LECTURE NOTES

ON

INSTRUMENTATION

2019- 2020

IV B. Tech II Semester (JNTUA-R15)

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SYLLABUS

UNIT-I CHARACTERISTICS OF SIGNALS AND THEIR REPRESENTATION
Measuring Systems, Performance Characteristics, - Static Characteristics, Dynamic Characteristics; Errors in Measurement – Gross Errors, Systematic Errors, Statistical Analysis of Random Errors. Signals and Their Representation: Standard Test, Periodic, Aperiodic, Modulated Signal, Sampled Data, Pulse Modulation and Pulse Code Modulation.

UNIT-II DATA TRANSMISSION , TELEMETRY AND DAS
Methods of Data Transmission – General Telemetry System. Frequency Modulation (FM), Pulse Modulation (PM), Pulse Amplitude Modulation (PAM), Pulse Code Modulation (PCM) Telemetry. Comparison of FM, PM, PAM and PCM. Analog and Digital Data Acquisition Systems – Components of Analog DAS – Types of Multiplexing Systems: Time Division and Frequency Division Multiplexing – Digital DAS – Block Diagram — Modern Digital DAS (Block Diagram)

UNIT-III SIGNAL ANALYZERS, DIGITAL METERS Wave Analysers- Frequency Selective Analyzers, Heterodyne, Application of Wave Analyzers- Harmonic Analyzers, Total Harmonic Distortion, Spectrum Analyzers, Basic Spectrum Analyzers, Spectral Displays, Vector Impedance Meter, Q Meter. Peak Reading and RMS Voltmeters, Digital Voltmeters - Successive Approximation, Ramp and Integrating Type-Digital Frequency Meter-Digital Multimeter-Digital Tachometer

UNIT-IV TRANSDUCERS
Definition of Transducers, Classification of Transducers, Advantages of Electrical Transducers, Characteristics and Choice of Transducers; Principle of Operation of Resistive, Inductive, Capacitive Transducers, LVDT, Strain Gauge and Its Principle of Operation, Gauge Factor, Thermistors, Thermocouples, Synchros, Piezoelectric Transducers, Photovoltaic, Photo Conductive Cells, Photo Diodes.

UNIT-V MEASUREMENT OF NON-ELECTRICAL QUANTITIES
Measurement of strain, Gauge Sensitivity, Measurement of Displacement, Velocity, Angular Velocity, Acceleration, Force, Torque, Temperature, Pressure, Flow, Liquid level.

TEXT BOOKS:
1. A course in Electrical and Electronic Measurements and Instrumentation, A.K. Sawhney, Dhanpat Rai & Co., 2012.
2. Transducers and Instrumentation, D.V.S Murty, Prentice Hall of India, 2nd Edition, 2004.

REFERENCES:
1. Modern Electronic Instrumentation and Measurement technique, A.D Helfrick and W.D.Cooper, Pearson/Prentice Hall of India., 1990.
2. Electronic Instrumentation, H.S.Kalsi Tata MCGraw-Hill Edition, 2010.
3. Industrial Instrumentation – Principles and Design, T. R. Padmanabhan, Springer, 3rd re print, 2009.

LECTURE NOTES

UNIT–I:
Signals and their representation

Measuring Systems, Performance Characteristics, – Static characteristics – Dynamic Characteristics – Errors in Measurement – Gross Errors – Systematic Errors – Statistical analysis of random errors – Signal and their representation – Standard test, periodic, aperiodic, modulated signal – Sampled data pulse modulation and pulse code modulation.

INTRODUCTION

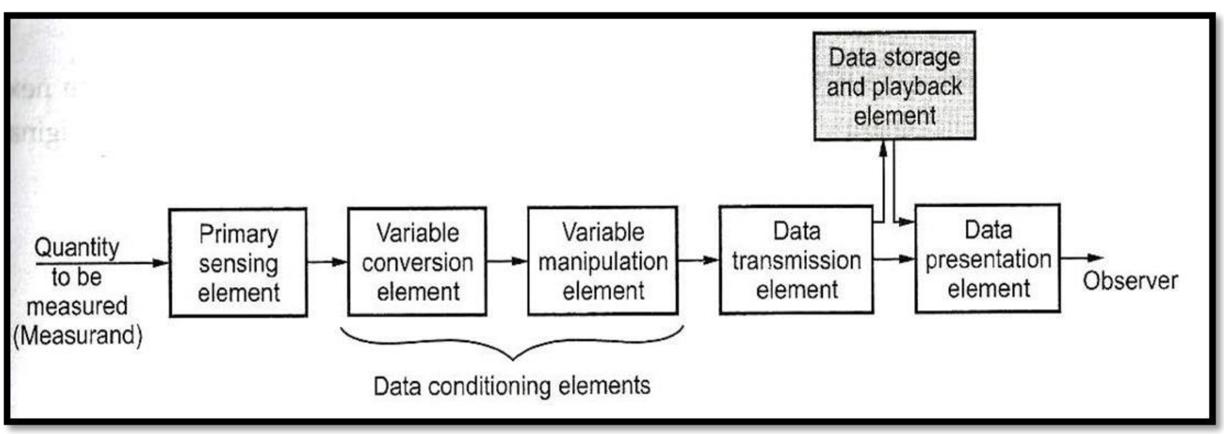
Determining a quantity or variable using a physical means is called the measurement and the means by which the quantity is determined is called Measuring Instruments. Thus, an instrument may be defined as a device for determining the value or magnitude of a quantity or variable. An instrument enables a person to determine the value of an unknown quantity.
Some of terms are used in the measurement work, which are defined below.

1. **True Value:** It is the average of an infinite number of measured values.
2. **Error:** It is the difference between the measured value and the true value.
3. **Index Scale:** It is the set of marks or divisions.
4. **Index Number:** It is the number of divisions moved.

The essential requirements of a measuring instrument are:
(i) It should not alter the circuit conditions,
(ii) Power consumed by it should be small.

Measurement system any of the systems used in the process of associating numbers with physical quantities and phenomena. Although the concept of weights and measures today includes such factors as temperature, luminosity, pressure, and electric current, it once consisted of only four basic measurements: mass (weight), distance or length, area, and volume (liquid or grain measure). The last three are, of course, closely related. Basic to the whole idea of weights and measures are the concepts of uniformity, units, and standards.Uniformity, the essence of any system of weights and measures, requires accurate, reliable standards of mass and length .

Functional elements of Instruments



- Primary sensing element
- Variable conversion element
- Data presentation element

Primary sensing element

The quantity under measurement makes its first contact with primary sensing element of a measurement system here, the primary sensing element transducer. This transducer converts measured into an analogous electrical signal.

Variable conversion element

The output of the primary sensing element is the electrical signal. It may be a voltage a frequency or some other electrical parameter. But this output is not suitable for this system.

For the instrument to perform the desired function, it may be necessary to convert this output to some other suitable form while retaining the original signal. Consider an example, suppose output is an analog signal form and the next of system accepts input signal only in digital form . Therefore we have to use and to digital converter in this system.

Variable manipulation element

The main function of variable manipulation element is to manipulation element is to manipulate the signal presented to it preserving the original nature of the signal. Here, manipulation means a change in numerical value of the signal.

Consider a small example, an electric amplifier circuit accepts a small voltage signal as input and produces an output signal which is also voltage but of greater amplifier. Thus voltage amplifier acts as a variable manipulation element.

Data presentation element

The information about the quantity under measurement has to be conveyed to the personal handling the instrument or system for control or analysis purposes. The information conveyed must be in the form of intelligible to the personnel. The above function is done by data presentation element.

The output or data of the system can be monitored by using visual display devices may be analog or digital device like ammeter, digital meter etc. In case the data to be record, we can use analog or digital recording equipment. In industries , for control and analysis purpose we can use computers.

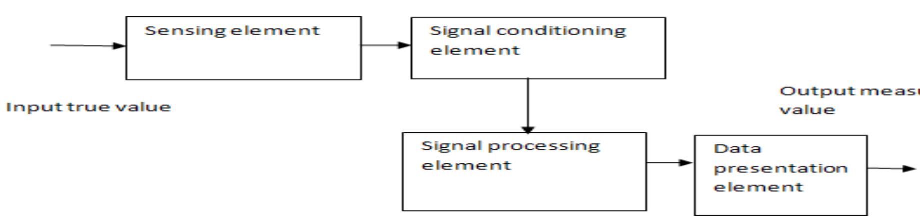
The final stage in a measurement system is known as terminating stage . when a control device is used for the final measurement stage it is necessary to apply some feedback to the input signal to accomplish the control 0bjective.

The term signal conditioning includes many other functions in addition to variable conversion and variable manipulation. In fact the element that follows the primary sensing element in any instrument or instrumentation system should be called signal conditioning element.

When the element of an instrument is physically separated, it becomes necessary to transmit data from one to another. This element is called transmitting element. The signal conditioning and transmitting stage is generally known as intermediate stage.

MEASUREMENT SYSTEMS

All measurement systems can be thought of being made of one or more of these blocks of Figure1. At the input we have the input element to be measured, temperature, displacement, .etc. that affecting the sensing element. Actually, sensing element is the process of continuous energy conversion from one form depending on what we want to measure, e.g, from mechanical form, optical form to finally electrical form, and then the electrical form get finally transform further to digital form before the output. The signal at the sensing element is in the form of voltage and current. The real pressure or real temperature which it exist at the sensing element, then the sensing element brings it generally to some sort of electrical form or electrical parameters like resistors, capacitor changes or in the form of voltage and current which have be further manipulated by electrical circuit called signal conditioning element.(sometimes amplifier or conversion from resistor to voltage). Then further signal processing goes on to remove noise and make it linear or something like that. Some of it can be analog and some of it can be digital. Finally, it goes to the data presentation element where data is utilized so it can be recorded, or can be displayed or can be controlled.



Here is the weight measurement system as an example. The input is the true weight which is sensed by a mechanical member that called load cell. The load cell converts the input (weight) to the strain that sensed by another member called strain gauge. The latter converts it to a resistance form then we feed it to the electrical circuit called wheat-stone. The wheatstone converts the resistance to a low voltage level. The low voltage goes to the amplifier. Finally, the amplified signal passes to the digital signal processing and from there to a microcontroller where some digital processing is done. Finally, the data may be displayed along with a unit. Here is how real measurement system looks like. It is basically cascaded of several blocks including the sensor, signal conditioning, plus some computer elements.

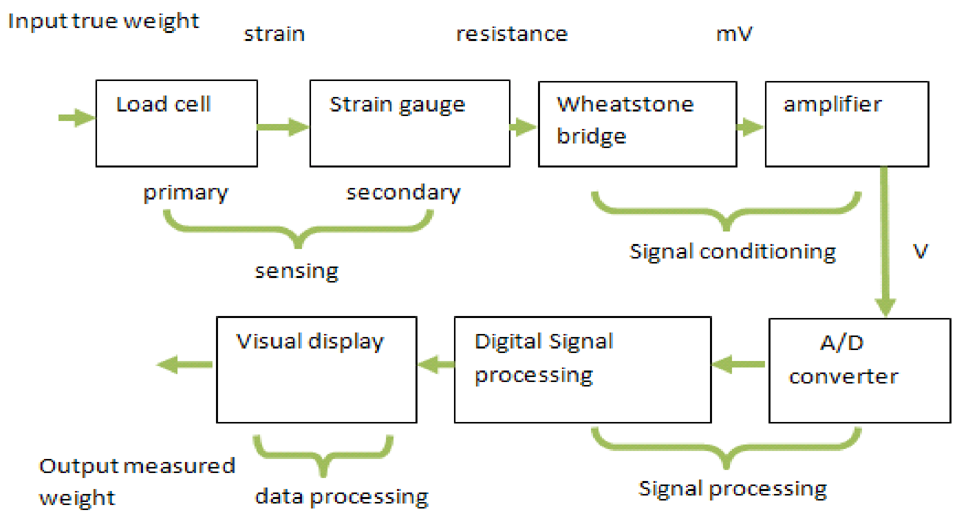


Figure 2: Weight measurement system

Sensing is actually extremely important in automation from various points of view:

a. Product quality control, because quality control is actually accessed by a sensor element.

b. Manufacturing process control. All the process control are closed feedback control. So the critical element is the feedback element. The performance of the control system is critical to the sensor.

c. Process monitoring and supervision. All these can be done plus providing energy efficient, obtaining set-point, form all these we need sensors.

d. Manufacturing automation, this how the manufacturing automation systems can be put together using programmable logic controllers. Then you find that they use various kinds of sensors. So sensors are extremely important in automation. They will give a value or information about physical quantity we need to know how to characterize the behavior of this device called a sensor in instrument, we need to understand instrument characteristics.

The performance characteristics may be broadly divided into two types, namely, 'statistics' and 'dynamic' characteristics. Static characteristics where the performance criteria for the measurement of quantities that remain constant. Or vary only quite slowly. Dynamic characteristics on the other hand, shows the relationship between the system input and output when the measured quantity is varying rapidly.

Static characteristics :-

Calibration

The procedure that involves a comparison of the particular instrument with either a primary standard or a secondary standard with a higher accuracy than the instrument to be calibrated.

From Figure 3, the measurand 1 is considered to be the true value, while the measurand 2 is not only from the sensor instrument under calibration but it can be a result of other factors. It may be a result of temperature. For example, in the case of the weight measurement, the strain gauge,(the resistance change) is not only a function of the weight, it also a function of temperature. Because every resistance has some temperature coefficient. There are some noise can be induced from a power supply or from some power lines especially in the industry environment, there are plenty of noise sources. This signal (noise) can affect the measurement. When you want to characterize the instrument, you have to characterize it to respond these kinds on inputs.

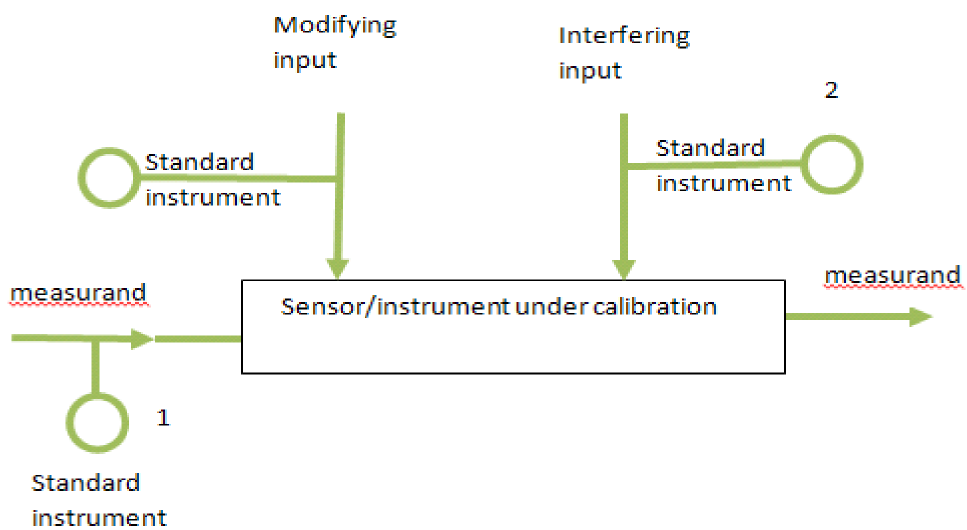


Figure 3 Calibration of an instrument

Essentially, we try to measure the measurand, the output of the instrument, and the modifying input like the temperature. Then we establish the characteristics of the instrument. Since the instrument must happen constructed to be unaffected by modifying input, so the most important thing is to see how the instrument characteristics depend on the measurand. There are different standards of instrument. The instrument can be calibrated against laboratory standard. The laboratory standard instrument can also be calibrated from time to time against other standard like the secondary standard which is special instrument that exists in some testing houses. So from time to time you should send the instrument to test houses and get calibrated. On the other hand, the guest house instruments again have to be calibrated against very accurate national standards. So in this way you have what can be called change of standards of increasing accuracy and add different levels you always calibrate according with respected instrument.

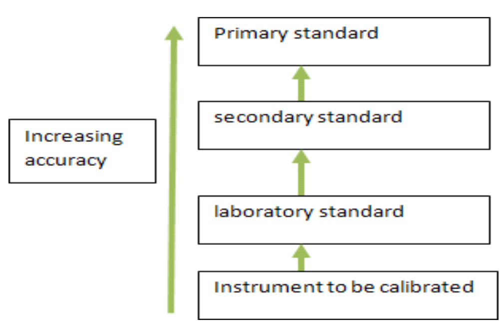


Figure 4: increasing accuracy with different levels of standards

Span

If in a measurement instrument the highest point of calibration is x2 units and the lowest point is x1 units, then the instrument range is x2 units and the instrument span is x2-x1.

