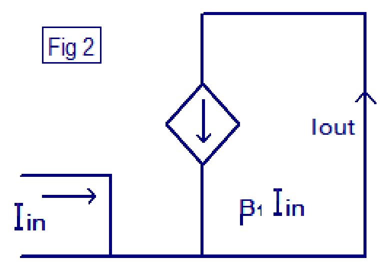


Fig 1



Ideal voltage buffer symbol

Fig 2



Ideal current buffer symbol

Voltage buffer

A circuit which transfers a voltage from a circuit with high output impedance to a circuit with low input impedance is call a voltage buffer. The voltage buffer connected between these two circuit prevents the low input impedance circuit (second one) from loading the first one. Infinite input impedance, zero output impedance, absolute linearity, high speed etc are the features on an ideal voltage buffer.

- If the voltage is transferred from the first circuit to the second circuit without any change in amplitude, then such a circuit is called unity gain voltage buffer or voltage follower. The output voltage just tracks or follows the input voltage. The voltage gain of the voltage follower is unity (Av = 1). Even though there is no voltage gain, there will be a sufficient amount of gain in current. So when a voltage follower is connected between two circuit, it will transfer the voltage from first one to second one without any change in amplitude and drives the second circuit without loading the first circuit. A voltage buffer can be realized using opamp, BJT or MOSFET. Voltage follower using transistor (BJT) is shown in Fig 3. Voltage follower using BJT is also known as emitter follower. +Vcc is the transistor's collector voltage, Vin is the input voltage, Vout is the output voltage and Re is the transistors emitter resistor.

- Voltage follower implemented using opamp is shown in Fig 2. This is done by applying full series negative feedback to the opamp ie; by connecting the output pin to the inverting input pin. Here the opamp is configured in non inverting mode (refer Figure 2). So the equation for gain is Av= 1 + (Rf/R1).
- Since output and inverting input are shorted ,Rf=0 .
- Since there is no R1 to ground, it can be considered as an open circuit and so R1 = ∞
- There fore (Rf/R1) = (0/∞) = 0.
- Therefore Voltage gain Av = 1 + (Rf/R1) = 1+0 =1.

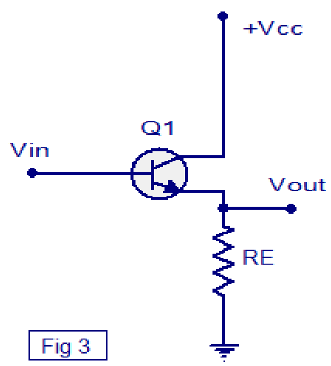


Fig 3

Voltage follower using transistor

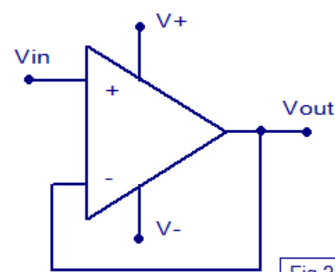


Fig 2

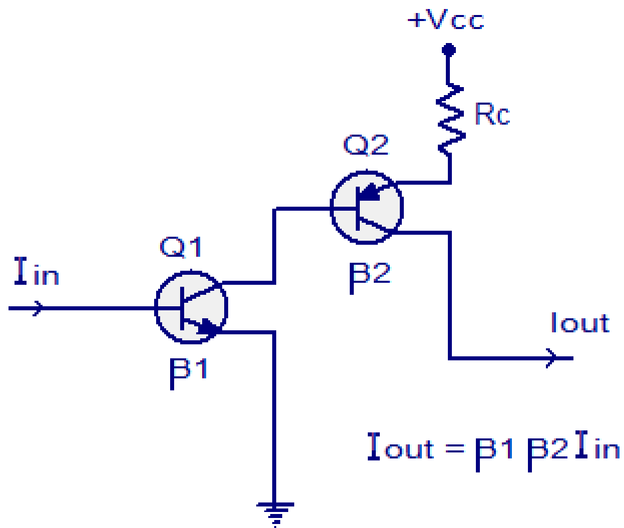
Voltage follower using opamp

Current buffer

Current buffer is a circuit that is used to transfer current from a low input impedance circuit to a circuit having high input impedance. The current buffer circuit connected in between the two circuits prevents the second circuit from loading the first circuit. The features of an ideal current buffer are infinite input impedance, zero output impedance, high linearity and fast response. A current buffer with unity gain (B=1) is called a unity gain current buffer or current follower. Here the output current just tracks or follows the input current. A current buffer can be realised using transistor (BJT or MOSFET).

Current amplifier circuit.

A current amplifier circuit is a circuit which amplifies the input current by a fixed factor and feeds it to the succeeding circuit. A current amplifier is somewhat similar to a voltage buffer but the difference is that an ideal voltage buffer will try to deliver whatever current required by the load while keeping the input and output voltages same, where a current amplifier supplies the succeeding stage with a current that is a fixed multiple of the input current. A current amplifier can be realized using transistors.The schematic of a current amplifier circuit using transistors is shown in the figure below. Two transistors are used in this circuit. β1 and β2 are the current gains of transistors Q1 and Q2 respectively. Iin is the input current, Iout is the output current and+Vcc is the transistor T2's collector voltage The equation for the output current is Iout = β1 β2 Iin .



Current amplifier using transistors

Signal conditioning can include Filtering, Amplification, converting, range matching, isolation and any other processes required to make sensor output suitable for processing after conditioning.

- **Filtering:** It is the most common signal conditioning function, as usually not all the signal frequency spectrum contains valid data.
- For example, the 50 or 60 Hz AC power lines, present in most environments induce noise on signals that can cause interference if amplified.
- **Amplification:** Signal amplification performs two important functions: increases the resolution of the input signal, and increases its signal-to-noise ratio. For example, the output of an electronic temperature sensor, which is probably in the millivolts range is probably too low for an analog-to-digital converter (ADC) to process directly. In this case it is necessary to bring the voltage level up to that required by the ADC.
- Commonly used amplifiers used for signal conditioning include sample and hold amplifiers, peak detectors, log amplifiers, antilog amplifiers, instrumentation amplifiers and programmable gain amplifiers.
- **Attenuation:** Attenuation, the opposite of amplification, is necessary when voltages to be digitized are beyond the ADC range. This form of signal conditioning decreases the input

signal amplitude so that the conditioned signal is within ADC range. Attenuation is typically necessary when measuring voltages that are more than 10 V.

- **Excitation:** External power is required for the operation of a passive sensor. (E.g. a temperature sensor like a thermistor & RTD, a pressure sensor (piezo-resistive and capacitive), etc.). The stability and precision of the excitation signal directly relates to the sensor accuracy and stability.

- **Linearization:** Linearization is necessary when sensors produce voltage signals that are not linearly related to the physical measurement. Linearization is the process of interpreting the signal from the sensor and can be done either with signal conditioning or through software.

- **Electrical isolation:** Signal isolation may be used to pass the signal from the source to the measuring device without a physical connection. It is often used to isolate possible sources of signal perturbations that could otherwise follow the electrical path from the sensor to the processing circuitry. In some situations, it may be important to isolate the potentially expensive equipment used to process the signal after conditioning from the sensor.

- Magnetic or optical isolation can be used. Magnetic isolation transforms the signal from a voltage to a magnetic field so the signal can be transmitted without physical connection (for example, using a transformer). Optical isolation works by using an electronic signal to modulate a signal encoded by light transmission (optical encoding). The decoded light transmission is then used for input for the next stage of processing.

Functions of a Signal Conditioner

- **Signal Conversion:** The main function of a signal conditioner is to pick up the signal and convert it into a higher level of electrical signal. Signal conversion is often used by industrial applications that use a wide range of sensors to perform measurements. Due to the different sensors being employed, the signals generated may need to be converted to be usable for the instruments they are connected too. Any sensor signal is capable of being converted to any standard process signal.

- **Linearization:** Certain signal conditioners can perform linearization when the signals produced by a sensor do not have a straight-line relationship with the physical measurement. This is the process of interpreting the signal from the software and it is common for thermocouple signals. This method is used to reach higher accuracy because every sensor is not completely linear. The parameters for the linearization are evaluated during the sensor-calibration and mentioned in the calibration protocol of the sensor.

- **Amplifying:** The next step is signal amplification and the process of increasing the signal for processing or digitization. There are two ways that signal amplification can be performed; by increasing the resolution of the input signal, or by increasing the signal-to-noise ratio.Signal conditioning uses a range of different amplifiers for different purposes, including instrumentation amplifiers, which are optimised for use with DC signals, and are characterized by high input impedance, high common mode rejection ratio (CMRR), and high gain. Another example of a signal conditioner used for amplification would be an isolation amplifier, which is designed to isolate high DC levels from the device while passing small AC or differential signal.

- **Filtering:** Another important function of a signal conditioner is filtering, and this is where the signal frequency spectrum is filtered to only include the valid data and block any noise. The filters can be made from either passive and active components or digital algorithm. A passive filter only uses capacitors, resistors, and inductors with a maximum gain of one. An active filter uses passive components in addition to active components such as operational amplifiers and transistors. State of the art signal conditioners use digital filters because they are easy to adjust and no hardware is required. A digital filter is a mathematical filter used to manipulate a signal, such as blocking or passing a particular frequency range. They use logic components such as ASICs, FPGAs or in the form of a sequential program with a signal processor.

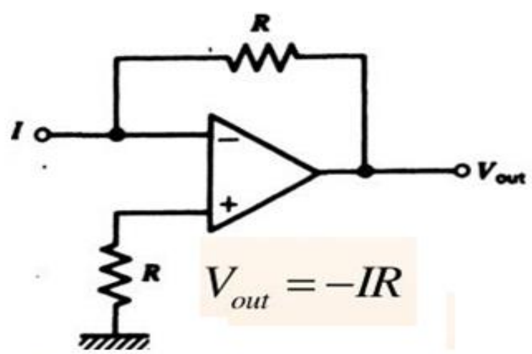
- **Evaluation and Smart-functions:** To provide additional benefits for the user and the process, modern signal conditioners have extra functions for signal evaluation and measurement data preprocessing. This helps to monitor and evaluate warning and alarms directly via an electrical switching output rapidly. Additional Smart-functions like an internal calculated channel can handle mathematical functions, like adding of sensor-signals, up to technological operations like a PID-controller. These functions help to get a fast reacting system and reduce the load from the machine control.

- **Interfaces:** Signal converters have to transmit the sensor signals via standard interfaces and protocols to the machine control. These interfaces can be analog or digital. Common analog interfaces are voltage (+/-10V) or current signals (+/-20mA) which are easy to handle but every signal needs a separate wiring. Modern digital interfaces are designed as Ethernet-based bus-interfaces (Profinet, Ethercat, Ethernet/IP) and allow the connection of several components with only one wire. This reduces the wiring and also allows additional information to be transmitted, such as diagnostic information of the components, which is very important for reducing down-times and speed up maintenance.

Conversion

- In many situations it is required to convert one form of signal or physical value into another form such as
  - resistance to voltage
  - voltage-to-current
  - current-to-voltage

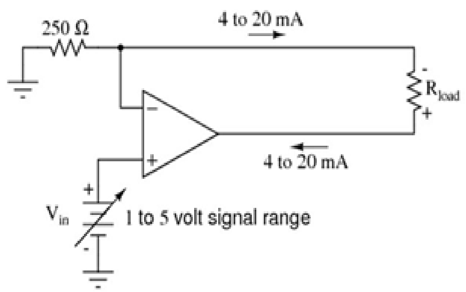
- For example, a typical standard in process control systems is to use current signals in the range 4 to 20 mA for transmission. This requires conversion from voltage to current at the sending end and a conversion from current to voltage at the receiving end.

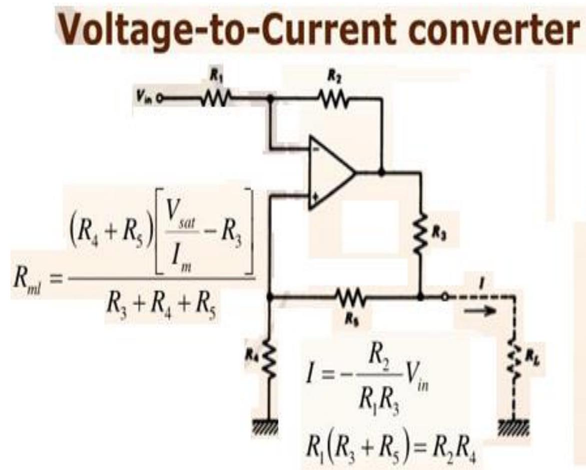


Current to voltage converter

Voltage to current converter

- In the following circuit, the current through the load resistor R_{Load} is equal to $V_{in}/(250\Omega)$.
- Hence, no matter what value of R_{Load} is, the current through it will be function of V_{in} only.





Conversion of sensor signals

Standard Signal

The 0/2 V ... 10 V voltage signal and the 0/4 mA ... 20 mA current signal have established themselves as the standard. Analog sensor signals from temperature sensors, load cells, strain gauges, resistance measuring bridges, as well as digital frequency signals, are converted into one of the two standard signals for processing in a wide variety of measurement, regulatory and control tasks. This offers the measurement and control technician an easy-to measure standard signal common to all manufacturers. Measurement value signals are converted into standard signals in so-called signal converters.

Figure shows a signal converter (A) which converts a resistance signal into a standard signal for further processing in control (B). If the sensor and signal converter form a single unit, they are referred to as a transmitter. The sensor characteristic curve is assigned to the standard signal in the transmitter signal converter. The start of the measurement value (0 %) is assigned to the 0/4 mA or 0/2 V signal, while the end of the measurement value (100 %) is assigned accordingly to the 20 mA or 10 V signal. This scaling can also be carried out in the control with simple sensors.

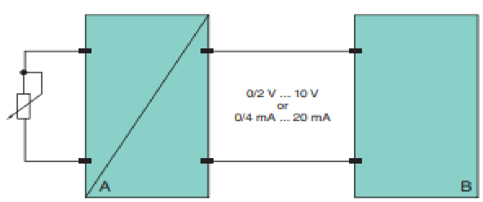


Figure: Conversion of sensor signals into standard signals

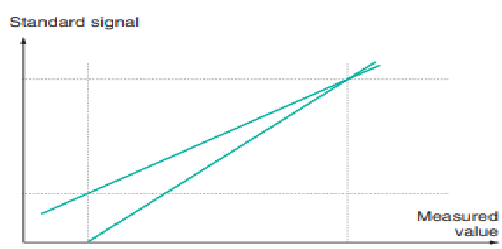


Figure: Assignment of measured values to standard signals

Frequency Current Conversion

- If the rotational speed is to be measured and processed in a control application, then conversion to a standard signal is normally required.
- Figure shows the conversion to a 0/4 mA ... 20 mA standard signal. However, it can also be converted to a 0/2 V … 10 V standard signal.

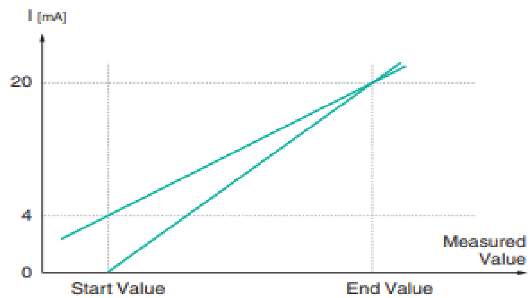


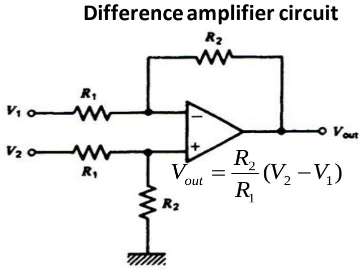
Figure: Frequency current conversion

AMPLIFICATION

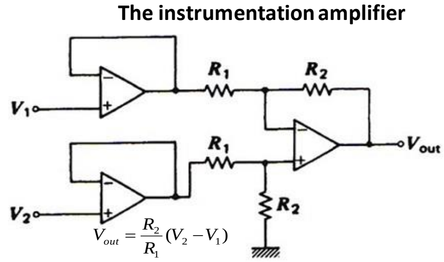
Amplifying: Signal amplification is the process of increasing the signal for processing or digitization. There are two ways that signal amplification can be performed; by increasing the resolution of the input signal, or by increasing the signal-to-noise ratio. Signal conditioning uses a range of different amplifiers for different purposes, including instrumentation amplifiers, which are optimised for use with DC signals, and are characterized by high input impedance, high common mode rejection ratio (CMRR), and high gain. Another example of a signal conditioner used for amplification would be an isolation amplifier, which is designed to isolate high DC levels from the device while passing small AC or differential signal.