Accuracy

It refers to the closeness of an instrument reading to the true value of the quantity or variable under measurement. This term describes the algebraic difference between the indicated value and the true value or theoretical value of the measurand. In practice, accuracy is usually expressed as a percentage of full scale output or percent of reading or digits for digital readouts.One of the most important parameter called accuracy. Usually, "accuracy is expressed as accurate to within x percent" of reading/span. It means that true value within ±x percent of instrument reading/span at all calibration points of the scale. When a temperature transducer with an error of ±1% of reading indicates 100oC, then the true temperature is between 99oC and 101oC.

Precision: It refers to the measure of the reproducibility or repeatability of the measurement. It is a measure of the degree to which successive measurements differ from one another. If a number of readings of a voltmeter are taken, then the expected value of 1.0 volt is not obtained on every occasion. A range of values such as 0.99, 1.01, 1.00, 1.02, 0.98, etc. are obtained about the expected value. The effect is termed as a lack of ***repeatability*** in the instrument.

Linearity

The calibration curve of a real instrument is typically not a exactly straight line. But still is very useful to imagine the system real one. It is very easily to interpret the true value. If you have an instrument sensitivity 10mV/oC, and if it gives 25mV signal, then you know that the temperature is 2.5 oC. So you can get just by dividing by a number. From that point of view, it is very attractive to express the characteristics of a linear one, but it is not line. Therefore, why you mention a line which can be used for inducing the true value from a reading. For ease of use, it is desirable that the reading of an instrument is considered Linearly related to the quantity being measured. The linearity specification indicates the deviation of the Calibration curve from a good fit straight line of it. How do you obtain the straight line? It can be obtained in various ways: (non-)linear method; this method is defined as the maximum deviation of an output reading from the good fit straight line and may be expressed as a percentage of full scale or reading. The true characteristics of the instrument is indicated by the curve shown in Figure5. So we can approximate it by the straight line. Therefore, the true value will be within two limits shown in Figure 5.

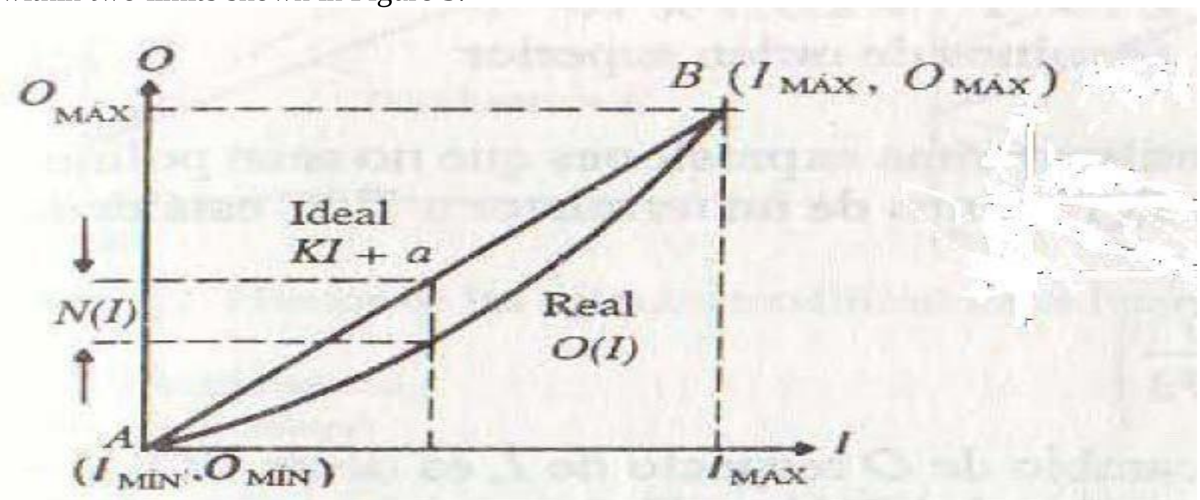


Figure 5: Non-linear method for obtaining a straight line

Actually linearity specification is only linear specification in the sense that it indicates deviation from linearity.

Sensitivity

The slope of an static calibration curve evaluated at an input value is the static sensitivity.

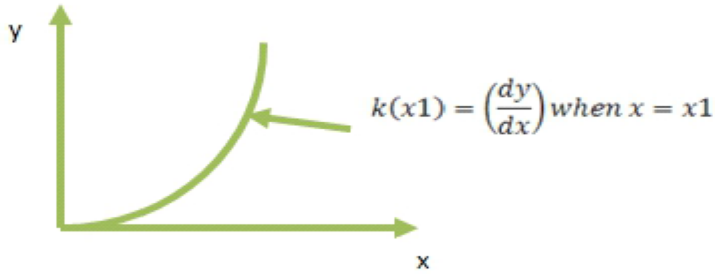


Figure 6: The slope of an static calibration curve

If you have a calibration curve, then you get a straight line. In case you have a linear characteristic, then you will have a single sensitivity. However, if you have a very non-linear one, sometime you do various things. In the case of three sensitivity figure, one sensitivity figure you apply along the line A, another sensitivity figure you apply at the region B which is the average slope of the line , and a third sensitivity figure you apply at the range of C.

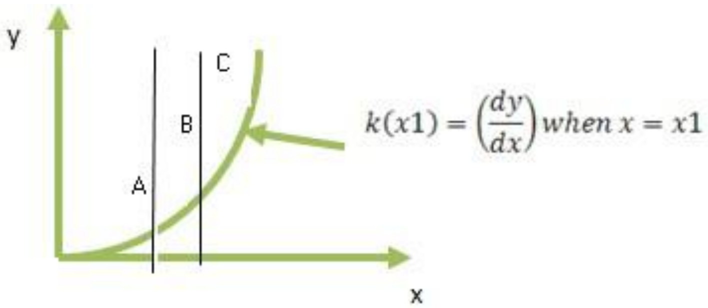


Figure7: Non-linear calibration characteristics curve

Repeatability or Precision

The repeatability of an instrument is the degree of closeness with which a measurable quantity may be repeatedly measured. It is defined as the maximum measure of variation in the measured data for a particular input value given by standard deviation δ.

Resolution

The measurement resolution of an instrument defines the smallest change in measured quantity that causes a detectable change in its output. For example, in a temperature transducer, if 0.2 $_o$C is the smallest temperature change that observed, then the measurement resolution is 0.2 $_o$C.

Dead Zone

Dead zone is the largest value of a measured variable for which the instrument output stays zero. It occurs due to factors such as static friction in a mechanical measurement system.

Hysteresis

Hysteresis error refers to the difference between responses to increasing and decreasing sequence of inputs. It can occur due to gear backlash in mechanism, magnetic hysteresis or due to elastic hysteresis.

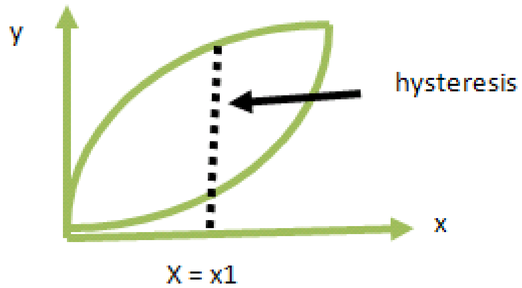


Figure 8: hysteresis

Bias/offset

It is the constant component of error that may be assumed to exist over the full range.

Sensitivity/Gain error

It is the component of error which is assumed to be proportional to the reading.

Correction

Instruments often provide facilities to correct for these error using signal conditioning circuitry.

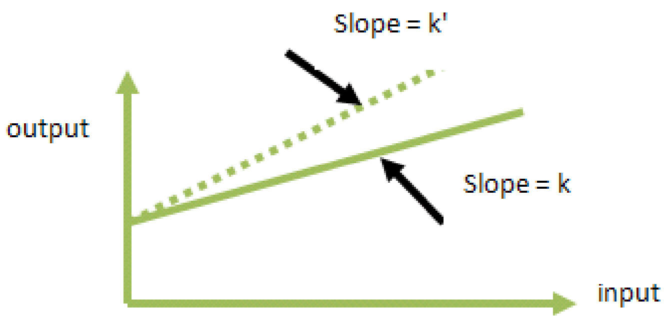


Figure 9: Bias and Gain error

now the errors that we have you know the, so we have actually typically an instrument is suppose to have a, suppose to have calibration curve. But, the reading that it has may not exactly match with the calibration curve it is if you, if you, if you read out an ammeter then it has some scale fixed. But, if you send exactly one ampere current then the, then the needle may not stand at one ampere, so this is the error. Now, the error is typically you know characterize as in into two different kinds, so since the instrument is actually assume to be linear instrument.

So, it is assume that the error can be of two types the first type is called bias of offset which is a constant error, which is, which is going to stay throughout the range. So, may be at half at when you have a reading of when you have an actual current of 2 amperes you reading shows 2.5. When you have 3 ampere it showed 3.5, when you have 10 ampere it shows 10.5, so you have a 0.5 ampere of bias. If you see ammeters normal ammeters you will find that such biases can be corrected by you know screwdrivers there are, there are, there are sometimes zero adjusts.

Similarly, there can be see there can be again error, so you have a sensitivity while we have a nominal sensitivity which is indicated by the scale and your actual instrument sensitivity may actually deviate from that and then you have a sensitivity or gain error. The error in reading due to this gain error is going to be proportional to the ready, so if you have if you have measuring 10 degree centigrade.

Then the error due to gain error is going to be half of if what you measure due to 20 degree when you when you measure 20 degree centigrade. So, we assume the errors are of two kinds and these typically in typical sensors and instruments very often they can be corrected by electronic signal conditioning means.

Output/Input Relationship

Instrument systems are usually built up from a serial linkage of distinguishable building blocks. The actual physical assembly may not appear to be so but it can be broken down into a representative diagram of connected blocks. In the Humidity sensor it is activated by an input physical parameter and provides an output signal to the next block that processes the signal into a more appropriate state.

A key generic entity is, therefore, the relationship between the input and output of the block. As was pointed out earlier, all signals have a time characteristic, so we must consider the behavior of a block in terms of both the static and dynamic states.

The behavior of the static regime alone and the combined static and dynamic regime can be found through use of an appropriate mathematical model of each block. The mathematical description of system responses is easy to set up and use if the elements all act as linear systems and where addition of signals can be carried out in a linear additive manner. If nonlinearity exists in elements, then it becomes considerably more difficult —

perhaps even quite impractical — to provide an easy to follow mathemat- ical explanation.

Fortunately, general description of instrument systems responses can be usually be adequately covered using the linear treatment.

The output/input ratio of the whole cascaded chain of blocks 1, 2, 3, etc. is given as:

[output/input]total = [output/input]1× [output/input]2× [output/input]3 …

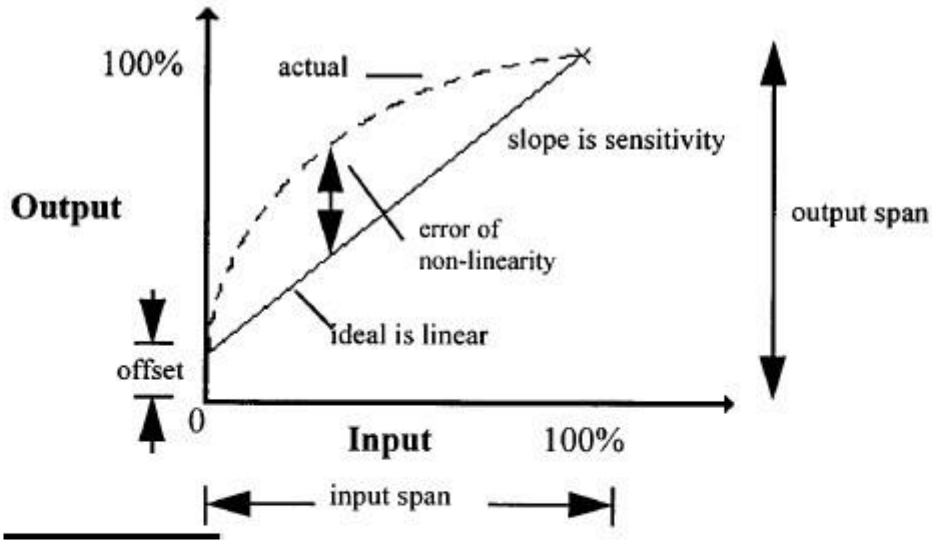
The output/input ratio of a block that includes both the static and dynamic characteristics is called the transfer function and is given the symbol G.

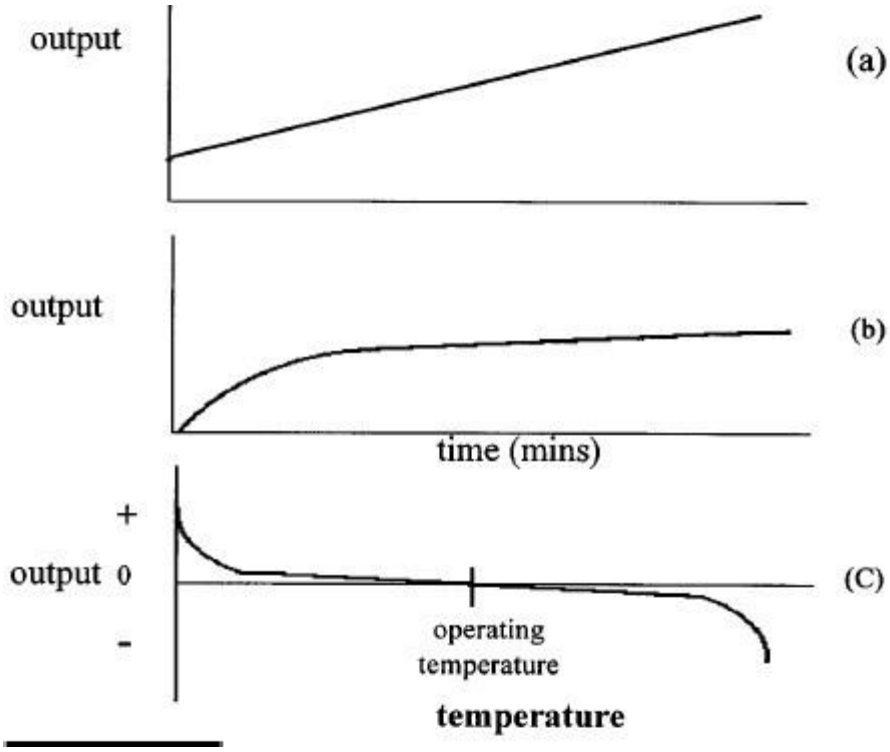
The equation forG can be written as two parts multiplied together. One expresses the static behavior of the block, that is, the value it has after all transient (time varying) effects have settled to their final state. The other part tells us how that value responds when the block is in its dynamic state. The static part is known as the transfer characteristic and is

often all that is needed to be known for block description.

The static and dynamic response of the cascade of blocks is simply the multiplication of all individual blocks. As each block has its own part for the static and dynamic behavior, the cascade equations can be rearranged to separate the static from the dynamic parts and then by multiplying the static set and the dynamic set we get the overall response in the static and dynamic states. This is shown by the sequence of Equations.

Instruments are formed from a connection of blocks. Each block can be represented by a conceptual and mathematical model. This example is of one type of humidity sensor.





Drift

It is now necessary to consider a major problem of instrument performance called instrument drift . This is caused by variations taking place in the parts of the instrumentation over time. Prime sources occur as chemical structural changes and changing mechanical stresses. Drift is a complex phenomenon for which the observed effects are that the sensitivity and offset values vary. It also can alter the accuracy of the instrument differently at the various amplitudes of the signal present.

Detailed description of drift is not at all easy but it is possible to work satisfactorily with simplified values that give the average of a set of observations, this usually being quoted in a conservative manner. The first graph (a) in Figure shows typical steady drift of a measuring spring component of a weighing balance. Figure (b) shows how an electronic amplifier might settle down after being turned on.

Drift is also caused by variations in environmental parameters such as temperature, pressure, and humidity that operate on the components. These are known as influence parameters. An example is the change of the resistance of an electrical resistor, this resistor forming the critical part of an electronic amplifier that sets its gain as its operating temperature changes.

Unfortunately, the observed effects of influence parameter induced drift often are the same as for time varying drift. Appropriate testing of blocks such as electronic amplifiers does allow the two to be separated to some extent. For example, altering only the temperature of the amplifier over a short period will quickly show its temperature dependence.

Drift due to influence parameters is graphed in much the same way as for time drift. Figure shows the drift of an amplifier as temperature varies. Note that it depends significantly on the temperature

Drift in the performance of an instrument takes many forms:

(a) drift over time for a spring balance;

(b) how an electronic amplifier might settle over time to a final value after power is supplied;

(c) drift, due to temperature, of an electronic amplifier varies with the actual temperature of operation.

so sometimes what happens is that even if you correct even if you correct at any at some point of time during calibration even if you correct for the bias of the gain error you have drifts in the bias on the gain. So, again such bias and gain errors can develop due to you know variations in temperature variations in time or some other conditions. So, the rate at which it these will develop are characterize by a performance characteristic called drift, so typically drift is characterized for temperature and time.

The calibration of an instrument is usually performed under controlled conditions. As variations occur in these conditions and also with passage of time, the instrument characteristics change. Usually, typical factors for which drift is characterized are temperature and time.

Dynamic Characteristics:

It describes the ways in which an instrument or measurement system responds to sudden changes to the input. In general, the dynamic response of the measurement system is expressed in the form of a differential equation. For any dynamic system, the order of the ***differential equation*** which describes the system is called the ***Order of the System***.

(i) Zero-order System: It has an ideal dynamic performance, because the output is proportional to the input for all frequencies and there is no amplitude or phase distortion. A linear potentiometer is an example of a zero-order element.

(ii) First-order System: A first-order instrument or system is characterized by a linear differential equation. The temperature transducer is an example of first-order measuring devices, since this is characterized by a single parameter, i.e., *time constant*, *T*.

The *differential equation* for the first-order system is given by

$$x(t) = y + T \cdot \frac{dy}{dx}$$

where, x = Input

$x(t)$ = Time function of the input

y = Output.

(iii) Second-order System: This type of system is characterized by the second-order differential equation. The example of the second-order system is the mass-spring system of the measurement of the force. The second-order instrument or system is defined by the equation

$$a_2 \frac{d^2y}{dt^2} + a_1 \frac{dy}{dt} + a_0 y = b_0 x$$

The solution of the *Equation* is given as

$$\frac{1}{\omega_n^2}\frac{d^2y}{dt^2} + \frac{2\xi}{\omega_n}\frac{dy}{dt} + y = Kx$$

where,
$$K = \frac{b_0}{a_0} = \textit{Static frequency}$$

$$\omega_n = \sqrt{\frac{a_0}{a_1}} = \textit{Natural frequency}$$

$$\xi = \frac{a_1}{2\sqrt{a_0 a_2}} = \textit{Damping ratio}$$

Thus, the second-order system is characterized by the two parameters —

the *natural frequency*, f_n or the *angular frequency*, ω_n $(= 2\pi f_n)$, and the

damping ratio, ξ .

In the second-order system, the *natural frequency* is the index of *speed of response*, whereas the *damping ratio* is a measure of the *system stability*. The second-order instrument is more common than first-order types.
The dynamic characteristics of an instrument or the measurement system are as follows:

(*i*) *Respond Time,* (*ii*) *Fidelity*,
(*iii*) *Measuring lag*, and (*iv*) *Dynamic error*.

(i) Respond Time: It is an important parameter to describe the dynamic response of an instrument. It characterizes the instrument to a step change in the measurand (input). It includes *rise time*, *delay time* and *time constant*.
(ii) Fidelity: It is defined as the degree of the measurement system. It indicates changes in the measurand without any dynamic error.
(iii) Measuring Lag: It is the retardation or delay in the response of a measurement system to changes in the measurand.
(iv) Dynamic Error: It is the difference between the true value of the quantity under measurement changing with time and the measured value of the quantity. It also referred to as ***Measurement error***.

ERRORS IN MEASUREMENTS

Error is the difference between *the true value* and *the measured value* of a quantity such as displacement, pressure, temperature, and the like. No electronic component of instrument is perfectly accurate. All have some error or inaccuracy. The measurements cannot be made with perfect accuracy. It is important to find out how different errors have entered into the measurement and what the accuracy is. A study of error is a first step in finding ways to reduce them. Such study also determines the accuracy of the final result. *Error* is inevitable in any measurement. Well-designed electronic instrumentation systems limit the error to a value that is acceptable in terms of the accuracies required in an engineering analysis or the control of a process.

Limiting or Guarantee Errors

The design, *the materials used* and *the workmanship* are the important factors for the accuracy and precision of an instrument. In most of the instruments the accuracy is guaranteed by the manufacturer for the quality of the instrument to be within a certain percentage of full scale reading. The values of the circuit components, like *resistors*, *capacitors* and *inductors*, are mentioned within a certain percentage of the rated values specified by the manufacturer. The limits of these deviations from the specified value are defined as ***Limiting errors***.

The magnitude of a quantity *Q* having a specified value *Q*1 and a *limiting error* ± _*Q* must have a value between the limits (*Q*1 – _*Q*) and (*Q*1 + _*Q*) or *Q* = (*Q*1 ± *dQ*).
For example, the specified value of a resistor is 560 _ with a limiting error of ±10 _. So, the value of the resistor will be between the limits (100 ± 10) ohm. An error of ± 2 ampere is negligible for the 1000 ampere of current measured, but the same error is not tolerable for the measurement of current of 10 ampere Thus, the quality of measurement is obtained by the *relative error*, *i.e.* the *ratio of limiting error* δQ to the *true value Q* of the quantity under measurement.
The *relative error*, ε_r is given by

$$\varepsilon_r = \frac{\text{Absolute error}}{\text{True value}} = \frac{\delta Q}{Q} = \frac{\varepsilon_0}{Q}$$

When the error of an instrument is known, the effect of this error can be computed when combined with other errors. The signs of *relative errors* are given and must be preserved in the calculation.

Types of Errors

There is no measurement with perfect accuracy, but it is important to find out what accuracy actually is and how the different errors are present into the measurement.
The aim of study of errors is to find out the ways to minimize them. Errors may be introduced from different sources. Errors are usually classified as follows:
1. *Gross Errors*,
2. *Systematic Errors*, and
3. *Random Errors*.

1. *Gross Errors*: These errors are largely due to human errors in reading of instruments, incorrect adjustment and improper application of instruments, and computational mistakes. Complete elimination of such errors is probably impossible. The common gross error is the improper use of an instrument for measurement. For example, a well calibrated voltmeter can give an error in reading when connected across a high resistance circuit. The same voltmeter will give more accurate reading when connected in a low resistance circuit. It means the voltmeter has a ―loading effect‖ on the circuit, altering the characteristics by the measurement process.

2. *Systematic Errors*: These errors are shortcomings of instruments, such as defective or worn parts, and effects of the environment on the equipment or the user.
This type of error is usually divided into two different categories:

(i) Instrumental Errors,
(ii) Environmental Errors.

(i) Instrumental Errors: These errors are defined as shortcomings of the instrument. Instrumental errors are inherent in measuring instruments due to their mechanical structure. For example, in the deflection type instrument friction in bearings of various moving components, irregular spring tension, stretching of the spring or reduction in tension due to improper handling or overloading of the instrument may cause incorrect readings, which will result in errors. Other instrumental errors may be due to calibration; improper zero setting, variation in the air gap, etc. Instrumental errors may be avoided by following methods:

(a) Selecting a suitable instrument for the particular measurement;
(b) Applying correction factors after determining the amount of instrumental error;
(c) Calibrating the instrument against a standard instrument.

(ii) Environmental Errors: These errors are due to external conditions surrounding the instruments which affect the measurements. The surrounding conditions may be the changes in temperature, humidity, barometric pressure, or of magnetic or electrostatic fields. Thus, a change in ambient temperature at which the instrument is used causes a change in the elastic properties of the spring in a moving-coil mechanism and so causes an error in the reading of the instrument. To reduce the effects of external conditions surrounding the instruments the corrective measures are to be taken as follows:

(a) *To provide air-conditioning*,
(b) *Certain components in the instrument should be completely closed i.e., hermetically sealed*, and
(c) *To provide magnetic and electrostatic shields*.

Systematic errors can also be subdivided into:
(a) *Static errors*, and
(b) *Dynamic errors*.

Static errors are caused by limitations of the measuring device or the physical laws governing its behaviour. A static error is introduced in a micrometer when excessive pressure is applied in twisting or rotating the shaft.

Dynamic errors caused by the instrument do not respond fast enough to follow the changes in a measured variable.

3. *Random Errors*: These errors are those errors which are due to unknown causes and they occur even when all systematic errors have been taken care of. This error cannot be corrected by any method of calibration or other known methods of control. Few random errors usually occur in well-designed experiments, but they become important in high-accuracy work. For example, a voltmeter with accurately calibrated is being used in ideal environmental conditions to read voltage of an electric circuitry system. It will be found that the readings vary slightly over the period of observation. This variation cannot be corrected by any method of calibration or other known method of control and it cannot be explained without minute investigation. The only way to offset these errors is by increasing the number of readings and using statistical methods in order to obtain the best approximation of the true value of the quantity under measurement.

STATISTICAL ANALYSIS

A statistical analysis of measurement data allows an analytical determination of the uncertainty of the final test result. The result of a certain measurement method may be predicted on the basis of sample data without having detailed information on all the disturbing factors. To make statistical methods and interpretation meaningful, a large number of measurements are usually required. And also, *systematic errors* should be small compared with *residual* or *random* errors, because statistical treatment of data cannot remove a fixed bias contained in all the measurements.

Arithmetic Mean

The most probable value of a measured variable is the arithmetic mean of the number of readings taken. The best approximation will be made when the number of readings of the same quantity is very large.

Theoretically, an infinite number of readings would give the best result, although in practice, only a finite number of measurements can be made.
For a data set, the mean is the sum of the observations divided by the number of observations. It identifies the central location of the data, sometimes referred to in English as the average. The mean is calculated using the following formula

$$M = \frac{\Sigma(X)}{N}$$

Where Σ = Sum of
X = Individual data points
N = Sample size (number of data points)

Mean Deviation
(i) Mean deviation for ungrouped data:

For n observation $x1$, $x2$, ..., xn, the **mean deviation about their mean** $\bar{x}$ is given by

$$\text{M.D}(\bar{x}) = \frac{\sum |x_i - \bar{x}|}{n}$$

Variance and Standard deviation
The mean, mode, median, and trimmed mean do a nice job in telling where the center of the data set is, but often we are interested in more. For example, a pharmaceutical engineer develops a new drug that regulates iron in the blood. Suppose she finds out that the average sugar content after taking the medication is the optimal level. This does not mean that the drug is effective. There is a possibility that half of the patients have dangerously low sugar content while the other half has dangerously high content. Instead of the drug being an effective regulator, it is a deadly poison. What the pharmacist needs is a measure of how far the data is spread apart. This is what the variance and standard deviation do. First we show the formulas for these measurements. Then we will go through the steps on how to use the formulas.

We define the *variance* to be

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x-\bar{x})^2$$

and the *standard deviation* to be

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x-\bar{x})^2}$$

Variance and Standard Deviation: Step by Step
1. Calculate the mean, x.
2. Write a table that subtracts the mean from each observed value.

3. Square each of the differences.
4. Add this column.
5. Divide by n -1 where n is the number of items in the sample This is the *variance*.
6. To get the *standard deviation* we take the square root of the variance.

STANDARD TEST INPUT SIGNALS

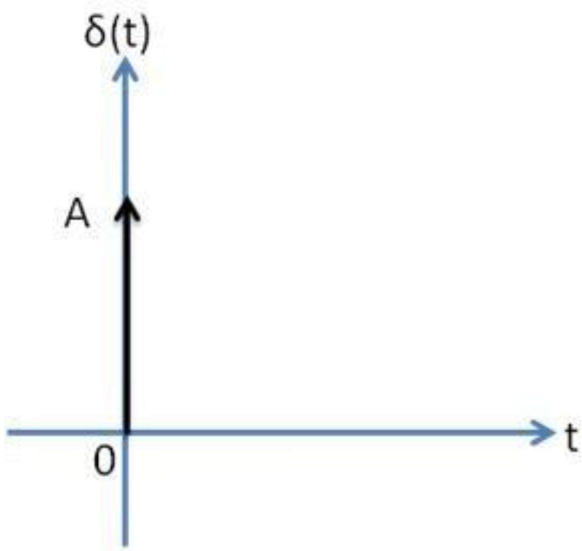
For the analysis point of view, the signals, which are most commonly used as reference inputs, are defined as standard test inputs. The performance of a system can be evaluated with respect to these test signals. Based on the information obtained the design of control system is carried out. The commonly used test signals are1. Step Input signals.2. Ramp Input Signals.3. Parabolic Input Signals. The transient response may be experimental or oscillatory in nature 4. Impulse input signal

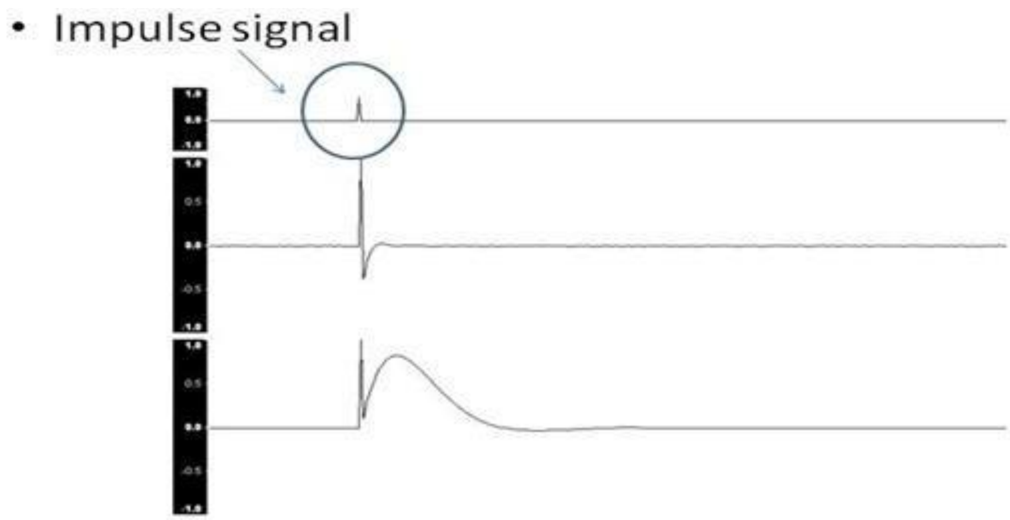
1. Impulse Signal

   Impulse response in control system imitates sudden shock quality of actual input signal. Impulse is the output of system when given by small input. Impulse response emphasis on change in the system in reaction to some external change. It is the reply of the system to the direct delta input.

$$\delta(t) = \begin{cases} A & t = 0 \\ 0 & t \neq 0 \end{cases}$$

   When A=1 then the impulse signal is called Unit impulse signal.



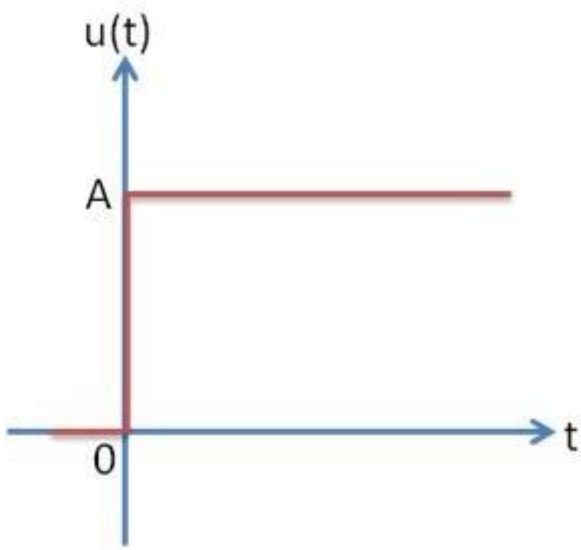


2. <u>Step Signal</u>

The step signal defines the sudden change in properties of actual signal. It is being used to see the transient response of system as it gives you the idea about how the system reply to interruption and somehow the system stability.

$$u(t) = \begin{cases} A & t \geq 0 \\ 0 & t < 0 \end{cases}$$

When A=1, the step is called unit step signal.