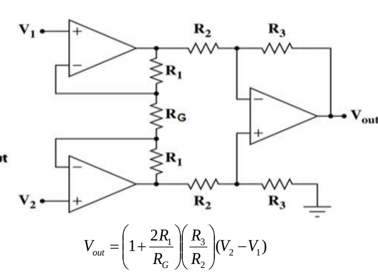
In signal conditioning, it is sometimes required to find the difference between two signals. This can be achieved using the following difference amplifier circuit. The input impedances of the difference amplifier can be relatively low and, hence, tend to load the sensor output. To have high input impedance, the difference amplifier is preceded by two voltage follower circuits to form the so-called *instrumentation amplifier*. One disadvantage of the previous differential circuit is that in order to change the gain, 2 pairs of resistors need to be changed. A more common differential amplifier in which the gain can be adjusted using one resistor (R_G) is shown below.

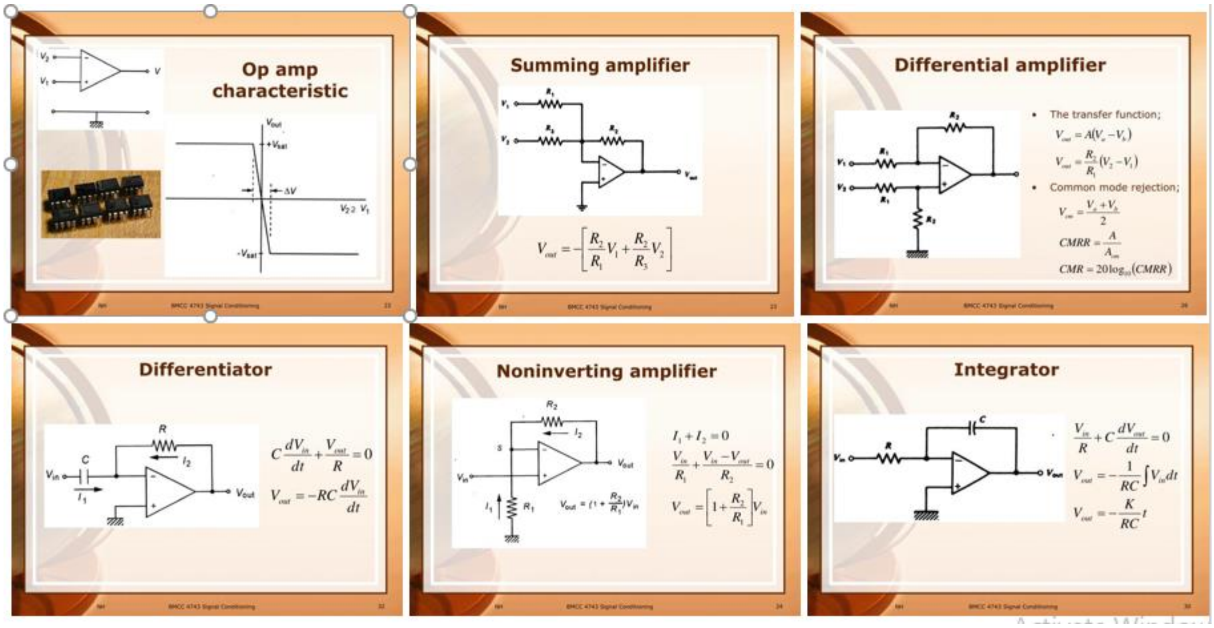
Difference amplifier circuit



The instrumentation amplifier

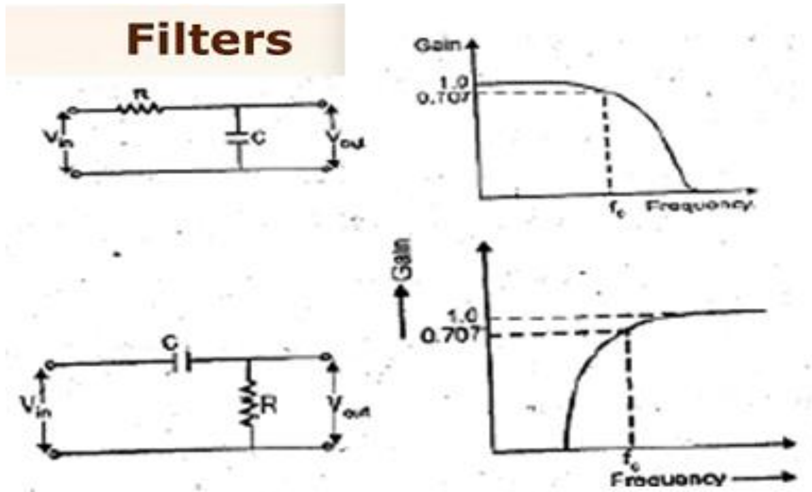






FILTERS

A network designed to attenuate certain frequencies but pass others without attenuation is called a filter. In measurement system the transducers often does not measure the physical parameter precisely. The information present is not in standard form, the need for further filtering and analysis. Filters can be designed to reject signals over specific desired frequency ranges like low pass filters, high pass filters, notch filters etc. The filter circuits can be implemented by using only resistors, capacitors and inductors called passive filters or using active devices such as transistors, op-amps called active filters. The passive low pass filter (LPF), high pass filter (HPF) and their respective frequency response curves. For LPF at low frequencies the capacitive reactance is very high and the capacitor circuit can be considered as an open circuit. Under this condition, the output equals the input or voltage gain is equal to unity. At very high frequencies, the capacitive reactance is very low and the output voltage v is small as compared to the input voltage V Hence as the frequency is increased the gain falls and drops off gradually. In high pass filter at low frequencies the capacitive reactance is high, the output is minimum and the gain is small. When frequency is high, the capacitive reactance is small; the output equals the input and. the gain approaches unity. Hence this circuit passes high frequencies while rejects low frequencies. The cut-off frequency for LPF or, HPF is given by



$$\omega_C = \frac{1}{RC} \qquad f_c = \frac{1}{2\pi RC}$$

Filter:

It is a circuit that is designed to pass signals with desired frequencies and reject or attenuate others

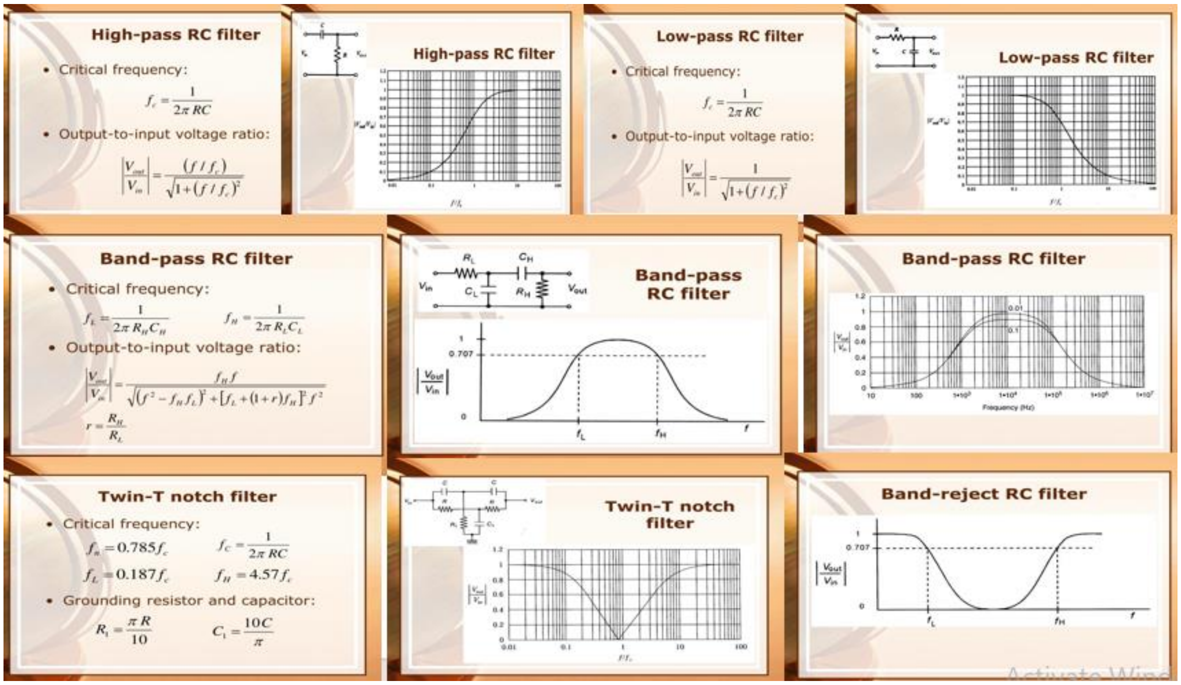
Types of filters:

Low-pass filter: passes low frequencies and stops high frequencies

High-pass filter: passes high frequencies and rejects low frequencies

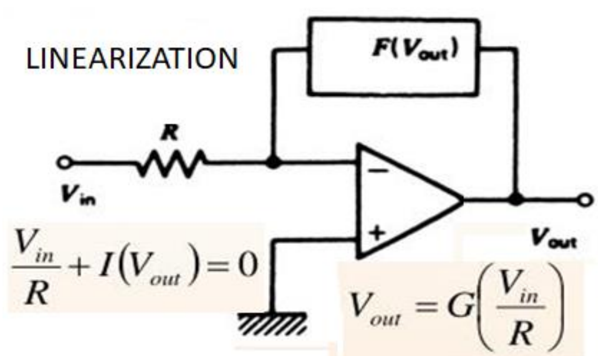
Band-pass filter: passes frequencies within a frequency band and blocks or attenuates frequencies outside the band

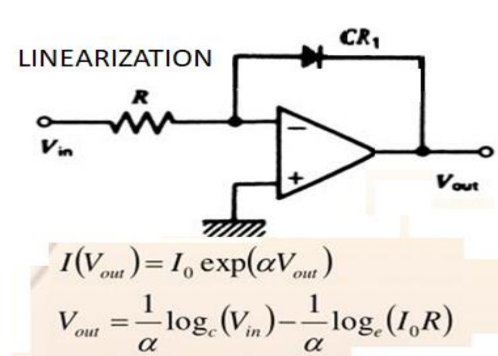
Band-reject filter: passes frequencies outside a frequency band and blocks or attenuates frequencies within the band



LINEARIZATION

- Linearization In many cases, the proportionality that exists between the input variable t& the transducer and its output signal, is non-linear. The readouts or recorders f systems ate generally designed to respond to signals which were assumed to be 'linear, so the actual nonlinearities cause errors in the measured data. To reduce these errors, the out of the transducer can be linearized, before it is passed into instruments and recorders. This can be done either with analog circuitry or by a computer. In analog linearization, the signal is passed through a circ that has a response which is the inverse of the transducer. Example, if the transducer has an exponential response, its output signal might be passed through an amplifier circuit that h logarithmic response, producing an output that is the linear of the measured variable. Alternatively, the signal could be dig after which a digital computer could be used to generate logarithm of the input signal.





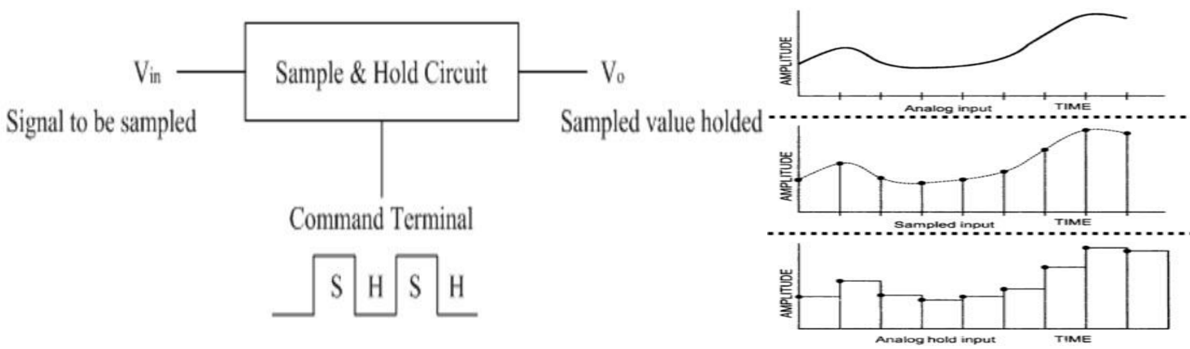
Sample and Hold Circuit

A Sample and Hold Circuit, sometimes represented as S/H Circuit or S & H Circuit, is usually used with an Analog to Digital Converter to sample the input analog signal and hold the sampled signal, hence the name 'Sample and Hold'.

In the S/H Circuit, the analog signal is sampled for a short interval of time, usually in the range of 10µS to 1µS. After this, the sampled value is hold until the arrival of next input signal to be sampled. The duration for holding the sample will be usually between few milliseconds to few seconds.

Need for Sample and Hold Circuits

- If the input analog voltage of an ADC changes more than ±1/2 LSB, then there is a severe chance that the output digital value is an error. For the ADC to produce accurate results, the input analog voltage should be held constant for the duration of the conversion.
- As the name suggests, a S/H Circuit samples the input analog signal based on a sampling command and holds the output value at its output until the next sampling command is arrived.
- The following image shows the input and output of a typical Sample and Hold Circuit.



Simple Sample and Hold Circuit

- Let us understand the operating principle of a S/H Circuit with

the help of a simplified circuit diagram.

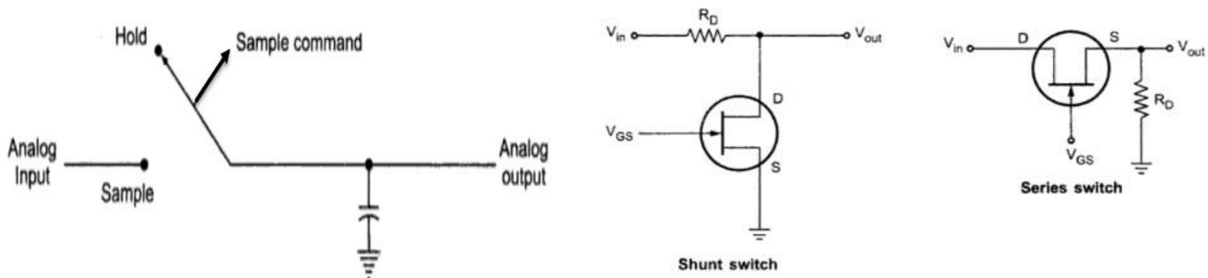
- This sample and hold circuit consist of two basic components:
- Analog Switch and Holding Capacitor

The following image shows the basic S/H Circuit.

- This circuit tracks the input analog signal until the sample command is changed to hold command. After the hold command, the capacitor holds the analog voltage during the analog to digital conversion.

Analog Switch

- Any FET like JFET or MOSFET can be used as an Analog Switch. The Gate-Source voltage VGS is responsible for switching the JFET.
- When VGS is equal to 0V, the JFET acts as a closed switch as it operates in its Ohmic region.
- When VGS is a large negative voltage (i.e. more negative than VGS(OFF)), the JFET acts as an open switch as it is cut-off.
- The switch can be either a Shunt Switch or a Series Switch, depending on its position with respect to input and output.
- The following image shows a JFET configured as both a Shunt Switch and as a Series Switch.