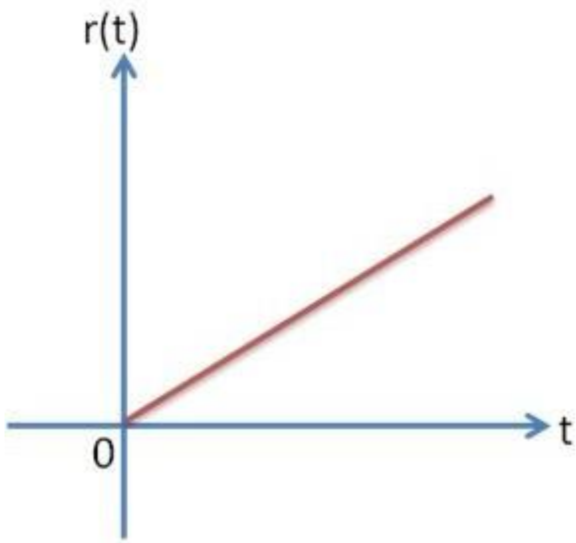


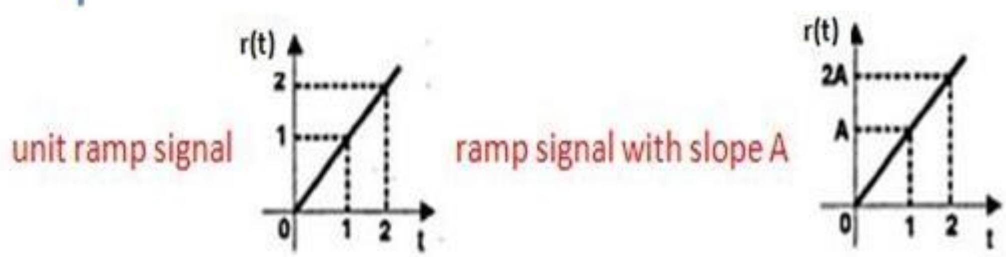
3. Ramp Signal

The ramp signal tells you the constant velocity attribute of actual input signal. It is being used to determine the behaviour of system with the velocity factor.

$$r(t) = \begin{cases} At & t \geq 0 \\ 0 & t < 0 \end{cases}$$

When A=1, ramp signal is called unit ramp signal.



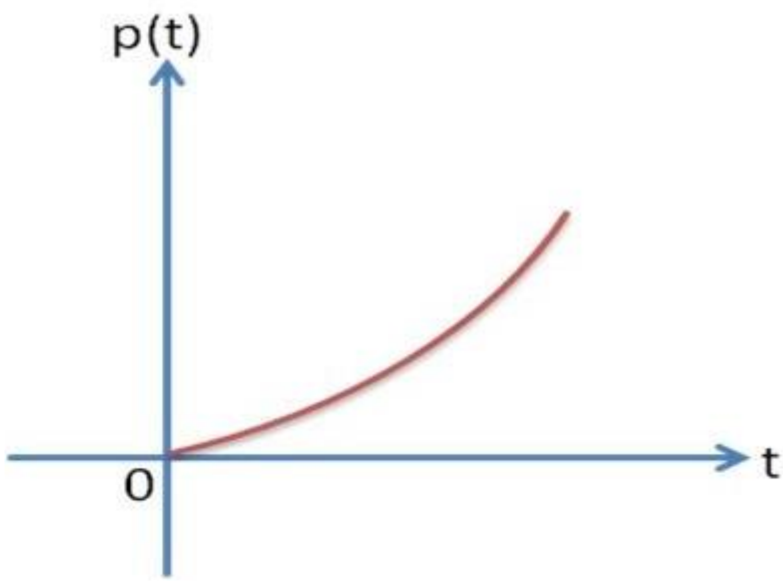


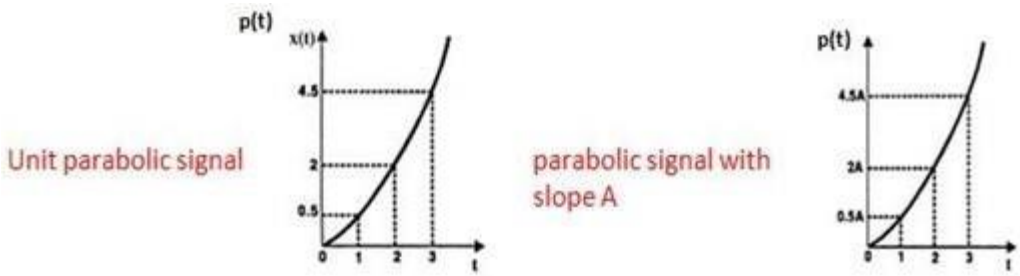
4. Parabolic Signal

Parabolic signal gives the constant acceleration distinction of actual input signal. It gives the idea about how the system will respond along with acceleration.

$$p(t) = \begin{cases} \dfrac{At^2}{2} & t \geq 0 \\ 0 & t < 0 \end{cases}$$

When A=1, the parabolic signal is called unit parabolic signal.





Periodic and aperiodic signals

A CT signal $x(t)$ is said to be *periodic* if it satisfies the following property:

$$x(t) = x(t + T_0),$$

at all time t and for some positive constant $T0$. The smallest positive value of $T0$ that satisfies the periodicity condition, Eq. , is referred to as the *fundamental period* of $x(t)$.
Likewise, a DT signal $x[k]$ is said to be *periodic* if it satisfies

$$x[k] = x[k + K_0]$$

at all time k and for some positive constant $K0$. The smallest positive value of $K0$ that satisfies the periodicity condition, Eq. is referred to as the fundamental period of $x[k]$. A signal that is not periodic is called an *aperiodic* or *non-periodic* signal. Figure shows examples of both periodic and aperiodic

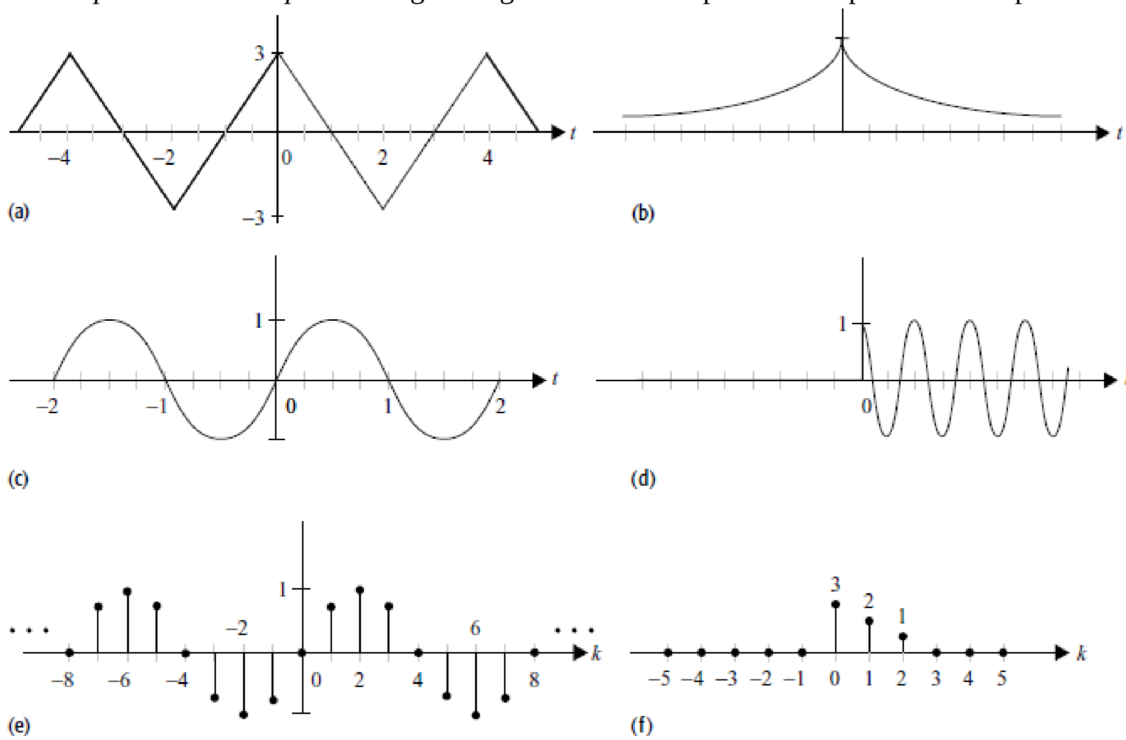


Fig. 1.6. Examples of periodic ((a), (c), and (e)) and aperiodic ((b), (d), and (f)) signals. The line plots (a) and (c) represent CT periodic signals with fundamental periods T_0 of 1.5 and 3, while the stem plot (e) represents a DT periodic signal with fundamental period $K_0 = 10$.

signals. The reciprocal of the fundamental period of a signal is called the *fundamental frequency*. Mathematically, the fundamental frequency is expressed as follows

$$f_0 = \frac{1}{T_0}, \text{ for CT signals,} \quad \text{or} \quad f_0 = \frac{1}{K_0}, \text{ for DT signals,}$$

where $T0$ and $K0$ are, respectively, the fundamental periods of the CT and DT signals. The frequency of a signal provides useful information regarding how fast the signal changes its amplitude. The unit of frequency is *cycles per second* (c/s) or *hertz* (Hz). Sometimes, we also use *radians per second* as a unit of frequency. Since there are 2_ radians (or 360◦) in one cycle, a frequency of $f0$ hertz is equivalent to 2_$f0$ radians per second. If radians per second is used as a unit of frequency, the frequency is referred to as the *angular frequency* and is given by

$$\omega_0 = \frac{2\pi}{T_0}, \text{ for CT signals,} \quad \text{or} \quad \Omega_0 = \frac{2\pi}{K_0}, \text{ for DT signals.}$$

A familiar example of a periodic signal is a sinusoidal function represented mathematically by the following expression:

$$x(t) = A\sin(\omega_0 t + \theta).$$

The sinusoidal signal $x(t)$ has a fundamental period $T_0 = 2\pi/\omega_0$ as we prove next. Substituting t by $t + T_0$ in the sinusoidal function, yields

$$x(t + T_0) = A\sin(\omega_0 t + \omega_0 T_0 + \theta).$$

Since

$$x(t) = A\sin(\omega_0 t + \theta) = A\sin(\omega_0 t + 2m\pi + \theta), \text{ for } m = 0, \pm 1, \pm 2, \ldots,$$

the above two expressions are equal iff $\omega_0 T_0 = 2m\pi$. Selecting $m = 1$, the fundamental period is given by $T_0 = 2\pi/\omega_0$.

The sinusoidal signal $x(t)$ can also be expressed as a function of a complex exponential. Using the Euler identity,

$$e^{j(\omega_0 t + \theta)} = \cos(\omega_0 t + \theta) + j\sin(\omega_0 t + \theta),$$

we observe that the sinusoidal signal $x(t)$ is the imaginary component of a complex exponential. By noting that both the imaginary and real components of an exponential function are periodic with fundamental period $T_0 = 2\pi/\omega_0$, it can be shown that the complex exponential $x(t) = \exp[j(\omega_0 t + \theta)]$ is also a periodic signal with the same fundamental period of $T_0 = 2\pi/\omega_0$.

Although all CT sinusoidals are periodic, their DT counterparts $x[k]$ = $A\sin(\Omega_0 k + \theta)$ may not always be periodic. An arbitrary DT sinusoidal sequence x[k] = $A\sin(\Omega_0 k + \theta)$ is periodic iff $\Omega_0/2\pi$ is a rational number.

Modulated signal – Sampled data pulse modulation and pulse code modulation.

Pulse modulaton

Digital Transmission is the transmittal of digital signals between two or more points in a communications system. The signals can be binary or any other form of discrete-level digital pulses. Digital pulses can not be propagated through a wireless transmission system such as earth's atmosphere or free space.

Alex H. Reeves developed the first digital transmission system in 1937 at the Paris Laboratories of AT & T for the purpose of carrying digitally encoded analog signals, such as the human voice, over metallic wire cables between telephone offices.

Advantages & disadvantages of Digital Transmission

Advantages

--Noise immunity

--Multiplexing(Time domain)

--Regeneration

--Simple to evaluate and measure

Disadvantages

--Requires more bandwidth

--Additional encoding (A/D) and decoding (D/A) circuitry

Pulse Modulation

-- *Pulse modulation* consists essentially *of* sampling analog information signals and then converting those samples into discrete pulses and transporting the pulses from a source to a destination over a physical transmission medium.

--The four predominant methods *of* pulse modulation:

1) pulse width modulation (PWM)

2) pulse position modulation (PPM)

3) pulse amplitude modulation (PAM)

4) pulse code modulation (PCM).

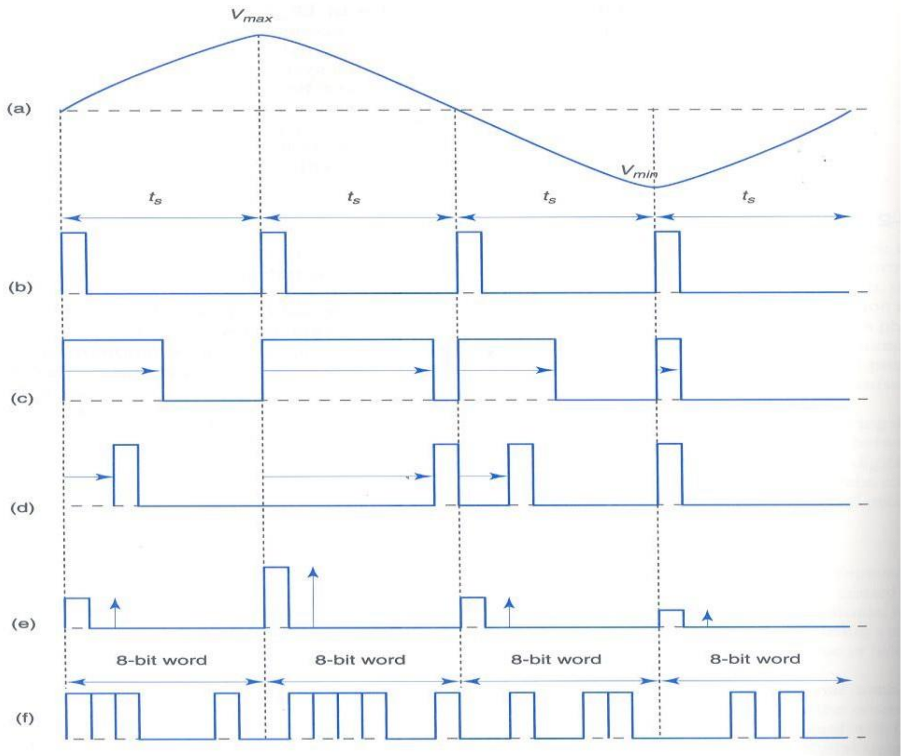


FIGURE 10-1 Pulse modulation: (a) analog signal; (b) sample pulse; (c) PWM; (d) PPM; (e) PAM; (f) PCM

Pulse Width Modulation

--PWM is sometimes called *pulse duration modulation* (PDM) or *pulse length modulation* (PLM), as the width (active portion *of* the duty cycle) *of* a constant amplitude pulse is varied proportional to the amplitude *of* the analog signal at the time the signal is sampled.

--The maximum analog signal amplitude produces the widest pulse, and the minimum analog signal amplitude produces the narrowest pulse. Note, however, that all pulses have the same amplitude.

Pulse Position Modulation

--With PPM, the position *of* a constant-width pulse within a prescribed time slot is varied according to the amplitude *of* the sample *of* the analog signal.

--The higher the amplitude *of* the sample, the farther to the right the pulse is positioned within the prescribed time slot. The highest amplitude sample produces a pulse to the far right, and the lowest amplitude sample produces a pulse to the far left.

Pulse Amplitude Modulation

--With PAM, the amplitude of a constant width, constant-position pulse is varied according to the amplitude *of* the sample *of* the analog signal.

--The amplitude *of* a pulse coincides with the amplitude *of* the analog signal.

--PAM waveforms resemble the original analog signal more than the waveforms for PWM or PPM.

Pulse Code Modulation

--With PCM, the analog signal is sampled and then converted to a serial n-bit binary code for transmission.

--Each code has the same number *of* bits and requires the same length *of* time for transmission

Pulse Modulation

--PAM is used as an intermediate form *of* modulation with PSK, QAM, and PCM, although it is seldom used by itself.