Types of Sample and Hold Circuits

Let us now see a few different types of Sample and Hold circuits. Note that all the below mentioned circuits use JFET as the switch. During the sampling period, the JFET is turned ON and the charging in the holding capacitor rises to the level of the input analog voltage. At the end of the sampling period, the JFET is turned OFF and the holding capacitor is isolated from the input signal. This makes sure that the output voltage is held constant at the value of the input voltage irrespective of minor changes in the input value.

To compensate for the low drop-out voltage across the holding capacitor, two buffers (voltage followers) are used, one at the input and one at the output. Keeping this in mind, let us take a look at the first S/H Circuit. The following image shows an open-loop type S/H Circuit. As there is no feedback, this circuit is relatively faster than the coming circuits (which all are in closed-loop configuration). But the feedback in the closed-loop architectures provide higher accuracy figures. The acquisition time (discussed in the next section) must be as low as possible. It is dependent on three factors:

The RC time constant, where R is the ON Resistance of the JFET (ron) and C is the holding capacitor CH.

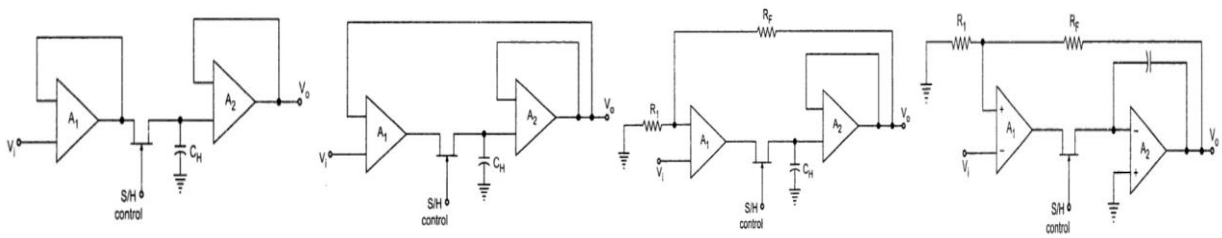
Maximum output current

Slew-rate of the Op-Amp

A slightly improved circuit than the first one is presented in the next circuit. In this configuration, the ON Resistance of the JFET is brought into the feedback loop and hence, the acquisition time is dependent on the other two factors. The next circuit is further improved when compared to the previous circuit by providing voltage gain. The voltage gain of the circuit can be calculated using the input resistor R1 and the feedback resistor RF as follows:

$A = 1 + (R_F / R_1)$

The final circuit offers additional advantages than the previous circuit. The important one is that the position of the holding capacitor is changed and as a result, the voltage at non-inverting terminal of A_2 is equal to the voltage across the capacitor divided by the open-loop gain of A_2. This ensure a faster charging time of the holding capacitor and subsequently a shorter acquisition time.



Performance Parameters

The performance of an S/H Circuit can be characterized by parameters that are commonly used for an amplifier like Input Offset Voltage, Gain Error, Non-linearity and so on. But there are a few characteristics that are specific to the S/H Circuits. These characteristics are helpful in analyzing its performance during the transition from sampling mode to hold mode (and vice versa) and also during hold mode operations. Let us understand these characteristics with the help of the following image.

Acquisition Time (t_{ac})

The time required for the charge in the holding capacitor to rise up to a level that is close to the input voltage during the sampling is called acquisition time. It is affected by three factors: The RC Time Constant, The Slew-Rate of the Op-Amp and The maximum output current of the Op-Amp

Aperture Time (t_{ap}): The time delay between the initiation of V_o tracking the V_i and the initiation of the hold command is called the Aperture Time. This delay is usually due to the propagation delays through the driver and the switch circuits.

For a precise timing operation, the hold command must be initiated in advance by an amount of aperture time.

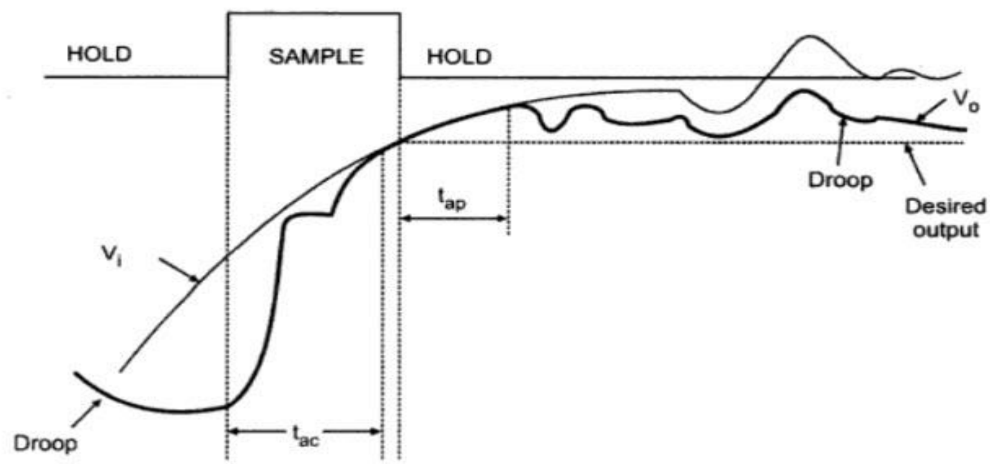
Aperture Uncertainty (Δ t_{ap}): The Aperture time will not be the same for all the sample and will vary from sample to sample. This uncertainty is called Aperture Uncertainty. This will severely affect the advancing of the hold command.

Hold Mode Settling Time (t_s): The hold mode settling time is the time taken by the output V_o to settle within the specified error band (usually 1%, 0.1% or 0.01%) after the application of hold command.

Hold Step : During the switching from sample mode to hold mode, there might an unwanted transfer of charge between the switch and the holding capacitor (mainly due to the parasitic capacitances). This will affect the capacitor voltage as well as the output voltage. This change in the output voltage from the desired voltage is called Hold Step.

Feedthrough: Again, the parasitic capacitances in the switch may cause AC coupling between V_o and V_i in hold mode. As a result, the output voltage may vary with changes in the input voltage and this is referred to as feedthrough.

Droop: Voltage Droop is a phenomenon where the voltage across the holding capacitor drops down due to leakage currents



Advantages

The main and important advantage of a typical SH Circuit is to aid an Analog to Digital Conversion process by holding the sampled analog input voltage.

In multichannel ADCs, where synchronization between different channels is important, an SH circuit can help by sampling analog signals from all the channels at the same time.

In multiplexed circuits, the crosstalk can be reduced with an SH circuit.

Applications of Sample and Hold Circuit

Some of the important applications are mentioned below:

Analog to Digital Converter Circuits (ADC)

Digital Interface Circuits

Operational Amplifiers

Analog De-multiplexers

Data distribution systems

Storage of outputs of multiplexers

Pulse Modulation Systems

Quantization

The digitization of analog signals involves the rounding off of the values which are approximately equal to the analog values. The method of sampling chooses a few points on the analog signal and then these points are joined to round off the value to a near stabilized value. Such a process is called as **Quantization.**

Quantizing an Analog Signal

The analog-to-digital converters perform this type of function to create a series of digital values out of the given analog signal. The following figure represents an analog signal. This signal to get converted into digital, has to undergo sampling and quantizing. The quantizing of an analog signal is done by discretizing the signal with a number of quantization levels.

Quantization is representing the sampled values of the amplitude by a finite set of levels, which means converting a continuous-amplitude sample into a discrete-time signal. The following figure shows how an analog signal gets quantized. The blue line represents analog signal while the brown one represents the quantized signal.

Both sampling and quantization result in the loss of information. The quality of a Quantizer output depends upon the number of quantization levels used. The discrete amplitudes of the quantized output are called as **representation levels** or **reconstruction levels**. The spacing between the two adjacent representation levels is called a **quantum** or **step-size**.

The following figure shows the resultant quantized signal which is the digital form for the given analog signal. This is also called as **Stair-case** waveform, in accordance with its shape.

Quantization, is the process of mapping input values from a large set (often a continuous set) to output values in a (countable) smaller set, often with a finite number of elements. Rounding and truncation are typical examples of quantization processes.

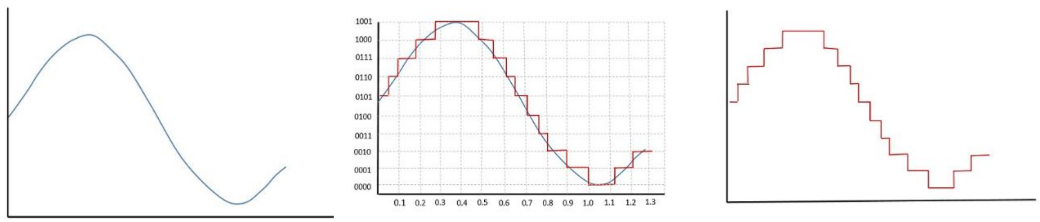
Quantization is involved to some degree in nearly all digital signal processing, as the process of representing a signal in digital form ordinarily involves rounding.

Quantization also forms the core of essentially all lossy compression algorithms. The difference between an input value and its quantized value (such as round-off error) is referred to as **quantization error**. A device or algorithmic function that performs quantization is called a **quantizer**. An analog-to-digital converter is an example of a quantizer.

Analog-to-digital converter[edit]

An analog-to-digital converter (ADC) can be modeled as two processes: sampling and quantization. Sampling converts a time-varying voltage signal into a discrete-time signal, a sequence of real numbers. Quantization replaces each real number with an approximation from a finite set of discrete values. Most commonly, these discrete values are represented as fixed-point words. Though any number of quantization levels is possible, common word-lengths are 8-bit (256 levels), 16-bit (65,536 levels) and 24-bit (16.8 million levels).

Quantizing a sequence of numbers produces a sequence of quantization errors which is sometimes modeled as an additive random signal called **quantization noise** because of its stochastic behavior. The more levels a quantizer uses, the lower is its quantization noise power.



Types of Quantization

There are two types of Quantization - **Uniform Quantization and Non-uniform Quantization**.

The type of quantization in which the quantization levels are uniformly spaced is termed as a **Uniform Quantization**.

The type of quantization in which the quantization levels are unequal and mostly the relation between them is logarithmic, is termed as a **Non-uniform Quantization**.

There are two types of uniform quantization. They are Mid-Rise type and Mid-Tread type.

Figure 1 shows the mid-rise type and figure 2 shows the mid-tread type of uniform quantization.

- The **Mid-Rise** type is so called because the origin lies in the middle of a raising part of the stair-case like graph. The quantization levels in this type are even in number.
- The **Mid-tread** type is so called because the origin lies in the middle of a tread of the stair-case like graph. The quantization levels in this type are odd in number.
- Both the mid-rise and mid-tread type of uniform quantizers are symmetric about the origin.

Quantization Error

For any system, during its functioning, there is always a difference in the values of its input and output. The processing of the system results in an error, which is the difference of those values.

The difference between an input value and its quantized value is called a **Quantization Error**. A **Quantizer** is a logarithmic function that performs Quantization rounding off the value. An analog-to-digital converter (**ADC**) works as a quantizer. The following figure illustrates an example for a quantization error, indicating the difference between the original signal and the quantized signal.

Quantization Noise

It is a type of quantization error, which usually occurs in analog audio signal, while quantizing it to digital. For example, in music, the signals keep changing continuously, where a regularity is not found in errors. Such errors create a wideband noise called as **Quantization Noise**.

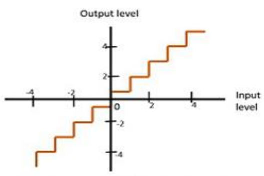


Fig 1 : Mid-Rise type Uniform Quantization

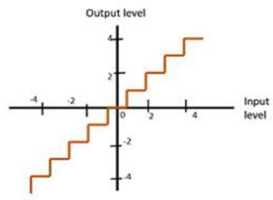
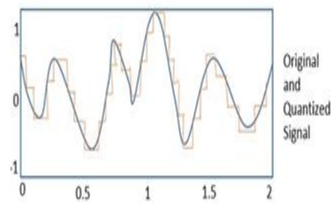
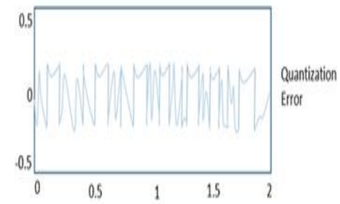


Fig 2 : Mid-Tread type Uniform Quantization





Mutliplexer

A Multiplexer is a circuit that accept many inputs but gives only one output. A Demultiplexer functions exactly in the reverse way of a multiplexer i.e., a demultiplexer accepts only one input and gives many outputs. Generally, multiplexer and demultiplexer are used together in many communication systems.

Multiplexer means many into one. A multiplexer is a circuit used to select and route any one of the several input signals to a single output. A simple example of an non-electronic circuit of a multiplexer is a single pole multi-position switch.

Multi-position switches are widely used in many electronics circuits. However, circuits that operate at high speed require the multiplexer to be automatically selected. A mechanical switch cannot perform this task efficiently. Therefore, multiplexer is used to perform high speed switching are constructed of electronic components.

Multiplexers can handle two type of data i.e., analog and digital. For analog application, multiplexer are built using relays and transistor switches. For digital application, they are built from standard logic gates.

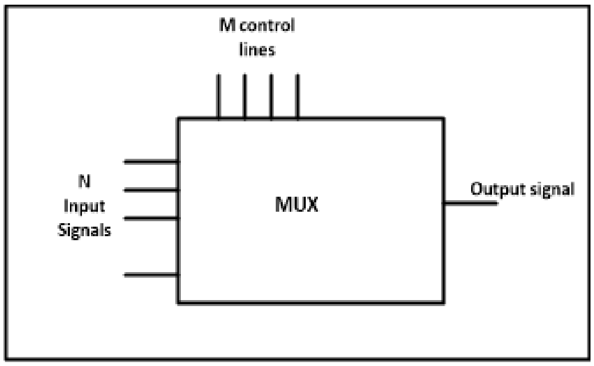
The multiplexer used for digital applications, also called digital multiplexer, is a circuit with many input but only one output. By applying control signals (also known as Select Signals), we can steer any input to the output. Some of the common types of multiplexer are 2-to-1, 4-to-1, 8-to-1, 16-to-1 multiplexer. Following figure shows the general idea of a multiplexer with n input signal, m control signals and one output signal.

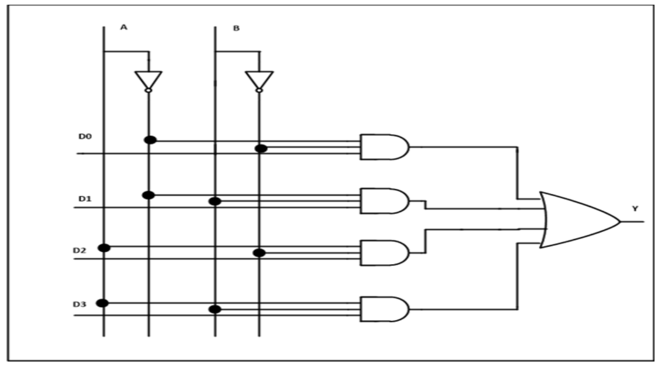
Understanding 4-to-1 Multiplexer

The 4-to-1 multiplexer has 4 input bits, 2 control or select bits, and 1 output bit. The four input bits are D0,D1,D2 and D3. Only one of this is transmitted to the output Y. The output depends on the values of A and B, which are the control inputs. The control input determines which of the input data bit is transmitted to the output.

For instance, as shown in figure, when A B = 0 0 , the upper AND gate is enabled, while all other AND gates are disabled. Therefore, data bit D0 is transmitted to the output, giving Y = Do. If the control input is changed to A B = 1 1 , all gates are disabled except the bottom AND gate. In this case, D3 is transmitted to the output and Y = D3.

- An example of 4-to-1 multiplexer is IC 74153 in which the output is same as the input, 45352 in which the output is the compliment of the input. Example of 16-to-1 line multiplexer is IC 74150.





Applications of Multiplexer: Multiplexer are used in various fields where multiple data need to be transmitted using a single line. Following are some of the applications of multiplexers –

1. **Communication System** – Communication system is a set of system that enable communication like transmission system, relay and tributary station, and communication network. The efficiency of communication system can be increased considerably using multiplexer. Multiplexer allow the process of transmitting different type of data such as audio, video at the same time using a single transmission line.