--PWM and PPM are used in special-purpose communications systems mainly for the military but are seldom used for commercial digital transmission systems.

--PCM is by far the most prevalent form *of* pulse modulation and will be discussed in more detail.

Pulse Code Modulation

--PCM is the preferred method *of* communications within the public switched telephone network because with PCM it is easy to combine digitized voice and digital data into a single, high-speed digital signal and propagate it over either metallic or optical fiber cables.

--With PCM, the pulses are of fixed length and fixed amplitude.

--PCM is a binary system where a pulse or lack of a pulse within a prescribed time slot represents either a logic 1 or a logic 0 condition.

--PWM, PPM, and PAM are digital but seldom binary, as a pulse does not represent a single binary digit (bit).

PCM system Block Diagram

--The band pass filter limits the frequency of the analog input signal to the standard voice-band frequency range of 300 Hz to 3000 Hz.

--The sample- and- hold circuit periodically samples the analog input signal and converts those samples to a multilevel PAM signal.

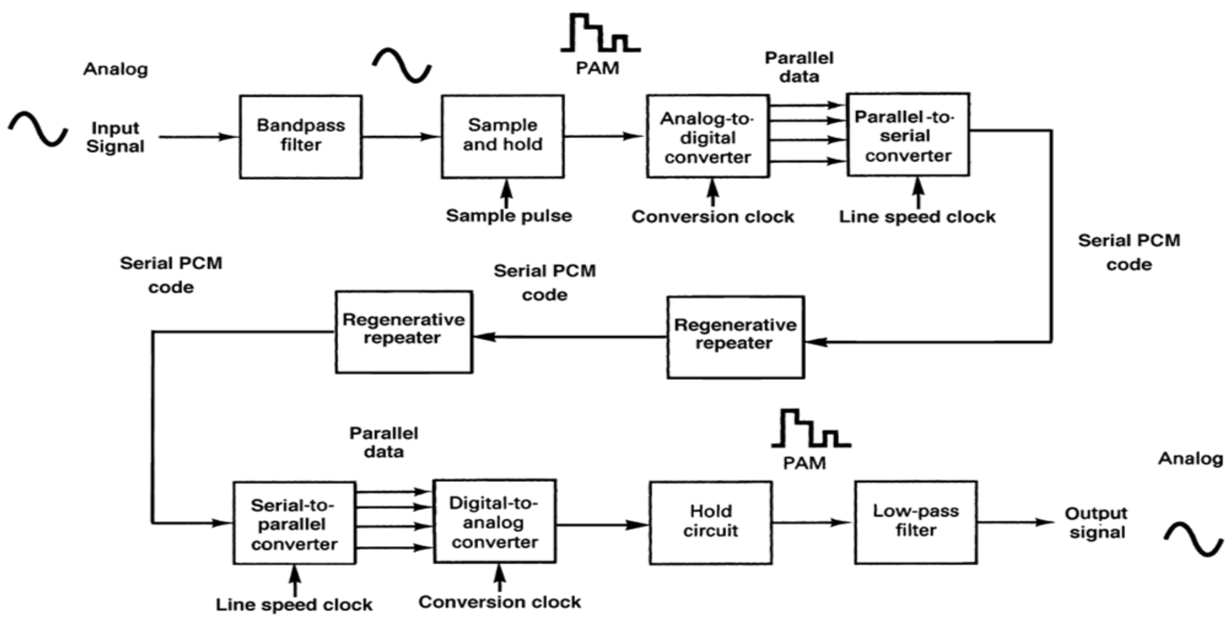
--The analog-to-digital converter (ADC) converts the PAM samples to parallel PCM codes, which are converted to serial binary data in the parallel-to-serial converter and then outputted onto the transmission linear serial digital pulses.

--The transmission line repeaters are placed at prescribed distances to regenerate the digital pulses.

--In the receiver, the serial-to-parallel converter converts serial pulses received from the transmission line to parallel PCM codes.

--The digital-to-analog converter (DAC) converts the parallel PCM codes to multilevel PAM signals.

--The hold circuit is basically a low pass filter that converts the PAM signals back to its original analog form.



The block diagram of a single-channel, simplex (one-way only) PCM system.

PCM Sampling:

--The function of a sampling circuit in a PCM transmitter is to periodically sample the continually changing analog input voltage and convert those samples to a series of constant- amplitude pulses that can more easily be converted to binary PCM code.

--A sample-and-hold circuit is a nonlinear device (mixer) with two inputs: the sampling pulse and the analog input signal.

--For the ADC to accurately convert a voltage to a binary code, the voltage must be relatively constant so that the ADC can complete the conversion before the voltage level changes. If not, the ADC would be continually attempting to follow the changes and may never stabilize on any PCM code.

--Essentially, there are two basic techniques used to perform the sampling function

1) natural sampling

2) flat-top sampling

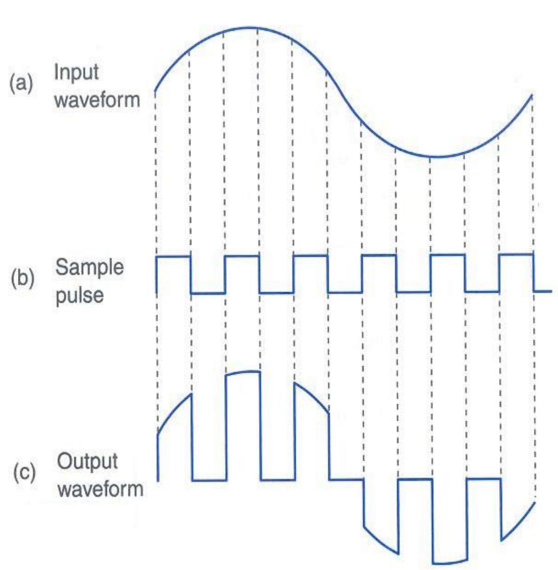


FIGURE 10-3 Natural sampling: (a) input analog signal; (b) sample pulse; (c) sampled output

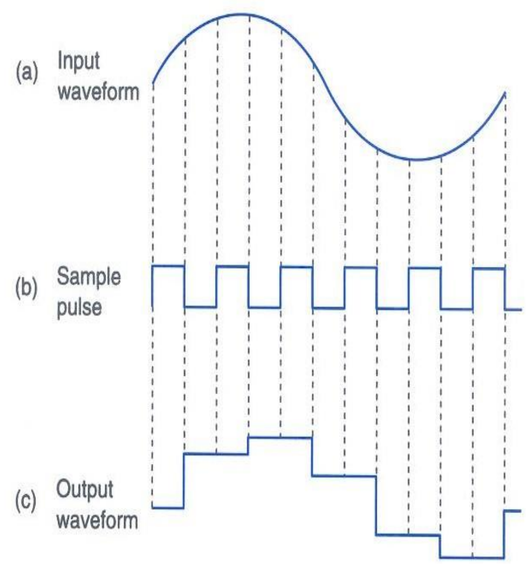


FIGURE 10-4 Flat-top sampling: (a) input analog signal; (b) sample pulse; (c) sampled output

--Natural sampling is when tops of the sample pulses retain their natural shape during the sample interval, making it difficult for an ADC to convert the sample to a PCM code.

--The most common method used for sampling voice signals in PCM systems is *flat- top sampling*, which is accomplished in a *sample-and-hold circuit.*

-- The purpose of a sample-and-hold circuit is to periodically sample the continually changing analog input voltage and convert those samples to a series of constant-amplitude PAM voltage levels.

Sampling Rate

--The *Nyquist sampling theorem* establishes the *minimum Nyquist sampling rate (fs)* that can be used for a given PCM system.

--For a sample to be reproduced accurately in a PCM receiver, each cycle of the analog input signal *(fa)* must be sampled at least twice.

--Consequently, the minimum sampling rate is equal to twice the highest audio input frequency.

--Mathematically, the minimum Nyquist sampling rate is:

$$fs \geq 2fa$$

--If *fs* is less than two times *fa* an impairment called *alias or foldover distortion* occurs.

Quantization and the Folded Binary Code:Quantization

--*Quantization* is the process of converting an infinite number of possibilities to a finite number of conditions.

--Analog signals contain an infinite number of amplitude possibilities.

--Converting an analog signal to a PCM code with a limited number of combinations requires quantization.

Folded Binary Code

--With quantization, the total voltage range is subdivided into a smaller number of sub-ranges.

--The PCM code shown in Table 10-2 is a three-bit sign- magnitude code with eight possible combinations (four positive and four negative).

--The leftmost bit is the sign bit (1 = + and 0 = -), and the two rightmost bits represent magnitude.

-- This type of code is called *a folded binary code* because the codes on the bottom half of the table are a mirror image of the codes on the top half, except for the sign bit.

Table 10-2 Three-Bit PCM Code

8 Sub ranges

Sign	Magnitude		Decimal value	Quantization range
1	1	1	+3	+2.5 V to +3.5 V
1	1	0	+2	+1.5 V to +2.5 V
1	0	1	+1	+0.5 V to +1.5 V
1	0	0	+0	0 V to +0.5 V
0	0	0	−0	0 V to −0.5 V
0	0	1	−1	−0.5 V to −1.5 V
0	1	0	−2	−1.5 V to −2.5 V
0	1	1	−3	−2.5 V to −3.5 V

Quantization

--With a folded binary code, each voltage level has one code assigned to it except zero volts, which has two codes, 100 (+0) and 000 (-0).

--The magnitude difference between adjacent steps is called the *quantization interval* or *quantum.*

--For the code shown in Table 10-2, the quantization interval is 1 V.

--If the magnitude of the sample exceeds the highest quantization interval, *overload distortion* (also called *peak limiting)* occurs.

--Assigning PCM codes to absolute magnitudes is called quantizing.

--The magnitude of a quantum is also called the *resolution.*

--The resolution is equal to the voltage of the *minimum step size,* which is equal to the voltage of the *least significant bit* (V_{lsb}) of the PCM code.

--The smaller the magnitude of a quantum, the better (smaller) the resolution and the more accurately the quantized signal will resemble the original analog sample.

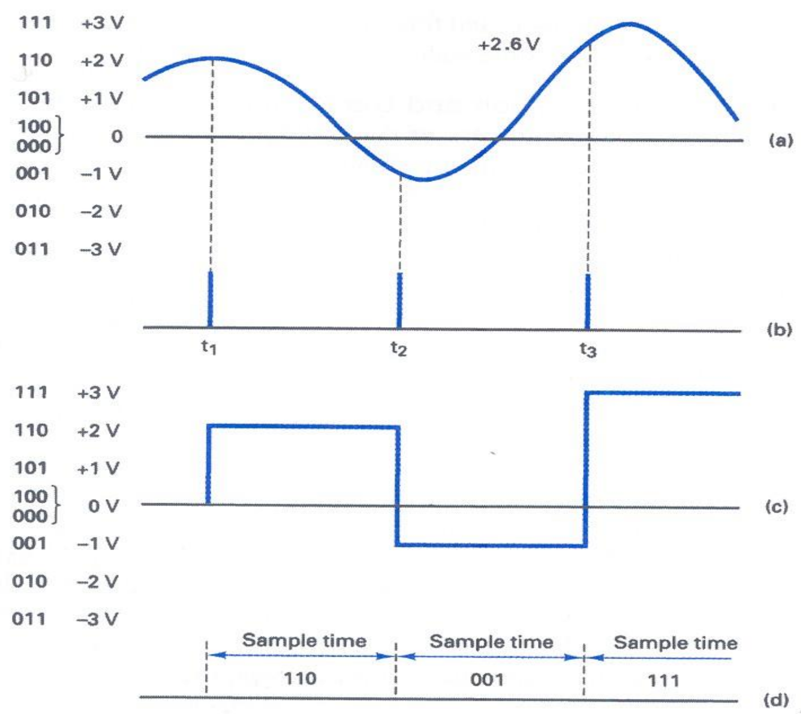


FIGURE 10-8 (a) Analog input signal; (b) sample pulse; (c) PAM signal; (d) PCM code

--For a sample, the voltage at *t3* is approximately +2.6 V. The folded PCM code is

$$\frac{\text{sample voltage}}{\text{resolution}} = \frac{2.6}{1} = 2.6$$

--There is no PCM code for +2.6; therefore, the magnitude of the sample is rounded off to the nearest valid code, which is 111, or +3 V.

--The rounding-off process results in a quantization error of 0.4 V.

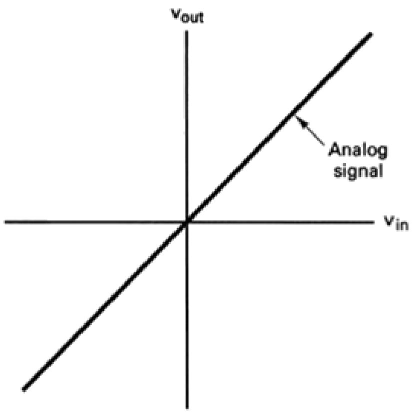
--The likelihood of a sample voltage being equal to one of the eight quantization levels is remote.

--Therefore, as shown in the figure, each sample voltage is rounded off (quantized) to the closest available level and then converted to its corresponding PCM code.

--The rounded off error is called the called the *quantization error (Qe).*

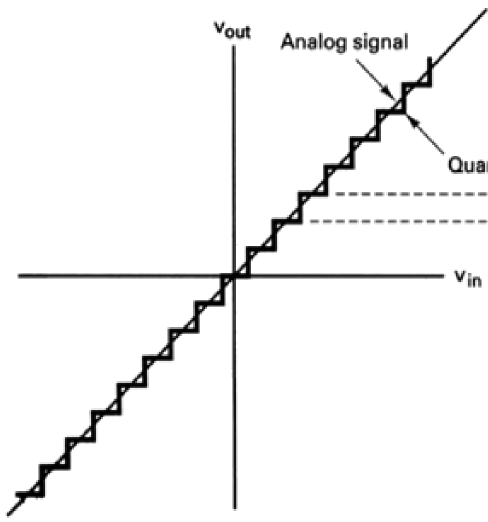
--To determine the PCM code for a particular sample voltage, simply divide the voltage by the resolution, convert the quotient to an n-bit binary code, and then add the sign bit.

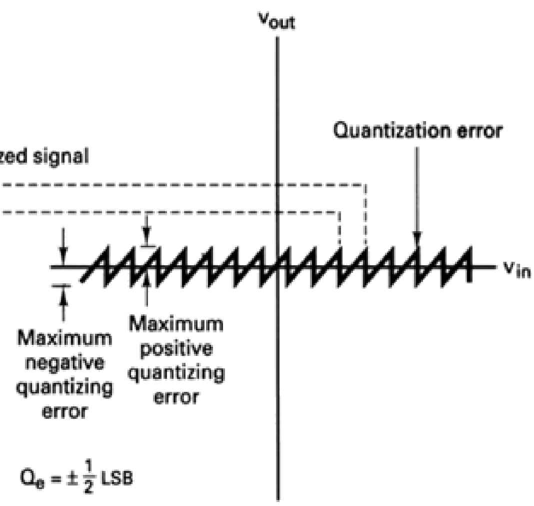
Linear input-versus-output transfer curve



$$Q_e = \frac{\text{resolution}}{2}$$

Linear transfer function





Quantization Quantization error *(Qe)*

1) For the PCM coding scheme shown in Figure 10-8, determine the quantized voltage, quantization error *(Qe)* and PCM code for the analog sample voltage of + 1.07 V.

A) To determine the quantized level, simply divide the sample voltage by resolution and then round the answer off to the nearest quantization level:

$$\frac{\mathbf{+1.07V}}{\mathbf{1V}} = \mathbf{1.07 = 1}$$

The quantization error is the difference between the original sample voltage and the quantized level, or *Qe* = 1.07 -1 = 0.07

From Table 10-2, the PCM code for + 1 is 101.

Dynamic Range (DR): It determines the number of PCM bits transmitted per sample.

-- Dynamic range is the ratio of the largest possible magnitude to the smallest possible magnitude (other than zero) that can be decoded by the digital-to-analog converter in the receiver.

Signal-to-Quantization Noise Efficiency

--For linear codes, the magnitude change between any two successive codes is the same.

--Also, the magnitude of their quantization error is also same.

The maximum quantization noise is half the resolution. Therefore, the worst possible signal voltage- to-quantization noise voltage ratio (SQR) occurs when the input signal is at its minimum amplitude (101 or 001.