2. **Telephone Network** – In telephone network, multiple audio signals are integrated on a single line for transmission with the help of multiplexers. In this way, multiple audio signals can be isolated and eventually, the desire audio signals reach the intended recipients.

3. **Computer Memory** – Multiplexers are used to implement huge amount of memory into the computer, at the same time reduces the number of copper lines required to connect the memory to other parts of the computer circuit.

4. **Transmission from the Computer System of a Satellite** – Multiplexer can be used for the transmission of data signals from the computer system of a satellite or spacecraft to the ground system using the GPS (Global Positioning System) satellites.

Demultiplexer

Demultiplexer means one to many. A demultiplexer is a circuit with one input and many outputs. By applying control signal, we can steer any input to the output. Few types of demultiplexer are 1-to 2, 1-to-4, 1-to-8 and 1-to 16 demultiplexer.

Following figure illustrate the general idea of a demultiplexer with 1 input signal, m control signals, and n output signals.

Understanding 1-to-4 Demultiplexer

The 1-to-4 demultiplexer has 1 input bit, 2 control or select bits, and 4 output bits. An example of 1-to-4 demultiplexer is IC 74155. The 1-to-4 demultiplexer is shown in figure below-

The input bit is labelled as Data D. This data bit is transmitted to the selected output lines, which depends on the values of A and B, the control or Select Inputs.

When A B = 0 1 , the second AND gate from the top is enabled while other AND gates are disabled. Therefore, data bit D is transmitted to the output Y1, giving Y1 = Data.

If D is LOW, Y1 is LOW. If D is HIGH, Y1 is HIGH. The value of Y1 depends upon the value of D. All other outputs are in low state.

If the control input is changed to A B = 1 0 , all the gates are disabled except the third AND gate from the top. Then, D is transmitted only to the Y2 output, and Y2 = Data.

Example of 1-to-16 demultiplexer is IC 74154. It has 1 input bit, 4 control / select bits and 16 output bit.

Applications of Demultiplexer

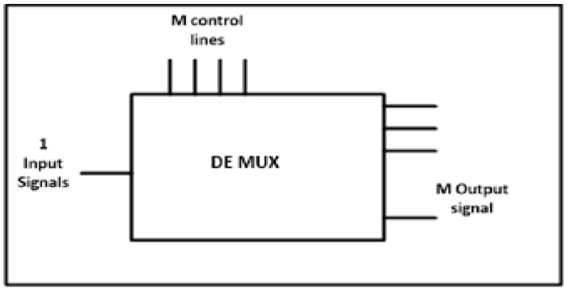
1. Demultiplexer is used to connect a single source to multiple destinations. The main application area of demultiplexer is communication system, where multiplexers are used. Most of the communication system are bidirectional i.e., they function in both ways (transmitting and receiving signals). Hence, for most of the applications, the multiplexer and demultiplexer work in sync. Demultiplexer are also used for reconstruction of parallel data and ALU circuits.

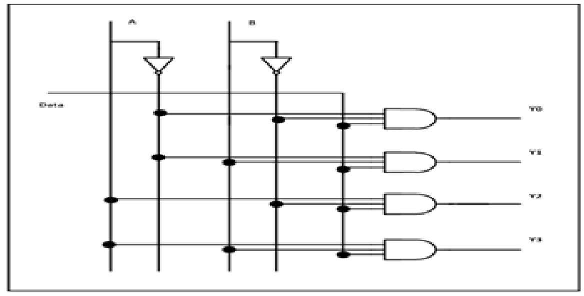
2. **Communication System** – Communication system use multiplexer to carry multiple data like audio, video and other form of data using a single line for transmission. This process make the transmission easier. The demultiplexer receive the output signals of the multiplexer and converts them back to the original form of the data at the receiving end. The multiplexer and demultiplexer work together to carry out the process of transmission and reception of data in communication system.

3. **ALU (Arithmetic Logic Unit)** – In an ALU circuit, the output of ALU can be stored in multiple registers or storage units with the help of demultiplexer. The output of ALU is fed as the data input to the demultiplexer. Each output of demultiplexer is connected to multiple register which can be stored in the registers.

4. **Serial to Parallel Converter** – A serial to parallel converter is used for reconstructing parallel data from incoming serial data stream. In this technique, serial data from the incoming serial data stream is given as data input to the demultiplexer at the regular intervals. A counter is attach to the control input of the demultiplexer. This counter directs the data signal to the output of the demultiplexer where these data signals are stored. When

all data signals have been stored, the output of the demultiplexer can be retrieved and read out in parallel.





Current to Pressure Converter

Current to Pressure Converter works on flapper nozzle method. The input is 4 to 20mA signal and the equivalent output is 3 to 15 PSI pressure.

In the Current to Pressure converter, we usually give input current signal as 4 – 20 mA . We also give a continuous supply of 20 P.S.I to the Flapper Nozzle assembly. As we give input current signal, Electromagnet gets activated.

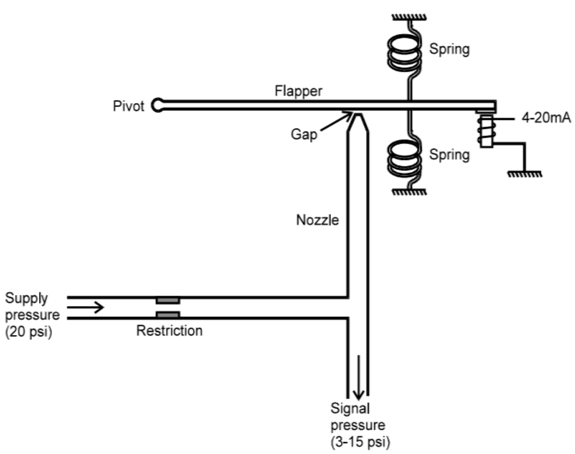
If the current is more, then the power of magnet will get increased. The Flapper of the Flapper-Nozzle instrument is connected to Pivot so that it can move up and down and a magnetic material was attached to other end of flapper and it is kept near the electromagnet.

As the magnet gets activated. the flapper moves towards the electromagnet and the nozzle gets closed to some extent. So some part of 20 P.S.I supplied will escape through nozzle and remaining pressure will come as output.

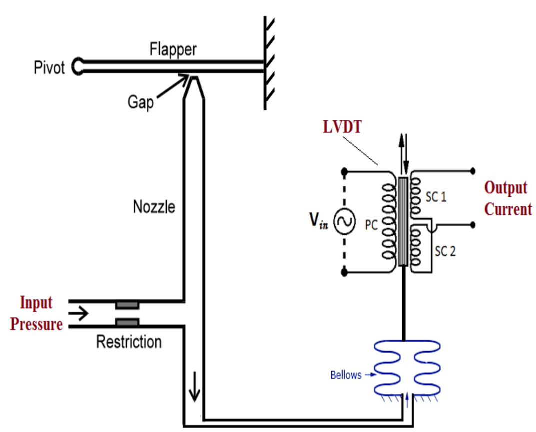
If the current signal is high, then power of the magnet will increase, then flapper will move closer to the nozzle, so less pressure will escape through nozzle and output pressure increases.

In this way the output pressure will be proportional to the input current.

For the input current of 4 – 20 mA we can get the output pressure of 3 – 15 P.S.I



Principles of a current-to-pressure converter



Principles of Pressure to Current Converter

Pressure to Current (P/I) Converter Principle

We can construct a **pressure to current converter** using a Flapper- Nozzle arrangement , Bellows and a Linear Variable Differential Transformer (LVDT) circuit.

Input pressure is given to Flapper-Nozzle arrangement and the output current will come through the LVDT.

Flapper Nozzle arrangement: It is type of pressure controlling device. It controls the input pressure by the moving the Flapper away or towards the nozzle, if we need high pressure, then nozzle will be closed by the Flapper and if we need less pressure, then nozzle will be opened by moving flapper away.

Bellows:- Bellows are one type of pressure measuring devices. They are the elements which will expand as per the applied pressure. Based on the displacement we can measure the pressure.

Linear Variable Differential Transformer (LVDT): It works on the principle of Mutual Inductance. In the LVDT three coils will be present. Primary coil is connected to a power source and secondary coils are connected in series opposition method.

At initial position, the voltage induced will be zero. If the core displaces, then due to inductance, voltage will be induced into the coils, resulting in the current.

Pressure to Current Converter

First Input pressure is supplied to the Flapper- Nozzle arrangement. Then it will supplied through a pipe and that pressure is given as input to the bellows. These bellows are connected to the Core of LVDT.

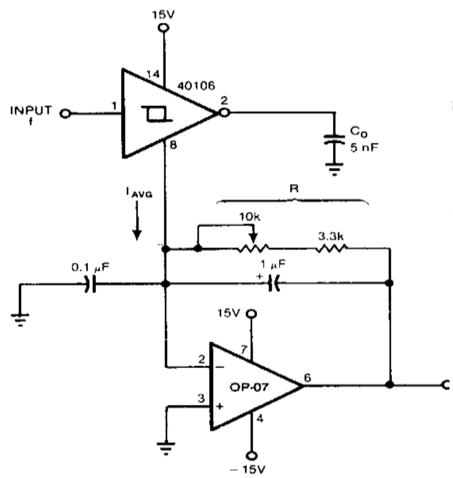
When pressure is applied to bellows, they will expand thus core displaces and the voltage is induced on the secondary coils of LVDT.

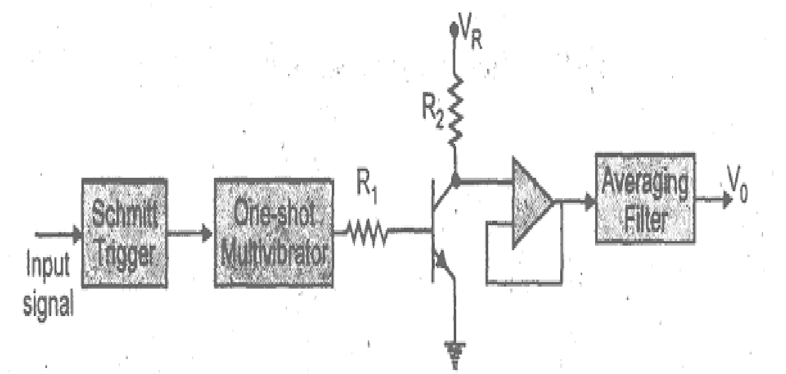
As voltage is induced, current will flow through the coil. That current is proportional to the input pressure applied. Thus Pressure is converted into equivalent current.

When compared with standard values we can covert 3-15 P.S.I of pressure can be converted to 4-20 mA of current

Frequency to voltage converter

Frequency to voltage converter is an electronic device which converts the sinusoidal input frequency into a proportional current or output voltage. The basic circuit includes operational amplifiers and RC circuits (Resistor Capacitor networks). The operational amplifiers are used for signal processing. And the RC networks are used to remove the frequency dependent ripples. The diagram below shows the basic circuit of frequency to voltage converter using op-amp and RC networks:The input frequency given to this converter can be in the range of 0-10 kHz. And the output can be between 0 to -10 V. The block diagram shows a frequency to voltage converter. The circuit charges the capacitor to a certain level. An integrator is connected in it and the capacitor discharges into this integrator or a low pass circuit. This happens for all the cycles of the input waveform. The precision switch and the monostable multivibrator generate a pulse of a specific amplitude and period which is fed into the averaging network. Hence we get a DC voltage at the output.





Block Diagram of F-V converter

This is the circuit diagram of frequency to voltage converter using LM331.

This IC is basically a voltage to frequency converter but it can be used as a frequency to voltage converter. Its applications also include A to D conversion and long term integration.

FV converter WORKING

In this circuit, lm331 is used to convert frequency into voltage. The voltage on the output is proportional to the frequency at the input. It is an 8 pins IC. The source is connected to pin 8 and supplies 15V DC. Pins 3 and 4 are connected to ground. The input frequency is given at pin 6 and the output voltage is taken from pin 1. The input frequency is differentiated by using the resistor R7 and capacitor C3 and then the resultant pulse train goes to pin 6. The timer circuit gets triggered by the built-in comparator circuit in the IC when the negative edge of the pulse train appears at pin 6.

The current flowing out of pin 6 is proportional to the values of capacitor C1 and resistor R1 (which are also known as the timing components) and the input frequency. Therefore we get the output voltage across the resistor R4 which is proportional to the frequency of the input. 15V DC is used in this circuit but the operating voltage of IC can be between 5 volts to 30 volts DC. The value of the resistor R3 is dependent upon the supply voltage.

APPLICATIONS OF F-V CONVERTERS

These converters are used in wide range of applications such as communication, power control, measurement and instrumentation systems etc. The applications are:

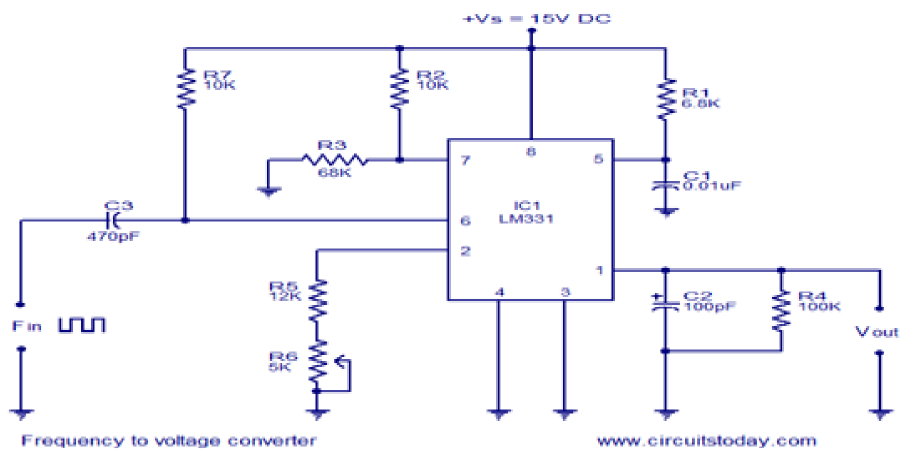
1. Frequency to voltage converter in tachometers. 2. Frequency difference measurement.

F/V CONVERTER AND DIGITAL TACHOMETER

A digital tachometer is an electronic device which measures the rate of rotation of a wheel. They display the rate of rotation in the form of voltage which is why a frequency to voltage converter is required in them. The diagram below shows a digital tachometer.

A digital tachometer

The rate of occurrence of some events can be measured by a rate meter. It counts the events for a certain time period and then divides the number of events by the total time and hence we get a rate. This is the theory of operation of a simple tachometer. We are using an IC LM2907 for this tachometer circuit. It is an 8 pins IC. At pin 1 we apply a frequency signal at the charge pump's input. At pin 2 the voltage will be between two values that are ¼ (V_{CC}) – V_{BE} and ¾ (V_{CC}) – V_{BE}. The diagram below shows the configuration of the IC LM2907:The capacitors C1 and C2 and the resistor R1 have specific values according to the circuit requirements. These values can be studied from the data sheet of LM2907.



F-V CIRCUIT DIAGRAM USING LM331

Interfacing of LM2907

The input signal is given at pin 1 and at pin 11 we apply a reference voltage. Pin 8 and pin 9 is supplied with a constant voltage. The op amp's inverting input is connected with the output of the emitter. We get a low impedance voltage at the pin 5 which is proportional to the given input frequency. From the pin 5 and pin 10 we get the output signal of 67 Hz/V. This output is sent to the ADC and then the DSP can read this output.

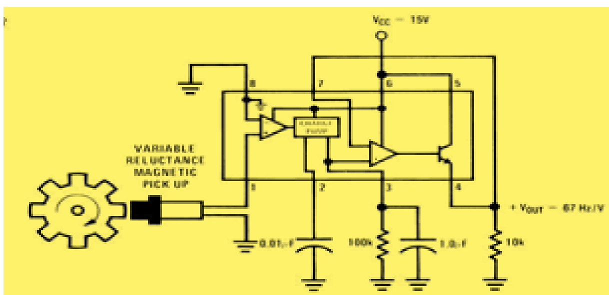
FREQUENCY DIFFERENCE MEASUREMENT

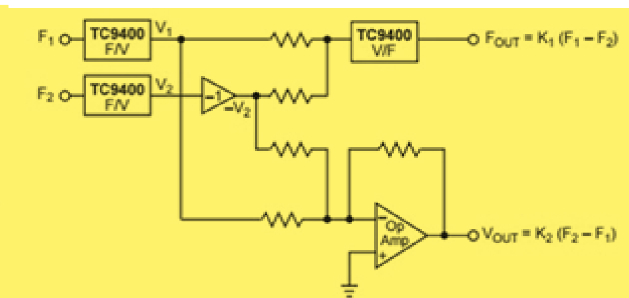
TC9400 is a frequency to voltage and voltage to frequency converter IC. Its basic circuit connections include three resistors, two capacitors and reference voltage. We can use two TC9400 ICs and operate both of them in the mode of frequency to voltage conversion in order to obtain the frequency difference measurements.

We use two converters and we get V1 and V2 as two separate outputs. A unity gain inverts the voltage V2 coming from the 2nd F/V converter. An op amp is connected which adds both the voltages V1 and the inverted –V2 voltage. This sum will be proportional to the actual frequency difference between F1 and F2.

A V/F converter is also connected in the circuit which gives the frequency output which is again proportional to the frequency difference between F1 and F2. Hence we get the frequency difference measurement in terms of frequency as well as in terms of voltages. The diagram below shows the circuit of **frequency difference measurement**.

Besides these two applications, there are numerous other applications of F/V converters such as frequency divider/multipliers, frequency decoders, frequency meters and motor speed control etc which can easily be found on several web pages.





Voltage-to-frequency Converter

A voltage-to-frequency converter (VFC) is an oscillator .Its frequency is linearly proportional to the control voltage. The voltage to frequency (VFC)/counter ADC is monotonic and free of missing codes. It integrates noise and can consume very small amount of power. The voltage to frequency converter(VFC) is also very useful for telemetry applications, since the VFC, which is cheap ,small, and low-powered can be mounted on the experimental subject (patient, artillery shell, wild animal, communication etc.) and communicate with the counter by the telemetry link as shown in Figure 1.

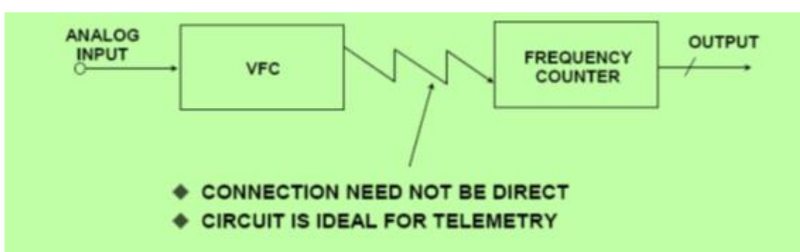
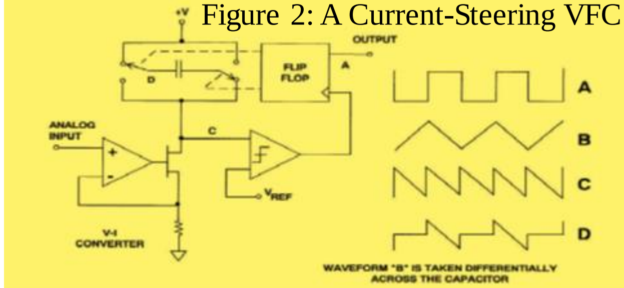


Figure 1: Voltage-to-Frequency Converters (VFC) and Frequency Counter Make a Low-Cost, Versatile, High-Resolution ADC

Voltage-to-frequency converters are sometimes needed in some instrumentation applications. In the present correspondence we shall discuss a new voltage-to-frequency converter which can obtain the excellent linearity between the input voltage and the frequency of oscillation. The linearity of this converter can be improved by adjusting the variable resistor connected to the op-Amp. There are two common VFC architectures: the current-steering multi vibrator VFC and the charge-balance VFC. The charge-balanced VFC may be made in synchronous (clocked) or asynchronous forms. There are many more VFO (variable frequency oscillator) architectures, including the 555 timer which is a unique functional building block, the key feature of VFCs is linearity, and a few VFOs are very linear.

- **A Current-Steering VFC:**
- The current-steering multi vibrator VFC is actually a current-to-frequency converter rather than a VFC, but, as shown in Figure 2, practical circuits invariably contain a voltage-to-current converter at the input side.
- The principle of operation is that: the current discharges the capacitor until the threshold is reached, and when the c terminals of the capacitor are reversed, the half-cycle is repeats itself again.
- The waveform across the capacitor is obtained a linear triangular wave, but the waveform on either terminal with respect to ground is the more complex waveform shown.
- Practical VFCs of this type have linearity around 14 bits, and comparably stable, although these may be used in ADCs without missing codes with higher resolution.
- The performance limits are set by threshold noise, comparator threshold temperature coefficient, and stability and the dielectric absorption (DA) of the capacitor, which is a discrete component.
- The comparator/voltage reference structures are shown in the diagram is more of a representation of the function performed than the actual circuit used in that diagram, which has much more integrated with the switching, and correspondingly difficult to analyze.
- This type of VFC is a simple, low-powered, and, inexpensive and mostly run for a wide range of supply voltages. They are basically suited for low cost medium accuracy ADC and data telemetry applications.

Figure 2: A Current-Steering VFC



Charge Balance Voltage-to-Frequency Converter (VFC)

The charge balance VFC shown in Figure 3 is more complex, and more accurate and more demanding in its supply voltage and current requirements, Practical VFCs of this type have linearity around 16-18 bits. Figure 3: Charge Balance Voltage-to-Frequency Converter (VFC) The integrator capacitor is charged by the signal as shown in Figure 3.

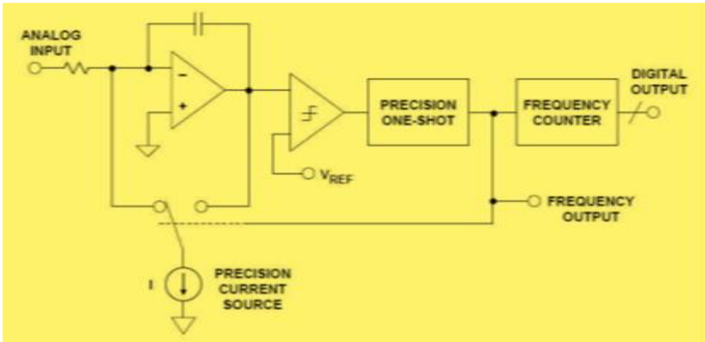


Figure 3: Charge Balance Voltage-to-Frequency Converter (VFC)

When it exceeds the comparator threshold, a fixed amount of charge is removed from the capacitor, but the input current flow continuously during discharge, therefore no input charge is lost. The fixed amount of charge is defined by the precision current source and the pulse width of the monostable. Thus the output pulse rate is accurately proportional to the rate at which the integrator charges from the input. At low frequencies, the limits on the performance of this VFC are set by the stability of the current source and the monostable timing (which only depends on the monostable capacitor, among other things). The exact value and temperature stability of the integration capacitor do not affect the accuracy, although its dielectric absorption (DA) and leakage do. At the high frequencies, the second-order effects, switching transients in the integrator and the precision of the monostable when it is retriggered very soon after a pulse is end, take their toll on the accuracy and the linearity. The changeover switch in the current source addresses the integrator transient problem.

Therefore by using a changeover switch instead of the on/off switch, more common on older VFC designs:

(a) there are no on/off transients in the precision current source and

(b) the output stage of the integrator sees a constant load, most of the time the current from the source flows directly in the output stage; but during charge balance, it still flows in the output stage, through the integration capacitor.

Data Acquisition Systems

Data Acquisition (DAQ) : Process of getting digital equivalent of analog signals (the measure of real world physical quantities) into computer for further processing

Data loggers: Records measurements of physical quantities with time stamp

Basic Functions of DAQ Systems :–

1. Analog Input : Conversion of analog signal to digital data and Transfer of converted data to computing platform using standard interface

2. Analog Output 3. Digital I/O 4. Timing I/O

A typical Data Acquisition System consists of individual sensors with the necessary signal conditioning, data conversion, data processing, multiplexing, data handling and associated transmission, storage and display systems. In order to optimise the characteristics of the system in terms of performance, handling capacity and cost, the relevant sub systems can be combined together. Analog Data Acquisition System is generally acquired and converted into digital form for the purpose of processing, transmission, display and storage.

Processing may consist of a large variety of operations, ranging from simple comparison to complicated mathematical manipulations. It can be for such purposes as collecting information (averages, statistics), converting the data into a useful form (e.g., calculations of efficiency of motor speed, torque and power input developed), using data for controlling a process, performing repeated calculations to separate signals buried in the noise, generating information for display, and various other purposes.

Data may be transmitted over long distances (from one point to another) or short distances (from test centre to a nearby PC). The data may be displayed on a digital panel or on a CRT. The same be stored temporarily (for immediate use) or permanently for ready reference later.Data acquisition generally relates to the process of collecting the input data in digital form as rapidly, accurately, and economically as necessary. The basic instrumentation used may be a DPM with digital outputs, a shaft digitiser, or a sophisticated high speed resolution device.

To match the input requirements with the output of the sensor, some form of scaling and offsetting is necessary, and this is achieved by the use of amplifier/attenuators. For converting analog information from more than one source, either additional transducers or multiplexers are employed. To increase the speed with which information is accurately converted, sample-hold circuits are used. (In some cases, for analog signals with extra-wide range, logarithmic conversion is used.) Data Acquisition System Block Diagram: A schematic block diagram of a General Data Acquisition System (DAS) is shown in Fig.

Based on the environment, a broad Classifications of data acquisition system into two categories.

1. Those suitable for favourable environments (minimum RF interference and electromagnetic induction)

2. Those intended for hostile environments

The former category may include, among other, laboratory instrument applications, test systems for collecting long term drift information on zeners, high calibration test instruments, and routine measurements in research, as mass spectrometers and lock-in amplifiers. In these, the systems are designed to perform tasks oriented more towards making sensitive measurements than to problems of protecting the integrity of analog data. The Classifications of data acquisition system specifically includes measure, protecting the integrity of the analog data under hostile conditions. Such measurement conditions arise in aircraft control systems, turbovisous in electrical power systems, and in industrial process control systems.

Most of these hostile measurement conditions require devices capable of a wide range of temperature operations, excellent shielding, redundant paths for critical measurements and considerable processing of the digital data acquisition system. On the other hand, laboratory measurements are performed over a narrow temperature range with much less electrical noise, employing high sensitivity and precision devices for higher accuracies and resolution.

The important Factors to Consider When Setting Up a Data Acquisition System are as follows.

1. Accuracy and resolution
2. Number of channels to be monitored
3. Analog or digital signal
4. Single channel or multichannel
5. Sampling rate per channel
6. Signal conditioning requirements of each channel
7. Cost

The various general Configuration of Data Acquisition System are

Single channel possibilities: Direct conversion, Pre-amplification and direct conversion, Sample and hold, and conversion, Pre-amplification, signal conditioning and any of the above

Multi-channel possibilities: Multiplexing the outputs of single channel converters, Multiplexing the output of sample-hold circuits, Multiplexing the inputs of sample-hold circuits, Multiplexing low level data

Objectives of Data Acquisition System:

- It must acquire the necessary data, at correct speed and at the correct
- Use of all data efficiently to inform the operator about the state of the
- It must monitor the complete plant operation to maintain on-line optimum and safe operations.
- It must provide an effective human communication system and be able to identify problem areas, thereby minimising unit availability and maximising unit through point at minimum cost.
- It must be able to collect, summarise and store data for diagnosis of operation and record purpose.
- It must be able to compute unit performance indices using on-line, real-time data.
- It must be flexible and capable of being expanded for future require
- It must be reliable, and not have a down time greater than 0.1%.

Single Channel Data Acquisition System:

A Single Channel Data Acquisition System consists of a signal conditioner followed by an analog to digital (A/D) converter, performing repetitive conversions at a free running, internally determined rate. The outputs are in digital code words including over range indication, polarity information and a status output to indicate when the output digits are valid.A Single Channel Data Acquisition System is shown in Fig. 17.3. The digital outputs are further fed to a storage or printout device, or to a digital computer device, or to a digital computer for analysis. The popular Digital panel Meter (DPM) is a well known example of this.

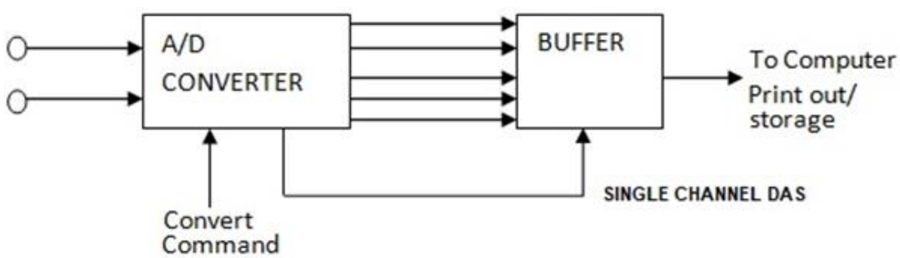
However, there are two major drawbacks in using it as a DAS.

1. It is slow and the BCD has to be changed into binary coding, if the output is to be processed by digital equipment.

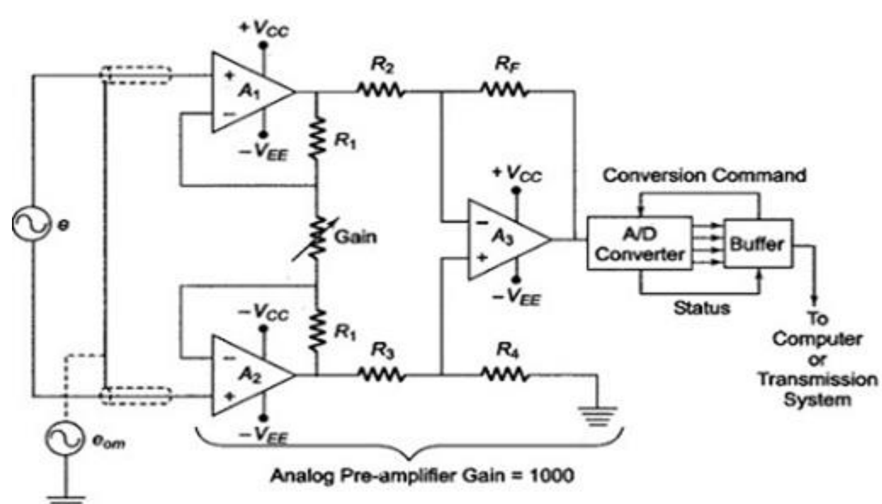
2. While it is free running, the data from the A/D converter is transferred to the interface register at a rate determined by the DPM itself, rather than commands beginning from the external interface.

Preamplification for DAS

Amplifiers can be used to improve the level of the input signal to match the converter input. This provides optimum accuracy and resolution. An arrangement for preamplification is shown in Figure.