For input signal maximum amplitude

SQR = maximum voltage / quantization noise

$$SQR_{(\max)} = \frac{V_{\max}}{Q_e}$$

SQR is not constant

$$SQR_{(dB)} = 10 \log \frac{v^2/R}{(q^2/12)/R}$$

where R = resistance (ohms)

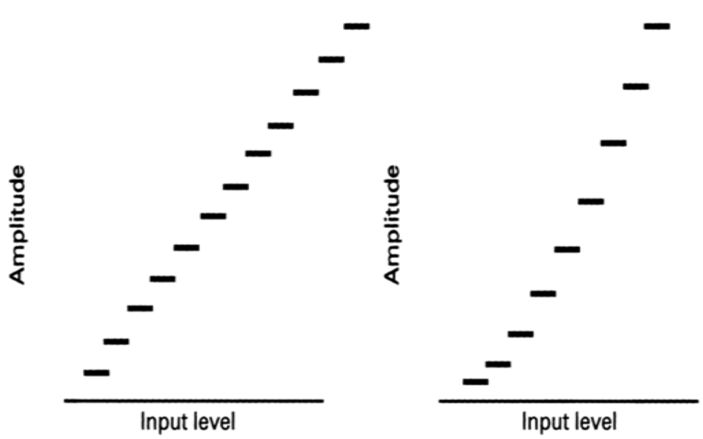
v = rms signal voltage (volts)

q = quantization interval (volts)

v^2/R = average signal power (watts)

$(q^2/12)/R$ = average quantization noise power (watts)

Linear vs. Nonlinear PCM codes



Linear Nonlinear

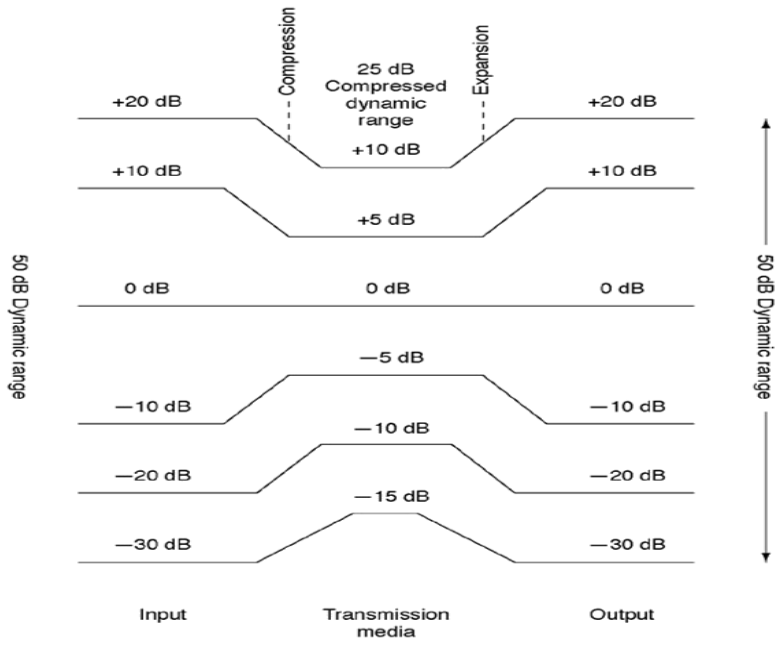
Companding

--Companding is the process of compressing and then expanding

--High amplitude analog signals are compressed prior to txn. and then expanded in the receiver

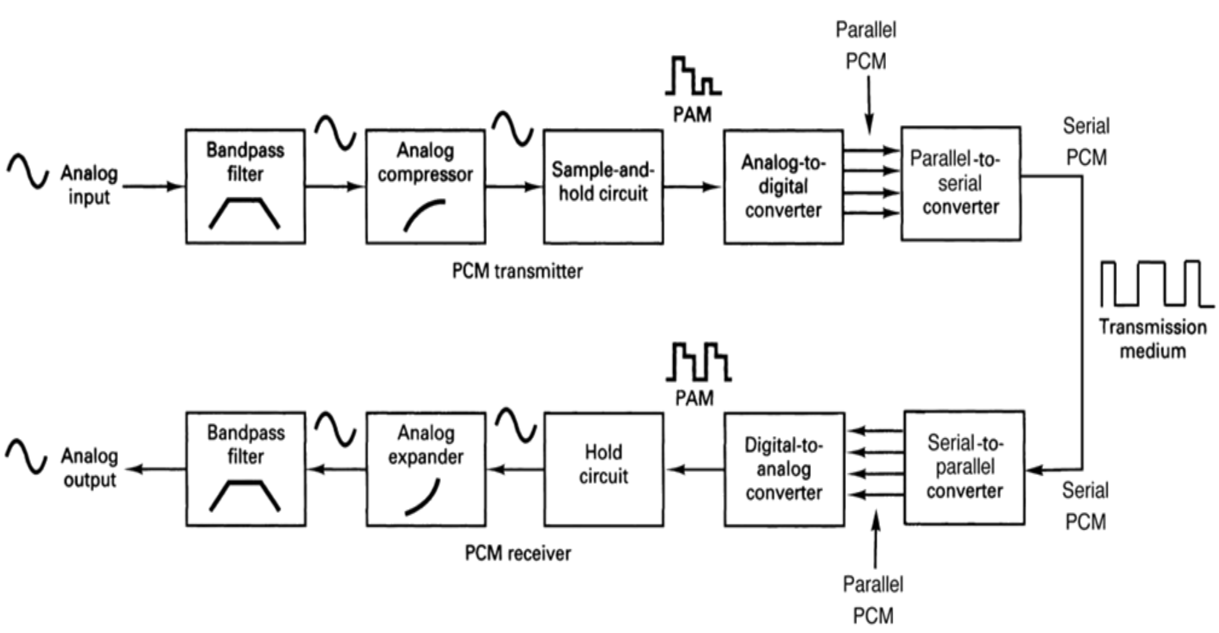
--Higher amplitude analog signals are compressed and Dynamic range is improved

--Early PCM systems used analog companding, where as modern systems use digital companding.



Basic companding process

Analog companding



PCM system with analog companding

--In the transmitter, the dynamic range of the analog signal is compressed, and then converted o a linear PCM code.

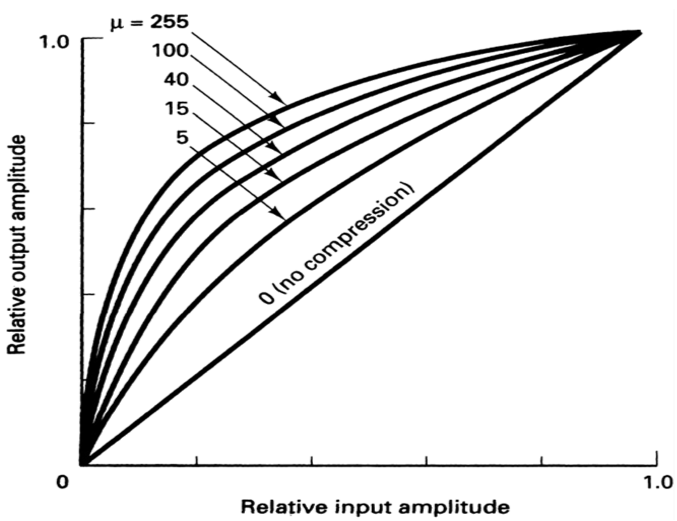
--In the receiver, the PCM code is converted to a PAM signal, filtered, and then expanded back to its original dynamic range.

-- There are two methods of analog companding currently being used that closely approximate a logarithmic function and are often called log-PCM codes.

The two methods are 1) μ-law and

2) A-law

μ-law companding



$$V_{out} = \frac{V_{max} \ln\left(1 + \mu \frac{V_{in}}{V_{max}}\right)}{\ln(1+\mu)}$$

where Vmax = maximum uncompressed analog input amplitude(volts)

Vin = amplitude of the input signal at a particular instant of time (volts)

μ = parameter used tio define the amount of compression (unitless)

Vout = compressed output amplitude (volts)

A-law companding

--A-law is superior to μ-law in terms of small-signal quality

--The compression characteristic is given by

$$|y| = \begin{cases} \dfrac{A|x|}{1+\log A}, & 0 \le |x| \le \dfrac{1}{A} \\ \dfrac{1+\log(A|x|)}{1+\log A}, & \dfrac{1}{A} \le |x| \le 1 \end{cases}$$

where y = Vout

x = Vin / Vmax

Digital Companding: Block diagram refer in text book.

--With digital companding, the analog signal is first sampled and converted to a linear PCM code, and then the linear code is digitally compressed.

-- In the receiver, the compressed PCM code is expanded and then decoded back to analog.

-- The most recent digitally compressed PCM systems use a 12- bit linear PCM code and an 8-bit compressed PCM code.

Digital compression error

--To calculate the percentage error introduced by digital compression

$$\%error = \frac{\text{12-bit encoded voltage} - \text{12-bit decoded voltage}}{\text{12-bit decoded voltage}} \times 100$$

PCM Line speed

--Line speed is the data rate at which serial PCM bits are clocked out of the PCM encoder onto the transmission line. Mathematicaly,

$$\text{Line speed} = \frac{\text{samples}}{\text{second}} \times \frac{\text{bits}}{\text{sample}}$$

Delta Modulation

--*Delta modulation* uses a single-bit PCM code to achieve digital transmission of analog signals.

--With conventional PCM, each code is a binary representation of both the sign and the magnitude of a particular sample. Therefore, multiple-bit codes are required to represent the many values that the sample can be.

--With delta modulation, rather than transmit a coded representation of the sample, only a single bit is transmitted, which simply indicates whether that sample is larger or smaller than the previous sample.

--The algorithm for a delta modulation system is quite simple.

--If the current sample is smaller than the previous sample, a logic 0 is transmitted.

--If the current sample is larger than the previous sample, a logic 1 is transmitted.

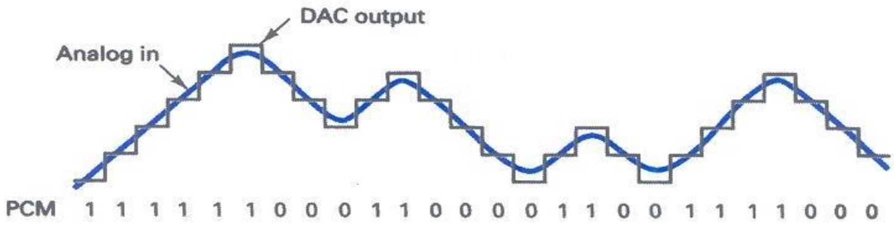


FIGURE 10-21 Ideal operation of a delta modulation encoder

Differential DM

--With Differential Pulse Code Modulation (DPCM), the difference in the amplitude of two successive samples is transmitted rather than the actual sample. Because the range of sample differences is typically less than the range of individual samples, fewer bits are required for DPCM than conventional PCM.

UNIT – II
DATA TRANSMISSION, TELEMETRY AND DAS

Methods of Data Transmission – General Telemetry System. Frequency Modulation (FM), Pulse Modulation (PM), Pulse Amplitude Modulation (PAM), Pulse Code Modulation (PCM) Telemetry. Comparison of FM, PM, PAM and PCM. Analog and Digital Data Acquisition Systems – Components of Analog DAS – Types of Multiplexing Systems: Time Division and Frequency Division Multiplexing – Digital DAS – Block Diagram — Modern Digital DAS (Block Diagram)

INTRODUCTION:

The modern measurement and process control system is made up of number of components. Such various components of the system may be placed far away from each other. Hence it is necessary to have a link or some sort of communication mode such that the data or information related to the measurement of parameter may be transmitted to other components of the system. To control various processes, it is necessary to collect the data, process it and display or record it.

Data transmission and telemetry means a process the information or data related to the parameter being measured is transmitted to the remote locations for further processing recording and displaying it. Many times the measurement is done with the help of suitable transducers and appropriate signal conditioning circuits. Many times these measurement points are located at inaccessible places. So to have a communication with all such locations, a modern technology called **Telemetry** is used extensively. The **Telemetry** is defined as a technology which allows user to collect information from inaccessible and inconvenient locations and to transmit it to the accessible places to process, record and display the information in presentable form. The **Telemetry** can also be defined as measurement at a distance.

DATA TRANSMISSION METHODS

The modern industrial plants are considerably complex with several stages. Hence the size of such complex modern plants is also considerably large. So to monitor and control various process simultaneously from one point (normally called control room) it is necessary to collect data of several parameters of the systems measured at different locations. The transmission of such information from the remote places in the plant to the accessible point in the control room is the significant task or process in the modern instrumentation system. In most of the industrial instrumentation systems, the most commonly measured variables are pressure, temperature, flow, stress, strain, velocity etc. These physical quantities are measured using measuring devices such as thermometers, pressure guages, fluid flow rate meters, velocity meters etc. To avoid excessive time lag in measurements, it is necessary to have fast transmission of the data.

The methods of data transmission are based on following to important parameters.

i) The process variable being measured, and

ii) The distance over which the data is to be transmitted.

Base on above parameters, the data transmission methods are classified as,

i) Pneumatic transmission,

ii) Hydraulic transmission, and

iii) Electrical and electronic transmission.

Out of these three methods, the modern instrumentation and measurement systems use electrical and electronic data transmission method. In this chapter, we will discuss this data transmission method in detail.

BASIC TELEMETRY SYSTEM:

The block diagram of a basic telemetry system is as shown in the Fig. 8.1.

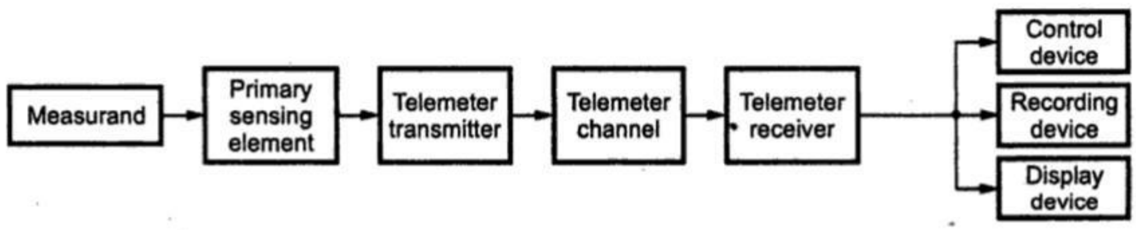


Fig. 8.1 Block diagram of basic telemetry system

The basic telemetry system consists three stages namely input stage, intermediate stage and output stage. The **input stage** consists **primary sensing element** which actually measures the physical quantity. The **intermediate stage** is made up of particularly three elements are follows.

A) Telemeter transmitter : This element converts the output of the primary sensing element into an electrical signal by means of appropriate electronic circuitary.

B) Telemeter channel : The electrical signal in relation with the input physical quantity being measured is transmitted over a distance through a channel. This is called **Telemeter channel.**

C) Telemeter receiver : This element of the intermediate stage receives the electrical signal transmitted through the telemeter channel. This receiver is placed over a distance from the measuring point at remote location. The function of the telemeter receiver is to convert the received electrical signal into a usable form so that it can be recorded or displayed.

The **output stage** consists **end devices** such as **recording device** to record data, **display device** to display the data or **control device** to take corrective action on measurand through feedback loop to control the output.

FREQUENCY MODULATION (F.M.) TELEMETRY SYSTEM:

In the R.F. telemetry systems, FM telemetry system is the earliest system which is still used in the telemetry field. A simple FM telemetry system used for mixing of various data channels is as shown in the Fig. 8.8.