SINGLE CHANNEL DAS



DAS with Pre-amplification

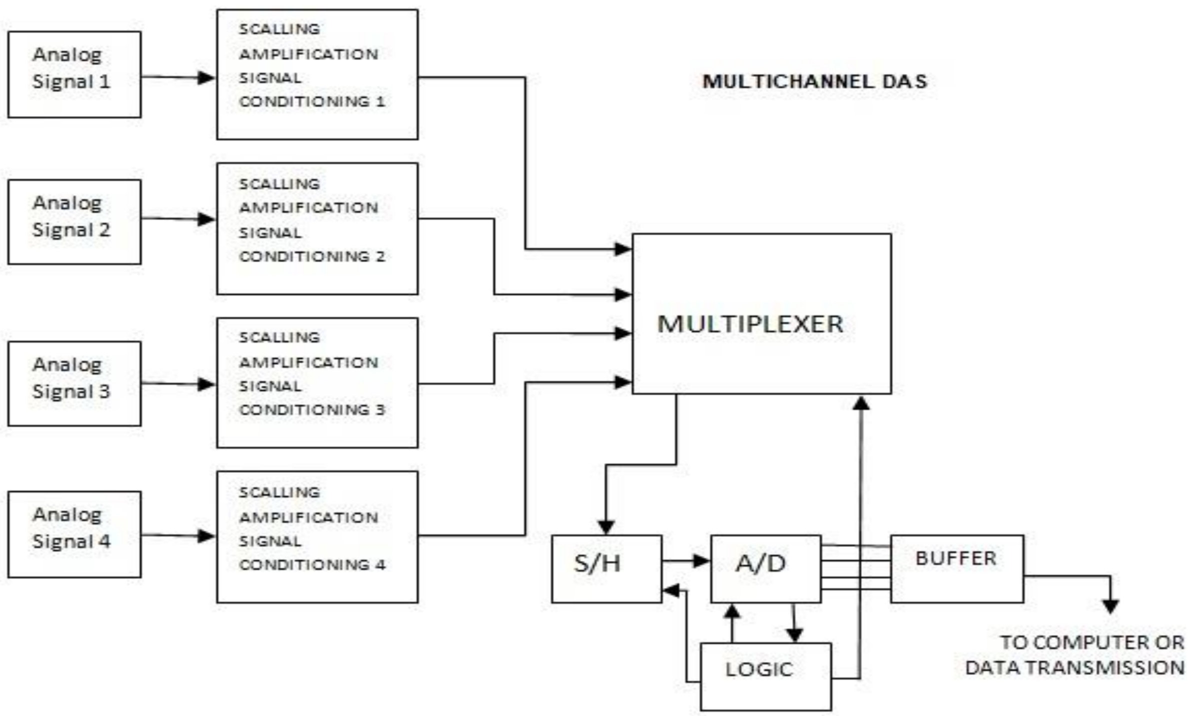
Differential amplifiers are necessary when the input signal levels are below one tenth of a mV, or when resolution of 14 bits or 16 bits. Instrumentation amplifiers are used when differential output is to be handled from a bridge network. The circuit shown in Figure, consists of three amplifier instrumentation amplifier. The output of the amplifier is given to the conditioning circuit. The accuracy, linearity and gain stability specifications must be carefully considered to see that the system has no limitations. If the input signals are to be isolated physically from the system the conductive paths are to be broken. This is done using transformer coupling or using optocoupled isolation amplifier. Such isolation is useful in handling signals from high voltage sources and transmission towers, Isolation is essential in biomedical applications. In order to eliminate noise and high frequency components the output of the preamplifiers can be fed to filters. Filters effectively compensate for transmission sensitivity loss at high frequency. Thus the dynamic range of measurement will be enhanced. To preserve the phase dependent data special filters like tracking filters are used.

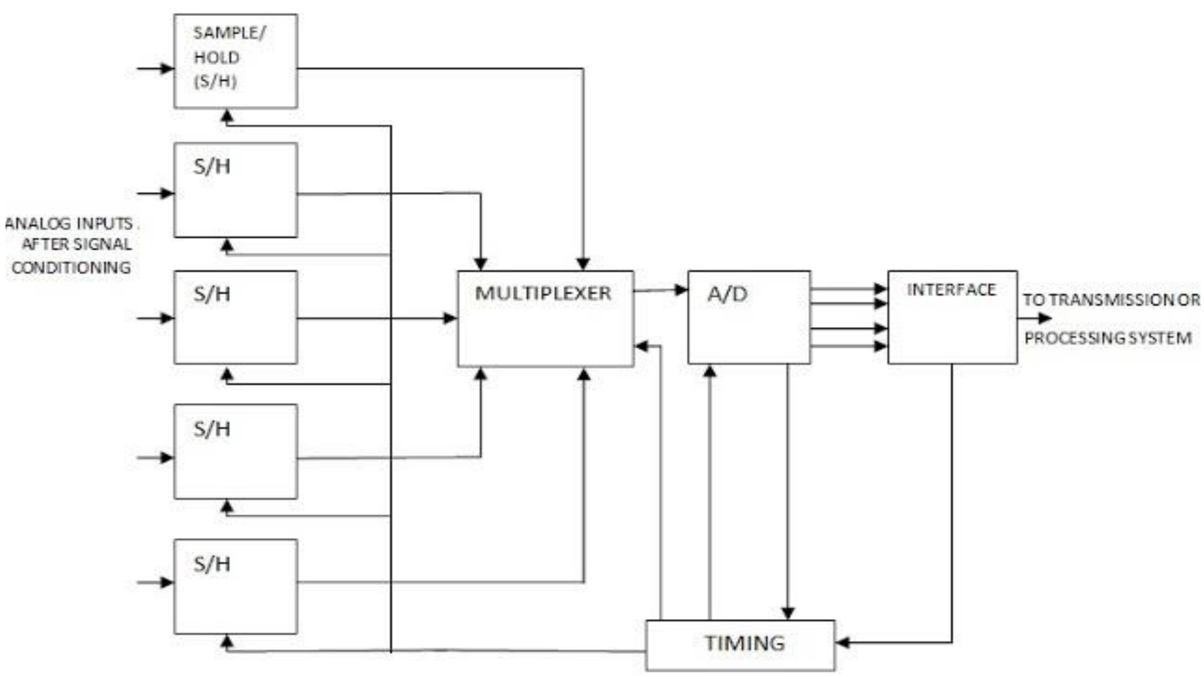
Multichannel DAS:

- There will be many subsystems in a data acquisition system. They can be time shared by two or more input sources. The numbers of techniques are used for time shared measurements depending on the desired properties of the multiplexed system. Some important techniques are explained here under.

Multichannel Analog Multiplexed System:

The multichannel DAS system is shown in Figure. It has a single A/D converter preceded by a multiplexer As can be seen from the figure there are four inputs analog in nature. There can be number of inputs. Each signal is given to individual amplifiers. The output of the amplifiers is given to Signal condition circuits. From the output of the signal conditioning circuits the signals go to the multiplexer'. The multiplexer output is converted into digital signals by the A/D converters sequentially. The multiplexer stores the data say of the first channel in the sample hold circuit. It then seeks the second channel. During this interval the data of the first channel will be converted into digital form. This permits utilization of time more efficiently. When once the conversion is complete, the status line from the converter causes the sample/hold circuit to return to the sample mode. It then accepts the signal of the next channel. After acquisition of-data either immediately or on a command the sample hold circuit will be switched to the hold mode. Now conversion begins and the multiplexer selects the next channel. This method is slow. Sample hold circuits or A/D converters are multiplexed for faster operation. However, this method is less costly as majority of subsystems are shared. If the signal variations are very slow satisfactory accuracy can be obtained even without the sample hold circuit.





Multiplexing the Outputs of Sample/hold:

This arrangement is called simultaneous sampled system multiplexer. The block diagram is shown in Figure. When large number of channels is to be monitored synchronously at moderate speeds this method is used. The analog signals after signal conditioning are supplied to individual sample hold circuits. The sample hold circuits an updated synchronously by the timing circuit. The multiplexer receives the outputs of all the sample hold circuits. The multiplexer is connected to the A/D converter. This results in a sequential readout of the outputs.

Applications:

1. Wind tunnel measurements 2. Seismographic experiments 3. Radar 4. Fire control system

Multiplexing after A/D Conversion:

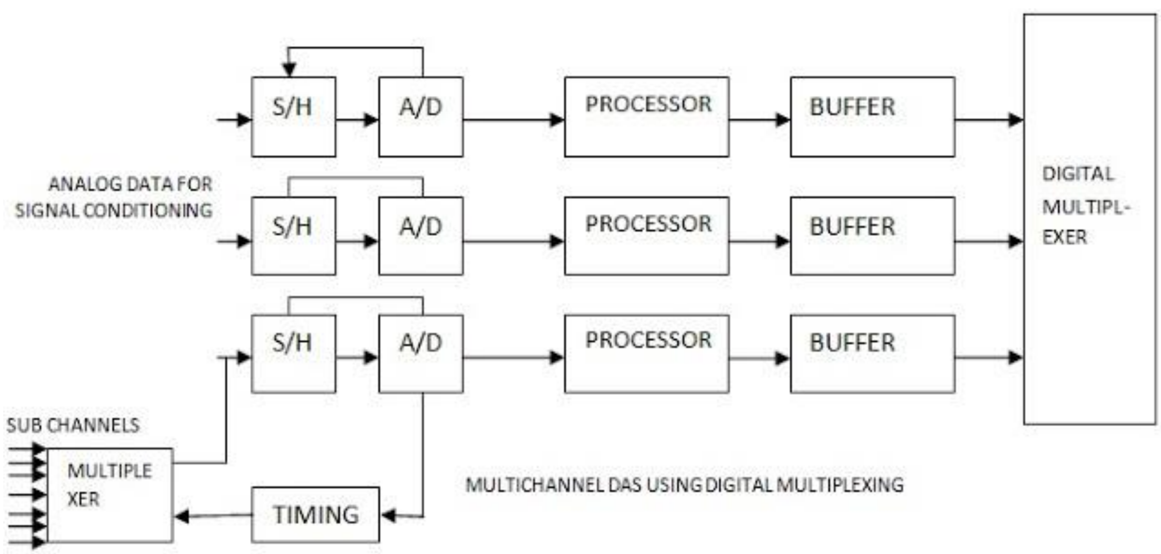
With the availability of A/D converters at considerably lower costs, it is feasible to use individual A/D converters for each analog channel. The available digital outputs of several A/D converters can be multiplexed. The advantage here is that as the A/D conversion is on individual basis, the desired conversion rates can be used on individual channels.

The parallel conversion scheme is shown in Figure. This type of scheme is advantageous in a data acquisition system that has several inputs distributed over vast plant area. The analog signals are converted into the required digital format at the source. Therefore, transmission of data to the data centre can be made without line frequency and ground loop interferences. The data in the digital form will be used to perform logic operations and decisions. Depending on the relative speed at which data changes take place scanning rate can be increased or decreased.

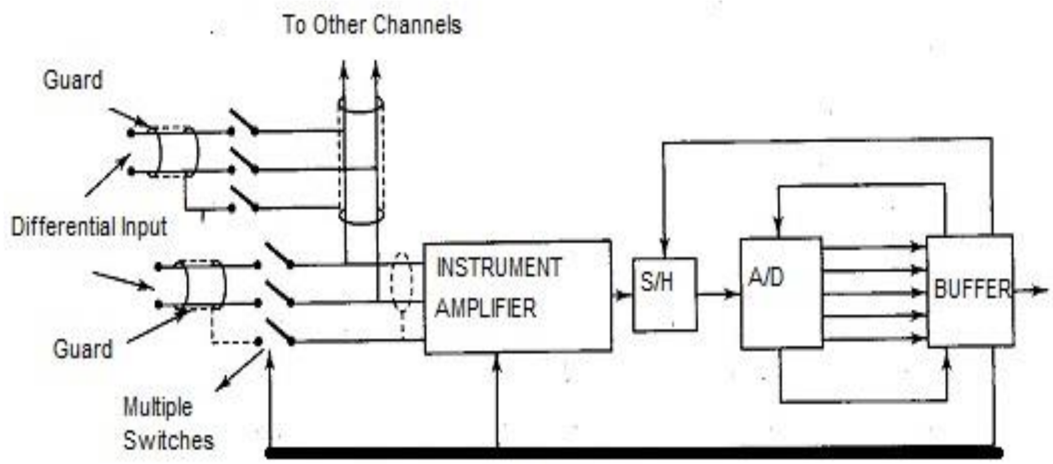
It can be observed from the block diagram that one channel of the main digital multiplexed system has an input from a multiplexer. This arrangement is for input channels that have slowly varying data. Such slow varying data outputs from transducers can be pre-multiplexed in any of the available forms. This results in sequentially multiplexed sub-channel. The sub-channel can be used as a channel feeding the main digital multiplexing system.

Multiplexing Low Level Data:

A single high quality data amplifier can be used for handling multichannel low level signal. Such an arrangement is shown in Figure.



MULTICHANNEL DAS USING DIGITAL MULTIPLEXING



LOW LEVEL MULTIPLEXING

Each low level signal is provided with individual amplifier. Individual amplifier's output goes to sample hold circuit from which it is converted to the digital format. The input of the individual amplifiers can be either of the common mode type or differential type.

This type of multiplexing is useful when large numbers of channels with low level outputs are available. As high quality amplifiers are available with affordable cost providing individual amplifiers is possible. The following factors are to be considered to implement low level multiplexing satisfactorily.

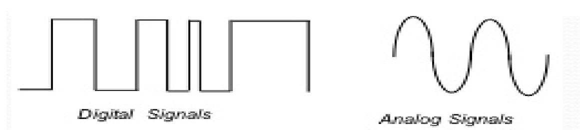
1. Guarding is to be provided for each channel.

2. Proper switching of guard is necessary.

3. Signal to signal and common mode to differential cross-talk is to be avoided.

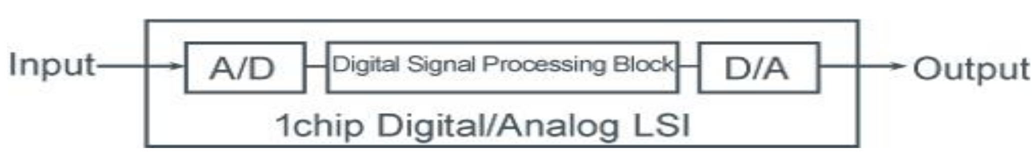
4. Capacitive balance is necessary.

Analog/Digital Converter and Digital/Analog Converter



A/D Converters

An A/D converter is a device that converts analog signals (usually voltage) obtained from environmental (physical) phenomena into digital format. Conversion involves a series of steps, including sampling, quantization, and coding.



A/D Converter Applications

Digital Audio: Digital audio workstations, sound recording, pulse-code modulation

Digital signal processing: TV tuner cards, microcontrollers, digital storage oscilloscopes

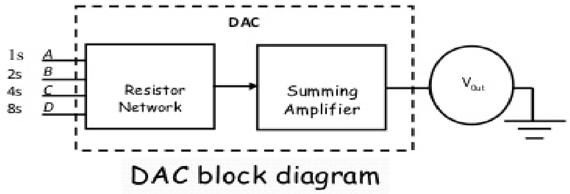
Scientific instruments: Digital imaging systems, radar systems, temperature sensors

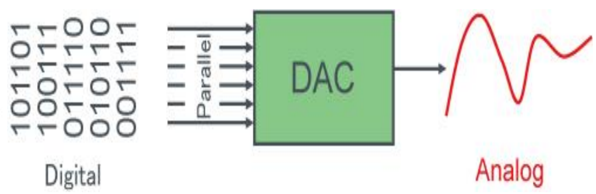
D/A Converters

D/A converters convert digital signals into analog format.

Digital Data: Evenly spaced discontinuous values, Temporally discrete, quantitatively discrete

Analog Data (Natural Phenomena): Continuous range of values, Temporally continuous, quantitatively continuous





D/A Converter Applications

Digital Audio：CD, MD, 1-bit Audio

Digital Video：DVD, Digital Still Camera

Communication Equipment：Smartphones, FAX, ADSl equipment

PCs：Audio, video cards

Measurement instruments：Programmable power supplies, etc.

A/D and D/A Requirements

Electrically sophisticated and high-speed processing are performed digitally in CPUs and DSPs. Natural phenomena are converted to digital signals using an A/D converter for digital signal processing, then converted back to analog signals via a D/A converter.

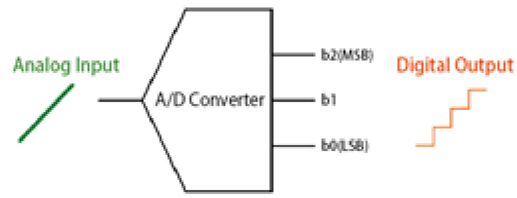
Advancements in Microfabrication Technology → Signal Processing Digitization→ A/D and D/A Converters Required

Basic Operation of a D/A Converter

A D/A converter takes a precise number (most commonly a fixed-point binary number) and converts it into a physical quantity (example: voltage or pressure). D/A converters are often used to convert finite-precision time series data to a continually varying physical signal.

An ideal D/A converter takes abstract numbers from a sequence of impulses that are then processed by using a form of interpolation to fill in data between impulses. A conventional D/A converter puts the numbers into a piecewise constant function made up of a sequence of rectangular functions that is modeled with the zero-order hold.

A D/A converter reconstructs original signals so that its bandwidth meets certain requirements. With digital sampling comes quantization errors that create low-level noise which gets added to the reconstructed signal. The minimum analog signal amplitude that can bring about a change in the digital signal is called the Least Significant Bit (LSB), while the (rounding) error that occurs between the analog and digital signals is referred to as quantization error.



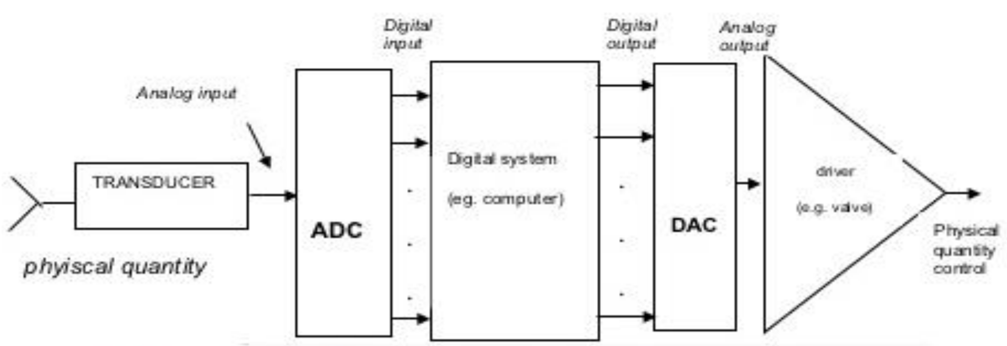
Basic Operation of an A/D Converter

Now, let's take a look at the basic operation of an A/D converter.

The A/D converter breaks up (samples) the amplitude of the analog signal at discrete intervals, which are then converted into digital values. The resolution of an analog to digital converter (indicating the number of discrete values it can produce over a range of analog values) is typically expressed by the number of bits. In the above case of a 3bit A/D converter, the upper value (b2) is referred to as the Most Significant Bit (MSB) and the lowest value (b0) the Least Significant Bit (LSB).

The graph below shows the relationship between the analog input and digital output.

In addition, the first digital change point (000→001) below 0.5LSB is the zero scale, while the last digital change point (110→111) is termed full scale and the interval from zero to full scale referred to as the full scale range.



ADC and DAC use as an interface between a computer with an analog world

Analog to digital converters (ADC)

Analog to digital converters used for DAS applications are usually designed to receive external commands to convert and hold.

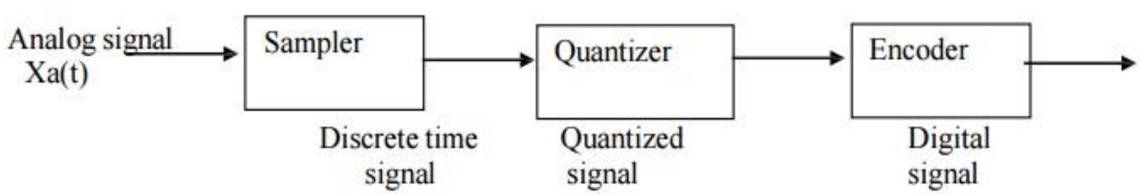
For dc and low frequency signals, a dual slope type converter is often used. The advantage is that it has a linear averaging capability and has a null response for frequencies harmonically related to the integrating period. (Generally, the integrating time is selected equal to the period of the line frequency, since a major portion of the system interference occurs at this frequency and its harmonics.)

A/D converters based on dual slope techniques are useful for conversion of low frequency data, such as from thermocouples, especially in the presence of noise.

The most popular type of converter for data system applications is the **successive approximation type** , since it is capable of high resolution and high speed at moderate cost. (For a conversion time of 10 μS, the maximum dv/dt for full scale and 0.1% resolution is about 1 V/ms, which is a considerable improvement.)

Higher speeds are obtained by preceding the A/D converter by a sample hold (S/H). The sample hold is particularly required with successive approximation type A/D converters, since at higher rates of input change the latter generates substantial non-linearity errors because it cannot tolerate changes during the conversion process.

Direct digital conversion carried out near the signal source is very advantageous in cases where data needs to be transmitted through a noisy environment. Even with a high level signal of 10 V, an 8 bit converter (1/256 resolution) can produce 1 bit ambiguity when affected by noise of the order of 40 mV.



Analog Signal to Digital Signal Conversion Methods

Analog to Digital Conversion (ADC)

Analog to Digital Conversion is the process by which analog signals are converted to their digitized forms. ADC occurs via three steps:- Sampling.- Quantization.- Encoding.

The idea of Sampling

The analog signal is sampled at regular intervals of time. The sampling rate must be at least twice the highest frequency of the signal (Nyquist Criterion).

Sampling: Sampling is the process of taking amplitude values of the continuous analog signal at discrete time intervals (sampling period Ts).

[Sampling Period Ts = 1/Fs (Sampling Frequency)].

Sampling is performed using a Sample and Hold (S&H) circuit.

Quantization

Quantization is defined as the process of converting the continuous sample amplitude into a discrete amplitude. Thus by then, the signal will be discrete in both; time and amplitude.

Quantization involves assigning a numerical value to each sampled amplitude value from a range of possible values covering the entire amplitude range (based on the number of bits).

[Quantization error: Sampled Value - Quantized Value]

Quantization Error: The difference between the actual analog value and quantized digital value.

Encoding

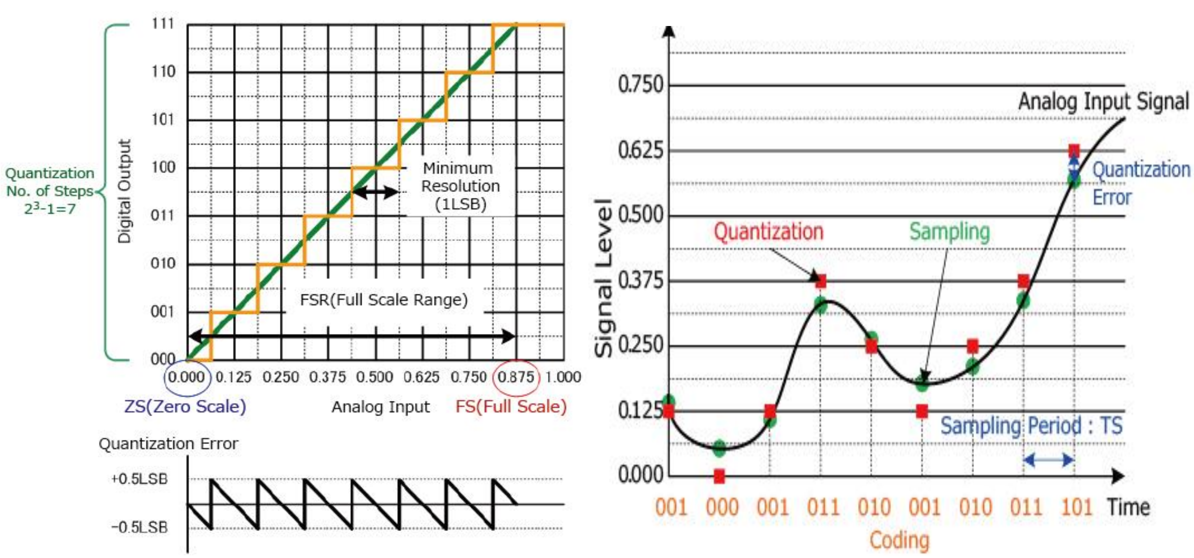
Encoding is the process which assigns ones and zeros (stream of bits) for every quantization level.The number of bits assigned for each level (n) depends on the levels' number (L) ; such that L= 2^n.

Ideal ADCQ= Δ=quantization step = full scale / levels' number.

In an ideal analog-to-digital converter, the quantization error is uniformly distributed between –Δ/2 and Δ/2.

The resolution of the ADC is the smallest detectable change in voltage.

Coding: Once the amplitude values have been quantized they are encoded into binary using an Encoder.



Types of ADCs

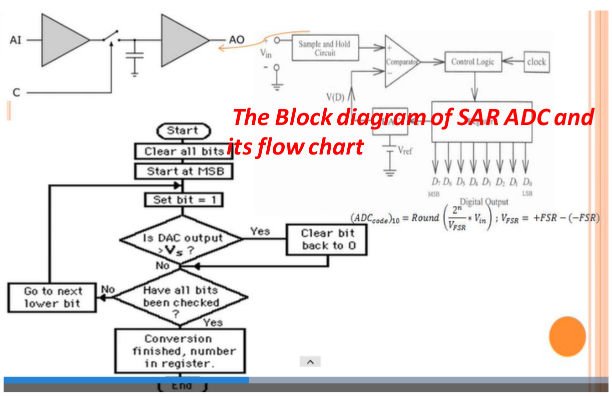
- There are many types of ADCs such as:
- Direct Conversion ADC.
- Successive Approximation Register (SAR) ADC.
- Integrating ADCs: Single slope, dual slope, and ramp ADC.
- Sigma-Delta ADC (over sampled ADC).
- ADC0804 Analog to Digital Converter.

ADC0804 Analog to Digital Converter

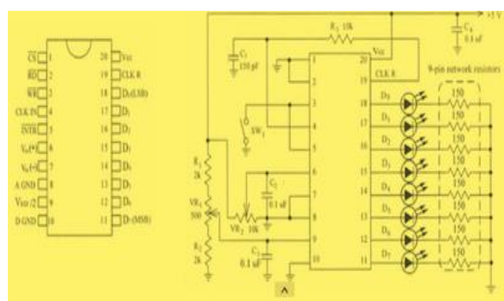
ADC0804 is a 20-pin IC with an 8-bit resolution.

- The analog input voltage range is from 0 V to 5 V, with 15 mW power consumption and 100 us conversion time .

SAR ADC: It is one of the popular ADCs for 8-16 bits. It has moderate conversion speeds ; the conversion time is around 1 Us.

- It doesn't consume a lot of power and its cost is low in comparison with the other types.
- On the other hand, it requires a sample and hold circuit and it can have missing output codes.
- 

The Block diagram of SAR ADC and its flow chart



ADC0804 Analog to Digital Converter

Description of operation

A successive approximation ADC works by using a digital to analog converter (DAC) and a comparator to perform a binary search to find the input voltage. A sample and hold circuit (S&H) is used to sample the analog input voltage and hold (i.e. keep a non-changing copy) the sampled value whilst the binary search is performed.

The binary search starts with the most significant bit (MSB) and works towards the least significant bit (LSB). For a 8-bit output resolution, 8 comparisons are needed in the binary search, taking a least 8 clock cycles.

The sample and hold circuit samples the analog input on a rising edge of the sample signal. The comparator output is a logic 1 if the sampled analog voltage is greater than the output of the DAC, 0 otherwise.

Digital to analog converter (DAC)

Digital to analog converter (DAC) is the device which converts digital signals to analog ones.

Most of the DACs consist of a network of resistors and analog switches.

The switches control the currents or voltages that are derived from a particular reference voltage and provide analog output current.

Types Of DACs

There are many types of DACs such as:

Weighted resistor DAC.

R-2R DAC.

General purpose DAC (DAC 0800).

Frequency to voltage converter.

Pulse width modulation

R-2R DAC

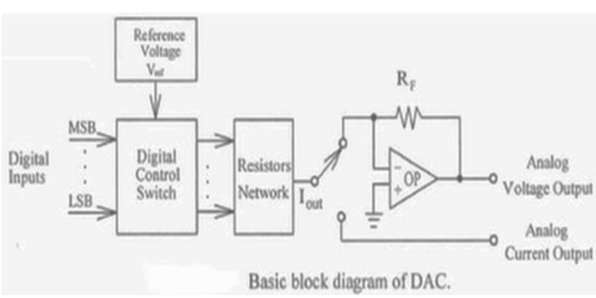
The analog output is given by the following equation: The highest resistance value is only 2R and thus requires an area inside the IC less 8 times than that of the weighted resistor DAC which highest resistance is 16R.

The DAC analog output is represented by current.

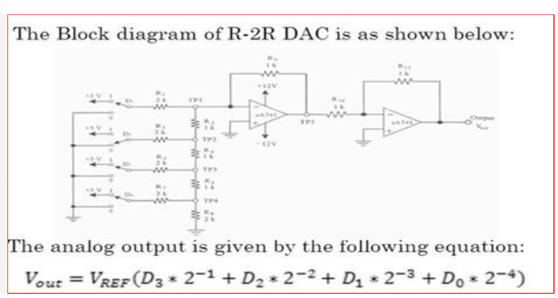
This current is the ratio of the input code to the full scale voltage (Vref) as given in the following equation:

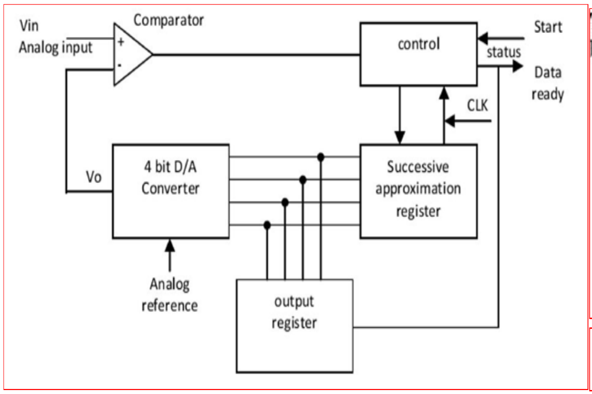
So, an operational amplifier is needed to convert the current to voltage level.
The General Purpose (DAC0800). It’s clear that it’s a 8-bit DAC with 16 pins IC.

The conversion time is around 100ns.

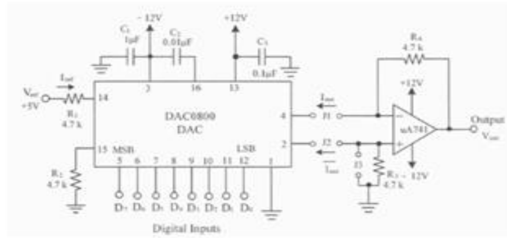


Basic block diagram of DAC.





The block diagram of DAC 0800 is as shown below:



$$I_{out} = \frac{V_{ref}}{R_1}\left(\frac{D_7}{2}+\frac{D_6}{4}+\frac{D_5}{8}+\frac{D_4}{16}+\frac{D_3}{32}+\frac{D_2}{64}+\frac{D_1}{128}+\frac{D_0}{256}\right)$$

Data logging

Data logging means to record events, observations, or measurements systematically. And, the device involved in data logging is known as a data logger. Data loggers come into picture whenever there’s a need to take continuous readings of an instrument. Significantly used in the field of geotechnical instrumentation and monitoring, data loggers are a necessary device.

Here is everything that you would like to know about data loggers – their types, relation with data acquisition system, working principle, specifications, and much more.

A data logger or a data recorder is an electronic device or a computer program that continuously records data over time in relation to the location either using a built-in instrument or through an externally interfaced one. The data loggers are primarily based on digital processors and usually look similar to a small portable box/case with batteries, wires, internal memory storage, sensors, and a programmable module.

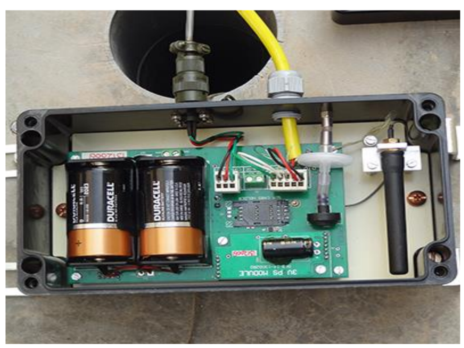


Figure 1: Inside of a Data Logger

A few of the data loggers interface with a PC to show data through a dedicated software while there are some other that connect directly to a device (LCD, PC, Mobile Phone) and show data as a stand-alone device. Data Loggers are used in geotechnical monitoring and instrumentation on a large scale because they automatically collect real-time data from the sensors and display it over the mobile device. One can leave the data loggers unattended and can still get the complete data anytime they wish to.