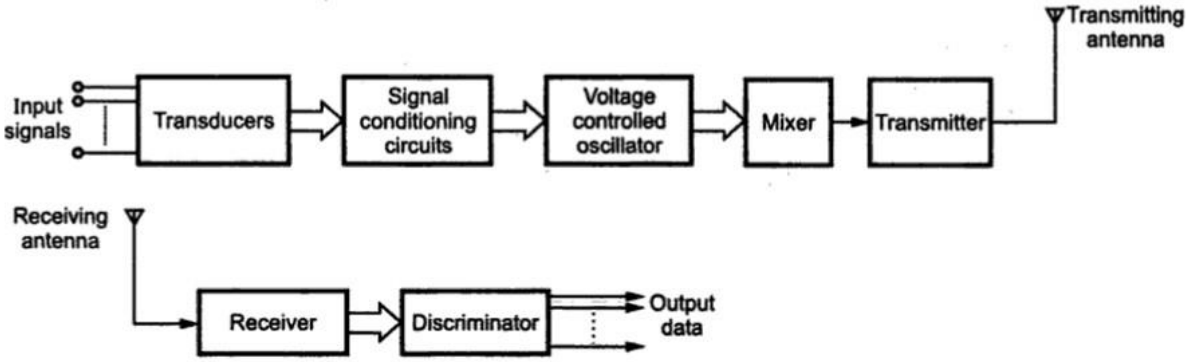


Fig. 8.8 FM telemetry system

Using transducers, different quantities are measured. The output of the transducer is obtained in the representable from by using appropriate signal conditioning circuits. The outputs of the signal conditioning circuits is given to the Voltage Controlled Oscillator (VCO) stage. There are number of VCOs present where each oscillator operates at a dedicated frequency output of each signal conditioner circuit modulates the frequency of the VCO and it is presented for radio transmission. As each VCO is assigned with a separate frequency of the frequency spectrum, so each signal can be modulated without interfering with other signals.

At receiver end, the FM demodulator called as **discriminator** is used. This discriminator is tuned to the frequency of each subcarrier and the bandwidth is equal to that of the modulated subcarrier. So when the value of the measured quantity changes, accordingly the output signal of the discriminator changes.

PULSE AMPLITUDE MODULATION (PAM) TELEMETRY:

The main disadvantages of the FM telemetry system is that the capacity of channels offered is less. So the basic need is to have higher capacity of channel than offered by the FM telemetry system within a limited bandwidth. To fulfil such requirement, the **Pulse Amplitude Modulation (PAM) telemetry system** is used extensively which empolys **time division multiplexing** technique.

Consider a basic time division multiplexing system as shown in the Fig. 8.9. All the channels use same frequency band of the alloted frequency spectrum but at different time. The commutator is used to sample signal of each channel in sequence. The amplitude of each sample represents the instantaneous value of the signal at that point. The sequence starts from first channel and the samples from other channels are interleaved from the first one by using bypass intervals.

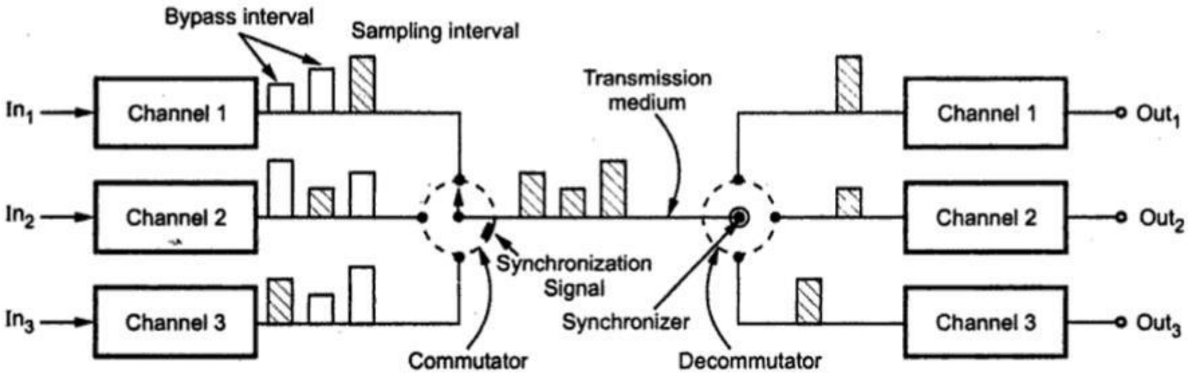
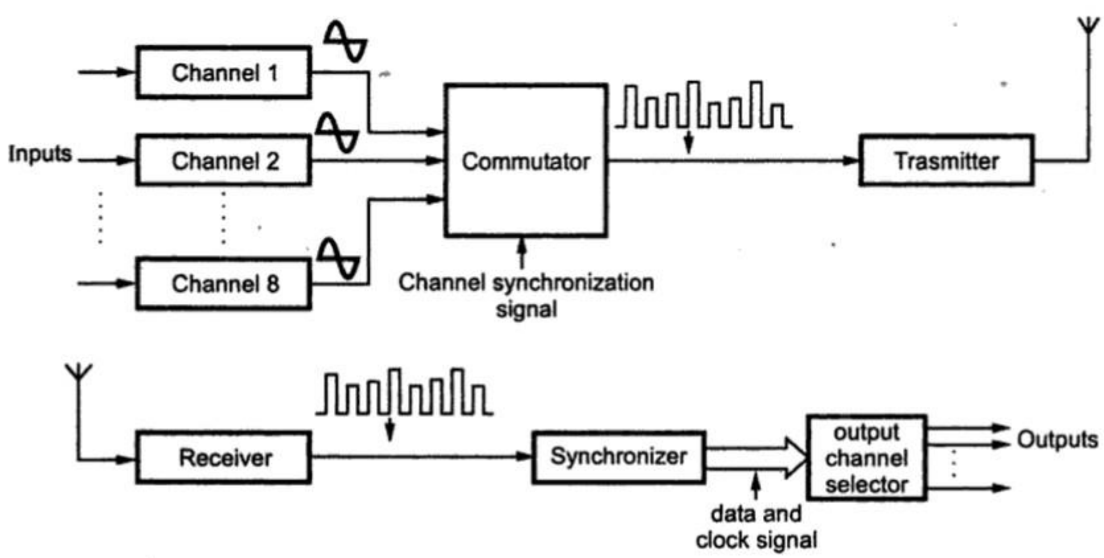


Fig. 8.9 Basic time division multiplexing system

As none of channel is monitored continuously, it is necessary that the rate of sampling must be higher so that in between sampling intervals, the amplitude of the channel does not vary much. And the information in the original signal is preserved. Typically the sampling rate in the practical telemetry system is five times the highest frequency component in the sampled signal. For example, in any general telemetry system if the highest frequency component is 50 Hz, then the sampling rate is selected as 250 times per second. Hence for 8 channels in the system, the samples per second that must be taken by commutator are 2000.

At the receiving end, the decommutator operates at exactly same frequency at which the commutator at the transmitting end operates. The main function of the decommutator is to distribute the multiplexed signal to proper output channel. For the precise timing, the commutator and the decommutator are synchronized properly using the synchronizing signal.



The PAM telemetry system uses same time division multiplexing system. It is the simplest form as the samples are transmitted with no modification. The data at the receiving end is demodulated only when the channels are properly recogonized. A simple PAM telemetry system is as shown in the Fig. 8.10.

PULSE CODE MODULATION (PCM) TELEMETRY SYSTEM:

The Pulse Code Modulation (PCM) telemetry system is as shown in the Fig. 8.11.

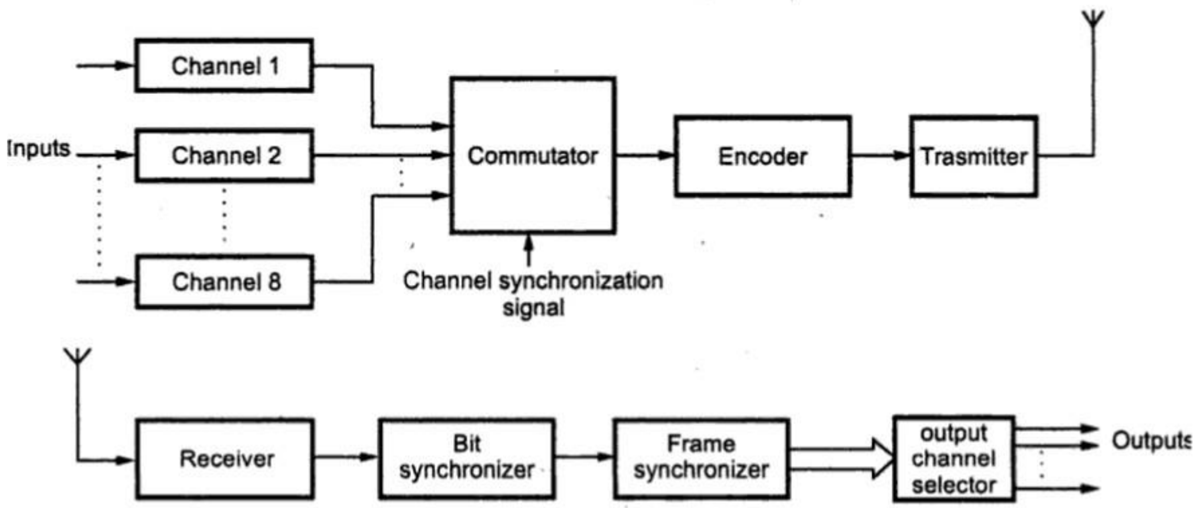


Fig. 8.11 PCM telemetry system

The PCM telemetry system also make used of the time division multiplexing system. The main difference with the PAM telemetry system is that in the PCM telemetry system, an encoder is used after the commutator stage. The function of the encoder is to accept each PAM sample and convert it into a binary number and shift the bits of each number serially. The encoder converts zero amplitude pulse to the binary number "0"; while the full scale pulse into binary number "1023" for examples. Each number is exactly proportional to the instantaneous amplitude of the signal at the measuring point.

The receiver section is synchronized on the serial data stream. The bit synchronizer and the frame synchronizer identify each sequence of bits and converts it into useful outputs. As the measured data is represented in the form of binary weighted codes, the system is known as pulse code modulation telemetry system.

UNIT – III

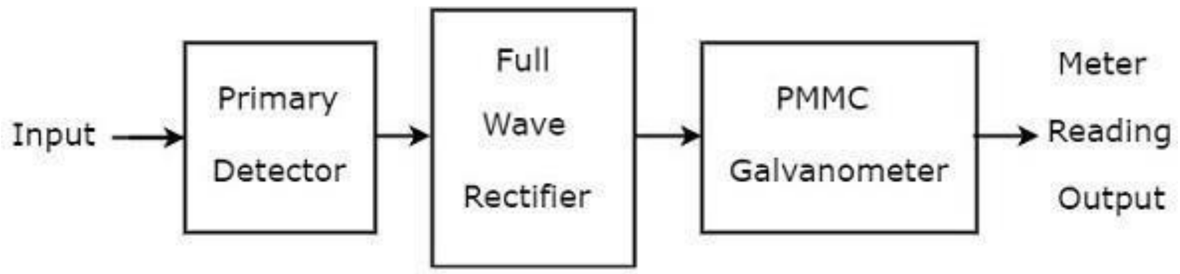
SIGNAL ANALYZERS, DIGITAL METERS

Wave Analysers- Frequency Selective Analyzers, Heterodyne, Application of Wave Analyzers-Harmonic Analyzers, Total Harmonic Distortion, Spectrum Analyzers, Basic Spectrum Analyzers, Spectral Displays, Vector Impedance Meter, Q Meter. Peak Reading and RMS Voltmeters, Digital Voltmeters - Successive Approximation, Ramp and Integrating Type-Digital Frequency Meter-Digital Multimeter-Digital Tachometer

WAVE ANALYZERS:

Basic Wave Analyzer

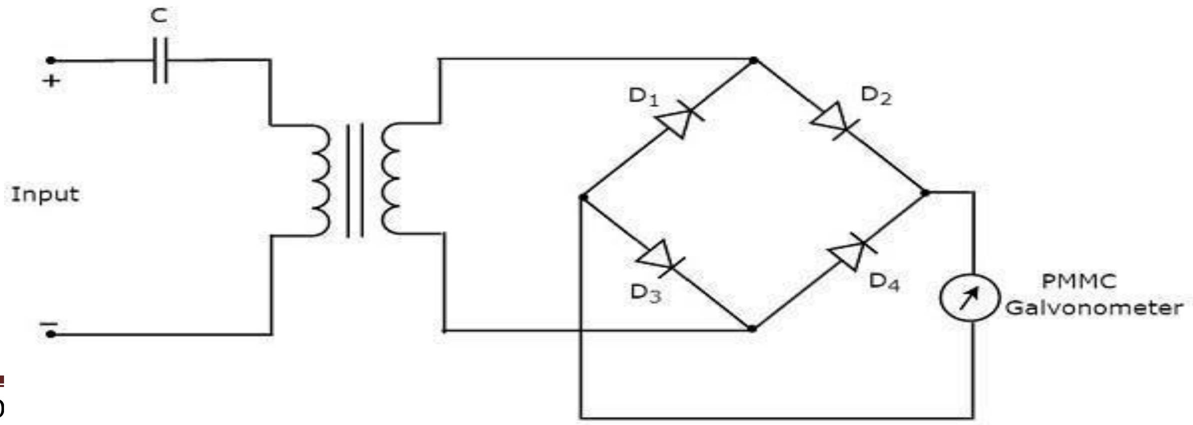
Basic wave analyzer mainly consists of three blocks − the primary detector, full wave rectifier, and PMMC galvanometer. The **block diagram** of basic wave analyzer is shown in below figure −



The **function** of each block present in basic wave analyzer is mentioned below.

- **Primary Detector** − It consists of an LC circuit. We can adjust the values of inductor, L and capacitor, C in such a way that it allows only the desired harmonic frequency component that is to be measured.
- **Full Wave Rectifier** − It converts the AC input into a DC output.
- **PMMC Galvanometer** − It shows the peak value of the signal, which is obtained at the output of Full wave rectifier.

We will get the corresponding circuit diagram, just by replacing each block with the respective component(s) in above block diagram of basic wave analyzer. So, the **circuit diagram** of basic wave analyzer will look like as shown in the following figure −



This basic wave analyzer can be used for analyzing each and every harmonic frequency component of a periodic signal.

Types of Wave Analyzers

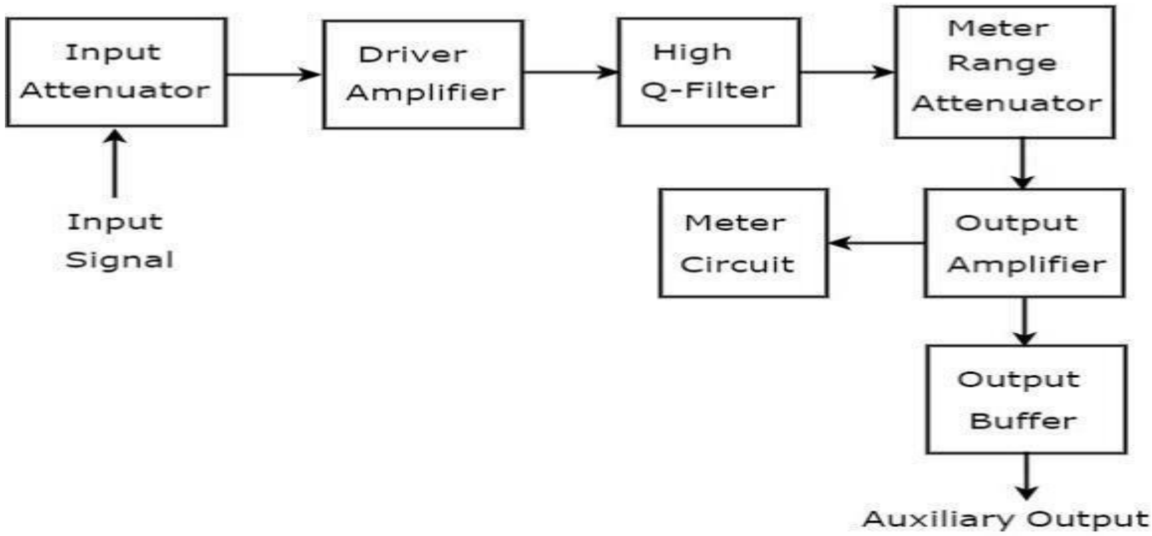
Wave analyzers can be classified into the following **two types**.

- Frequency Selective Wave Analyzer
- Superheterodyne Wave Analyzer

Now, let us discuss about these two wave analyzers one by one.

Frequency Selective Wave Analyzer

The wave analyzer, used for analyzing the signals are of AF range is called frequency selective wave analyzer. The **block diagram** of frequency selective wave analyzer is shown in below figure.



Frequency selective wave analyzer consists a set of blocks. The **function** of each block is mentioned below.

- **Input Attenuator** − The AF signal, which is to be analyzed is applied to input attenuator. If the signal amplitude is too large, then it can be attenuated by input attenuator.
- **Driver Amplifier** − It amplifies the received signal whenever necessary.
- **High Q-filter** − It is used to select the desired frequency and reject unwanted frequencies. It consists of two RC sections and two filter amplifiers & all these are cascaded with each other. We can vary the capacitance values for changing the range of frequencies in powers of 10. Similarly, we can vary the resistance values in order to change the frequency within a selected range.
- **Meter Range Attenuator** − It gets the selected AF signal as an input & produces an attenuated output, whenever required.
- **Output Amplifier** − It amplifies the selected AF signal if necessary.
- **Output Buffer** − It is used to provide the selected AF signal to output devices.