The need for data loggers depends upon the number of measurement points that you have or the number of sensors that you want to connect to it. Data loggers are available in multiple configurations so that you can choose according to your needs.

For instance, the ESCL-10VT data logger is a single channel data logger whereas the ESDL-30 is a multiple channel data logger with 160 inputs. However, the later one requires an SDI-12 interface to connect with sensors like piezometers, load cells, temperature sensors etc.

The duration of data logging depends upon two parameters – the power backup of the data logger and its memory capacity. While most of the data loggers have high longevity and durability, they continue to operate for many years. Whereas, a few of them work for a shorter time period only.

The Encardio's data loggers are battery operated and they can be programmed to record data from 5 to 168 seconds in linear mode. However, the number of readings taken per day should be kept minimum to save the battery. This data logger also gives you several power supply options.

The sample rate multiplied by the number of channels being recorded gives the length of time the logger can operate before the memory is filled. Some of the data loggers are programmed to over-write the data once the memory is filled while some of them stop logging data once the memory is full.

While monitoring structures like tunnels, dams, high-rise buildings, a certain alert level is pre-determined and, as soon as the deformation or fault reaches beyond that particular level, the data loggers send an emergency alert either through an SMS or an email.

There are a few other data loggers that come with in-built LEDs, alarms or buzzers to alert the local persons in case of an emergency.

There are two options available for data retrieval and transmission through Encardio's data loggers:

Telemetry through GSM/GPRS modem

In an area with GSM/GPRS service, the data from the automatic data logger can be transmitted remotely to a PC at a central location. The user will need to arrange a data SIM card for each data logger.

Readout/data retrieval using laptop PC

The logged data from the data logger is directly downloaded to a laptop/PC. Data can also be transferred to the central PC or server from the laptop using either a USB pen drive or through the Internet.

Most of the data loggers these days are configured rather than programmed. Encardio-rite provides a public cloud-based web monitoring service to its customers for retrieving data from ESDL-30 and ESCL-10VT data loggers.

The data retrieved is archived in a SQL database and presented in a graphical or tabular form for easy understanding. The tables and graphs related to any site or sites can be accessed by authorized personnel who can log in to their site using the supplied login ID

Block diagram of a data logger

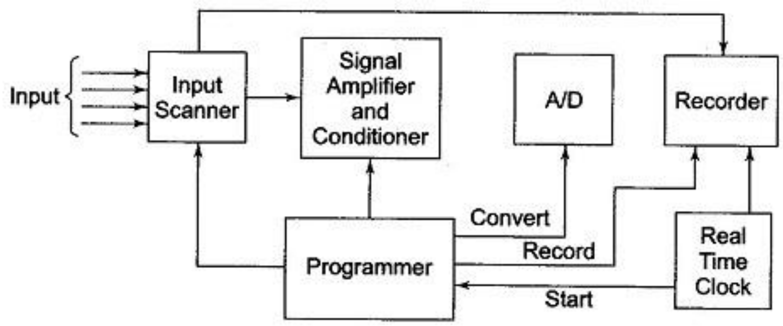


Fig. 17.24 Block Diagram of a Data Logger

Figure 2: Block Diagram of a Data Logger

These data logging devices are connected to geotechnical instruments like tilt meters, piezometers, extensometers, etc. These instruments send the measured physical parameters to the data logger.

The signals are then processed by them and further transmitted to a cloud web-based data management system so that you can get the data in readable form on your remote devices.

Working mechanisms of data loggers

Data loggers usually appear like a small box enclosing batteries for power supply, microprocessors, internal memory storage, sensors, and a programmable module. Encardio-Rite has two models of data loggers i.e. ESCL-10VT and ESDL-30.

The ESCL-10VT is a single channel data logger for vibrating wire sensors which means, it can be directly connected to vibrating wire sensors such as piezometers, strain gauges, extensometers etc. Whereas, ESDL-30 is an automatic data logger that uses SDI-12 interface to connect with the sensors.

Once the sensors are connected to the data loggers, the data through these sensors is logged at regular intervals by the data loggers and stored in its internal non-volatile memory. The users can retrieve this data remotely over their mobile device using Encardio's cloud service.

While monitoring of the structures, a certain alert level is pre-set. If the data logged is beyond the alert levels, an email or SMS emergency alert is sent to the user so that preventive measures can be taken before any mishap or accident.

Data Loggers are simply yet significant sensors having a wide range of application in the firld of geotechnical monitoring and instrumentation. They can be used to log all sorts of physical data through various instruments and sensors.

Data loggers are used for the following purposes:

1. Comprehensive tunnel monitoring for the long-term safety of the tunnel, to study the behaviour of the tunnel over the time, especially with respect to the rheological behaviour of the rock mass and obvious changes in the fault zones, walled sections, inflow, etc.
   Several instruments such as tilt meters, strain gauges, and extensometers, etc. are installed on the inner lining of the tunnels to monitor deformities if any. The data from these sensors is continuously logged by a data logger and stored in its internal memory.
2. Structural health monitoring of existing buildings to keep track of the building's performance over time and effect of nearby construction or excavation. Data loggers create an early warning in case of emergency so that the user can take preventive measures.
3. Landslide monitoring to avoid mishaps and create early warnings so that loss of life and property can be prevented.
4. Groundwater monitoring and rainfall management so that the most important freshwater resource can be saved from depleting and there's an even distribution of the resource among all.
5. Monitoring deformation of land and surrounding areas during deep excavations. Excavation in soft ground induces ground movement which imposes a threat to nearby sensitive structures in the zone of influence. Hence, deep excavation risk assessment and foundation crack monitoring are crucial at all the levels.
6. Monitoring of deformities in bridges so that early warning can be generated in case of an emergency
7. Unattended dam and nuclear power plant monitoring to avoid fatal accidents. Data loggers log data from different sensors and send it to user's remote device.
8. Unattended weather changing parameters recording through weather stations to aid in agricultural activities.
9. Monitoring of relay status in railway signalling

Data Transmission System

- Until the early 1980s the bulk of long-distance transmission was provided by analog systems in which individual telephone conversations were stacked in four-kilohertz intervals across the transmission band—a process known as frequency-division multiplexing (FDM). However, particularly with the development of fibre optics (*see below*), these analog systems were rapidly replaced by digital systems.
- In digital transmission, which may also be carried over the coaxial and microwave systems, the telephone signals are first converted from an analog format to a quantized, discrete time

format. The signals are then multiplexed together using time-division multiplexing (TDM), a method in which each digitized telephone signal is assigned a specific slot within a fixed time frame. In order to provide standard interfaces between transmission and switching equipment, multiplexed signals are further combined or aggregated in hierarchical arrangements.

- Modern telecommunication centres on the problems involved in transmitting large volumes of information over long distances without damaging loss due to noise and interference. The basic components of a modern digital telecommunications system must be capable of transmitting voice, data, radio, and television signals.
- Digital transmission is employed in order to achieve high reliability and because the cost of digital switching systems is much lower than the cost of analog systems. In order to use digital transmission, however, the analog signals that make up most voice, radio, and television communication must be subjected to a process of analog-to-digital conversion. (In data transmission this step is bypassed because the signals are already in digital form; most television, radio, and voice communication, however, use the analog system and must be digitized.)
- If the information to be transmitted is already in binary form (as in data communication), there is no need for the signal to be digitally encoded. But ordinary voice communications taking place by way of a telephone are not in binary form; neither is much of the information gathered for transmission from a space probe, nor are the television or radio signals gathered for transmission through a satellite link. Such signals, which continually vary among a range of values, are said to be analog, and in digital communications systems analog signals must be converted to digital form. The process of making this signal conversion is called analog-to-digital (A/D) conversion. The analog-to-digital (A/D) conversion occurs via three steps such as Sampling, Quantization and Encoding.
- Sampling converts a time-varying voltage signal into a discrete-time signal, a sequence of real numbers. A digital signal is a *sampled* signal, obtained by sampling the analogue signal at discrete points in time. These points are usually evenly spaced in time, with the time between being referred to as the **sampling interval**.
- Quantization replaces each real number with an approximation from a finite set of discrete values. Most commonly, these discrete values are represented as fixed-point words. Though any number of quantization levels is possible, common word-lengths are 8-bit (256 levels), 16-bit (65,536 levels) and 24-bit (16.8 million levels).
- **Source Encoding**: In analog-to-digital conversion, any available telecommunications medium has a limited capacity for data transmission. This capacity is commonly measured by the parameter called bandwidth. Since the bandwidth of a signal increases with the number of bits to be transmitted each second, an important function of a digital communications system is to represent the digitized signal by as few bits as possible—that is, to reduce redundancy. Redundancy reduction is accomplished by a source encoder, which often operates in conjunction with the analog-to-digital converter In many cases, the digitized signal

is passed through a source encoder, which employs a number of formulas to reduce redundant binary information.

- After source encoding, the digitized signal is processed in a channel encoder, which introduces redundant information that allows errors to be detected and corrected.
- As described in Source encoding, one purpose of the source encoder is to eliminate redundant binary digits from the digitized signal. The strategy of the channel encoder, on the other hand, is to add redundancy to the transmitted signal—in this case so that errors caused by noise during transmission can be corrected at the receiver. The process of encoding for protection against channel errors is called error-control coding. Error-control codes are used in a variety of applications, including satellite communication, deep-space communication, mobile radio communication, and computer networking.
- The encoded signal is made suitable for transmission by modulation onto a carrier wave and may be made part of a larger signal in a process known as multiplexing. The multiplexed signal is then sent into a multiple-access transmission channel. After transmission, the above process is reversed at the receiving end, and the information is extracted.

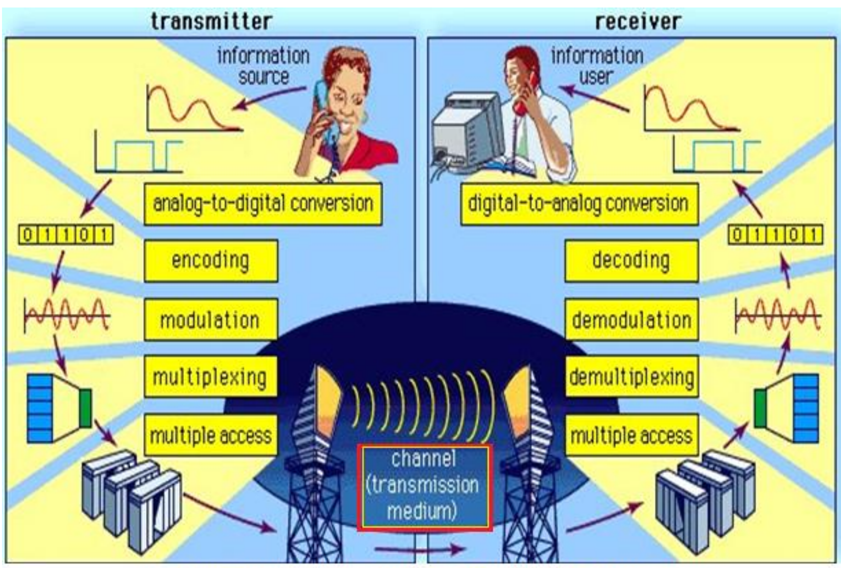


Fig. Block diagram of a digital telecommunications system

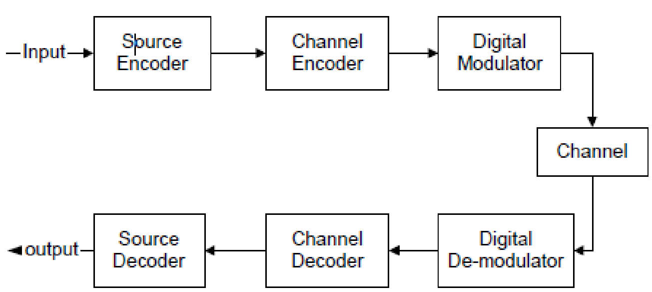


Figure Digital communication system

Components of a Communication System

The source originates a message, which could be a human voice, a television picture or data. The source is converted by an input transducer into an electrical waveform referred to as the baseband signal or message signal. The transmitter modifies the baseband signal for efficient transmission. **Transmitter:** The transmitter generally consists of one or more of the following subsystems: a pre-emphasizer, a sampler, a quantizer, a coder and a modulator.

The channel is a medium through which the transmitter output is sent, which could be a wire, a coaxial cable, an optical fiber, or a radio link, etc.

Based on the channel type, modern communication systems are divided into two categories: (1) wire lined communication systems and (2) wireless communication systems.

Receiver: The receiver reprocessed the signal received from the channel by undoing the signal modifications made at the transmitter and the channel. The task of the receiver is to extract the message from the distorted and noisy signal at the channel output. The receiver may consist of a demodulator, a decoder, a filter, and a de-emphasizer. The receiver output is fed to the output transducer, which converts the electrical signal to its original form.

When the signal is transmitted through the channel, it is not only distorted by the channel, but also contaminated/interfered by noise. Transmitters and receivers are carefully designed to overcome the distortion and noise.

Interface of Analog and Digital Systems-A/D and D/A Conversion: -

Sampling Theorem: A meeting ground exists for analog and digital signals: conversion of analog signals to digital signals. The backbone that supports the interface is Shannon's Sampling Theorem, which states that if the highest frequency in the signal spectrum is B (in hertz), then the signal can be recovered from its samples, taken at a rate not less than 2B samples per second.

Quantization: Each sample is approximated, or round off to the nearest quantized level, the information is thus digitalized. The quantized signal is an approximation of the original one. We can improve the accuracy of the quantized signal to any desired degree by increasing the number of levels L.

Pulse-code-modulation (PCM): The scheme of transmitting data by digitizing and then using pulse codes to transmit the digitized data.

Example: Multi-amplitude PCM vs. binary PCM.

During each sampling interval, we transmit one quantized sample, which takes on one of the L values. This requires L distinct waveforms, which may be constructed in two ways: Form L distinct waveforms directly or use a combination of only two basic pulsed. The latter is the so called binary case, where signaling is carried out by means of only two basic pulses or symbols.

The fundamental parameters that control the rate and quality of information transmission are the channel bandwidth Band the signal power S. The bandwidth of a channel is the range of frequencies that it can transmit with reasonable fidelity. For example, if a channel can transmit with fidelity a signal whose frequency components occupy a range from 0(dc) up to a maximum of 5000 Hz, the channel bandwidth Bis 5kHz.

Source coding (data compression): the process of efficiently converting the output of a source into a sequence of binary digit.

Channel coding: The introduction of redundancy in the information sequence for the purpose of combating the effects of noise and interference in the channel.

Modulation: A process that converts the digital information sequences into waveforms that are compatible with the characteristics of the channel.

Channel estimation: Generally, channels may introduce distortion to the source signal, and the characteristics of the channel/distortion need to be estimated or identified at the receiver end, in order to reduce or eliminate the distortion and recover the original signal. This is called channel estimation or identification.

Equalization is the process to compensate for the channel distortion. Very often, equalizer is designed to minimize the ISI and the noise jointly.

Model Questions

1. Explain the functions of Signal conditioning in detail.
2. Explain amplification, filtering, level conversion with neat diagrams
3. Explain Linearization, various types of Buffering used in signal processing with their circuits
4. Explain about Sample and Hold circuit, Quantization and Multiplexer / De multiplexer with diagrams.
5. Explain Analog to Digital converter and Digital to Analog converter with examples
6. Write notes on (a) I/P and P/I converter (b) Instrumentation Amplifier (c) V/F and F/V converter
7. Explain Data Acquisition and Data Logging processes in detail
8. Explain data conversion and digital transmission system with neat diagrams