- **Meter Circuit** − It displays the reading of selected AF signal. We can choose the meter reading in volt range or decibel range.
- This instrument is used in the MHz range. The input signal to be analysed is heterodyned to a higher IF by an internal local oscillator. Tuning the local oscillator shifts various signal frequency components into the pass band of the IF amplifier. The output of the IF amplifier is rectified and is applied to the metering circuit. The instrument using the heterodyning principle is called a heterodyning tuned voltmeter.

HETRODYNE ANALYZERS:

This instrument is used in the MHz range. The input signal to be analysed is heterodyned to a higher IF by an internal local oscillator. Tuning the local oscillator shifts various signal frequency components into the pass band of the IF amplifier. The output of the IF amplifier is rectified and is applied to the metering circuit. The instrument using the heterodyning principle is called a heterodyning tuned voltmeter.

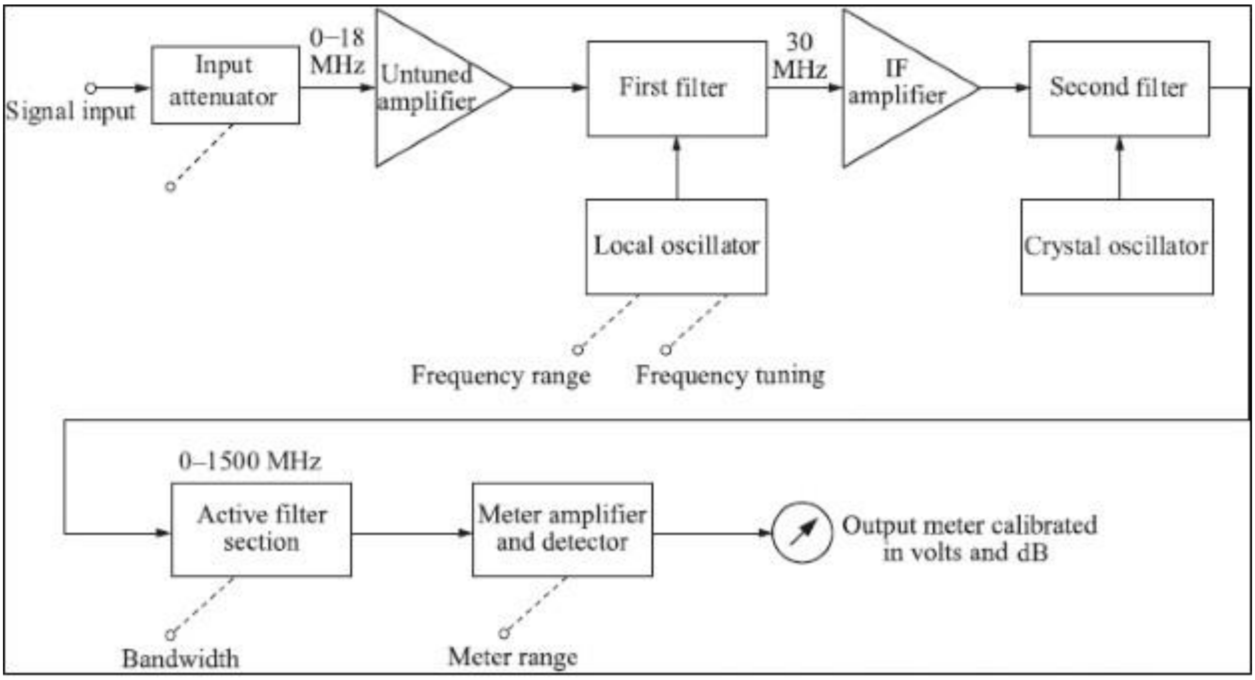


Figure 6 - Block Diagram of Heterodyne Wave Analyzer

Working –

- The input signal to be analyzed is heterodyned to a higher IF by an internal local oscillator
- Tuning the local oscillator shifts various signal frequency components into the pass band of the IF amplifier
- The output of the IF amplifier is rectified and is applied to the metering circuit. The instrument using the heterodyning principle is called a heterodyning tuned voltmeter
- The operating frequency range of this instrument is from 10 kHz to 18 MHz in 18 overlapping bands selected by the frequency range control of the local oscillator. The bandwidth is controlled by an active filter and can be selected at 200, 1000, and 3000

Hz

Applications of Wave Analyzers:

Wave analyzers have very important applications in the following fields:

1) Electrical measurements

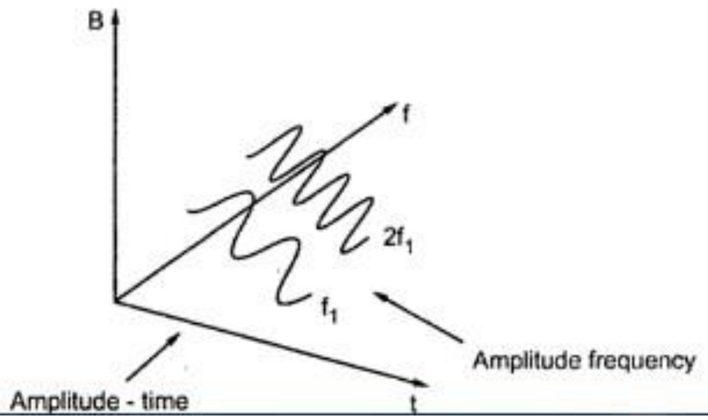
2) Sound measurements and
3) Vibration measurements.

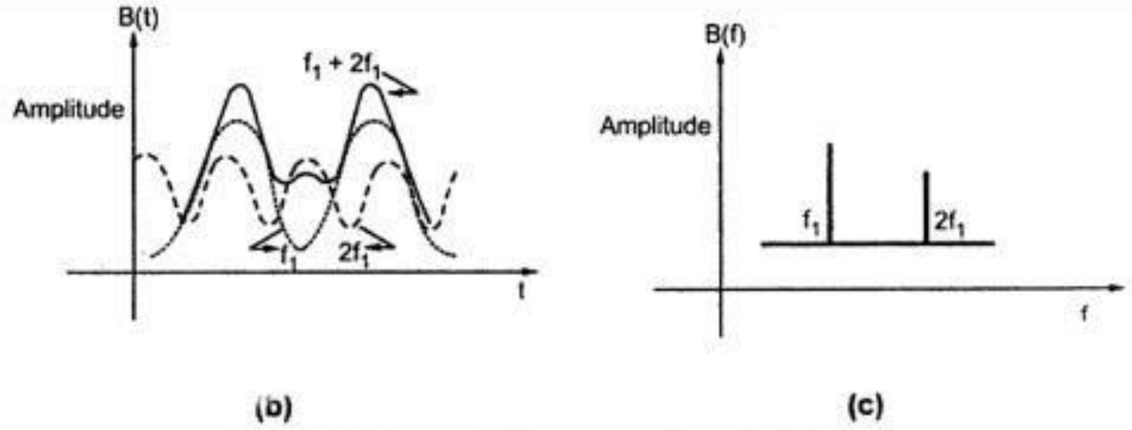
The wave analyzers are applied industrially in the field of reduction of sound and vibrations generated by rotating electrical machines and apparatus. The source of noise and vibrations is first identified by wave analyzers before it can be reduced or eliminated. A fine spectrum analysis with the wave analyzer shows various discrete frequencies and resonances that can be related to the motion of machines. Once, these sources of sound and vibrations are detected with the help of wave analyzers, ways and means can be found to eliminate them.

5.3 Introduction to Spectrum Analysis

The oscilloscope is the most common device used to display the signals, with time as x-axis. Such signals which require time as x-axis to display them are called **time domain signals**. Sometimes it is equally important to display the signal in the frequency domain. Such frequency domain display of the signal consists of the information of energy distribution of the signal. The analysis of such a frequency domain display of the signal is called the **spectrum analysis** of the signal.

The Fig. 5.4(a) shows the signal which is time and frequency dependent. The Fig. 5.4(b) shows the same signal as viewed in the time domain i.e. B(t) while Fig. 5.4(c) shows the same signal as viewed in the frequency domain i.e. B(f).





(b) (c)

Fig. 5.4 Time and frequency domain displays

The main signal consists of two frequency components f_1 and $2f_1$. In the time domain, a single display with a composite frequency $f_1 + 2f_1$ would be seen on the oscilloscope. But in the frequency domain the components of the composite signal can be clearly seen.

Thus the study of energy distribution across the frequency spectrum of a given signal is defined as the **spectrum analysis.**

The instrument which graphically provides the energy distribution of a signal as a function of the frequency on its CRT is called **spectrum analyzer**. It provides a calibrated graphical display with the frequency on the horizontal axis and the signal component on the vertical axis. The sinusoidal components of which the signal is made up of, are displayed as the vertical lines against the frequency co-ordinates. From the height of each vertical line, the absolute amplitude of the component can be measured while from the horizontal location its frequency can be measured.

The spectrum analysis of a signal provides the information about the following things :

i) the measurement of frequency and its response.

ii) the component levels.

iii) bandwidth.

iv) frequency stability.

v) harmonic and intermodulation distortion.

vi) spectral purity.

vii) modulation index and attenuation.

viii) spurious signal generation.

The spectrum analyzer provides information about all these things, by displaying the signal in the frequency domain.

Based on the instrumentation limitations and the capabilities, the spectrum analysis is divided into two major categories as,

i) Audio frequency (AF) analysis

ii) Radio frequency (RF) analysis

The radio frequency analysis is the most basic form of spectrum analysis and it is commonly known as **tuned radio frequency (TRF) analysis.** This can be realized using the tunable filters (with adjustable centre frequency) along with broadband detectors. The TRF analyzers are difficult to construct for wideband ranges as the wideband circuitry needs more power. As a result the operation is somewhat unstable over temperature and thus it turns out to be costly and low performance circuitary.

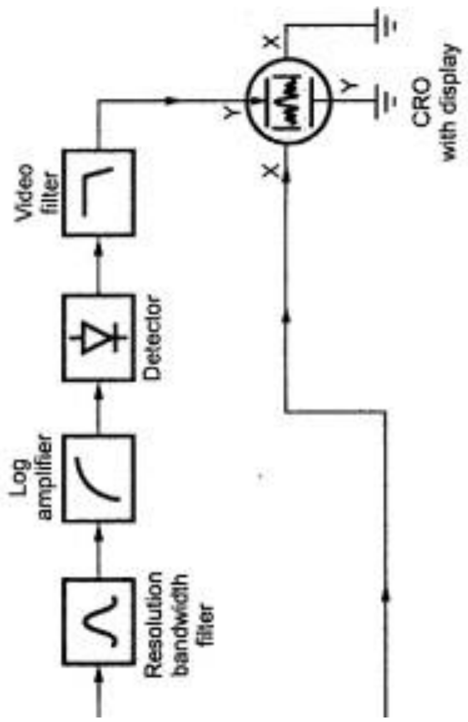
The RF spectrum analysis covers a frequency range of 10 MHz to 40 GHz and is more important. It is used in the areas like radar, navigation, communication and industrial instrumentation frequency bands.

5.4 Spectrum Analyzer

Based on the technique used, the spectrum analyzers can be classified as **scanning type** and **nonscanning type.** The scanning type analyzers use **swept technique**, while the nonscanning type are called **real time spectrum analyzers**.

Let us discuss the basic spectrum analyzer using swept technique. This analyzer uses a swept receiver of superheterodyne type hence this analyzer is also called **swept superheterodyne spectrum analyzer.**

The basic block diagram of such a spectrum analyzer is shown in the Fig. 5.5.



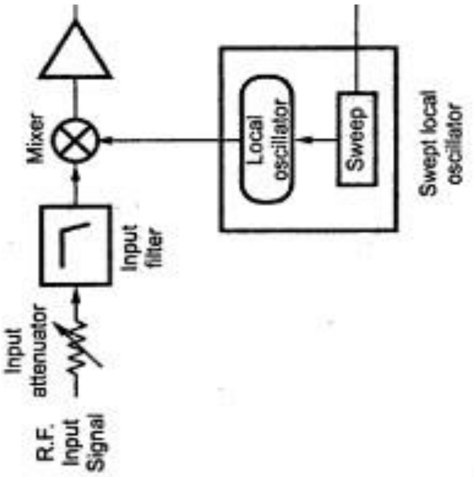


Fig. 5.5 Block diagram of swept superheterodyne spectrum analyzer

The impedance range switch operates in two modes. The constant current mode and the constant voltage mode are the two modes of operation. The three lower ranges (X1, X10 and X100) operate in constant current mode while higher ranges (X1K, X10K, X100K and X1M)operate in constant voltage mode.

Constant current mode : The unknown component is connected at the input of differential amplifier. The impedance switch decides the current to be supplied to the component. The trans-resistance or R_T amplifier maintains this current constant. The R_T amplifier is an op-amp whose output voltage is proportional to the input current. The output of the a.c. differential amplifier is fed to amplifier and filter section. The filter section consists of high and low band filters which are changed with the frequency range and restrict the amplifier bandwidth.

The filter output is applied to the detector that drives the Z magnitude meter. Since the current is maintained constant, the Z magnitude meter which measures the voltage across the unknown component deflects proportional to the magnitude of the impedance.

Constant voltage mode : The terminal that was connected to the input of trans-resistance amplifier in the constant current mode is now grounded.The other input of a.c. differential amplifier that was connected to the voltage terminal of the unknown component is now connected to a point on Z magnitude range switch which is held at a constant voltage.

The voltage across the unknown component is maintained at the constant level. The current through the unknown component is applied to the trans-resistance amplifier which again produces the output voltage proportional to the input current.

Now this output voltage is applied to the detector and the filter section. The Z magnitude meter deflects proportional to the magnitude of the impedance in the same manner as that in constant current mode. The roles of the a.c. differential amplifier and trans-resistance amplifier are reversed in constant voltage mode.

Phase angle measurement : The phase measurements are carried out simultaneously with the magnitude measurement. The output of the voltage and current channel are applied to the Schmitt triggers. The input to the Schmitt triggers is a sine wave. Thus Schmitt trigger produces a spike whenever input sine wave goes through the zero crossing. These spikes are applied to binary phase detector circuit. It consists of a bistable multivibrator a differential amplifier and integrating capacitor.The positive going pulse from constant current channel sets the multivibrator while pulse from constant voltage channel resets the multivibrator. These set and reset outputs are applied to the differential amplifier. It applies the difference voltage to an integrating capacitor. Thus the voltage across capacitor is directly proportional to the difference between the zero crossings of current and voltage waveforms. This is applied to the phase angle meter which directly indicates the phase difference in degrees.

The calibration of the vector impedance meter is performed by connecting standard components to the input terminals.

The applications of vector impedance meter are,

i) The magnitude and phase angle of unknown impedance can be determined simultaneously.

ii) Using the oscilloscope, displaying the Lissajous pattern, the reactance can be calculated.

iii) Impedance measurement over wide frequency range is possible.

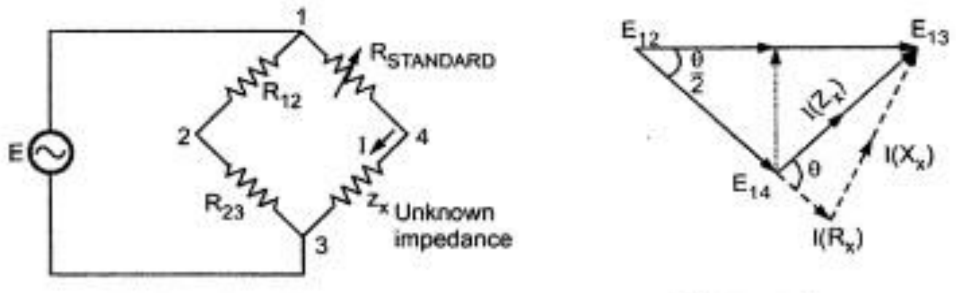
5.10.1.1 Vector Impedance Meter using Direct Reading Method

By using vector impedance meter one can get reading of impedance z directly. Also one can get additional information about resistive and reactive factors of the impedance z.

In general, by using this method, the value of the impedance under test is obtained in polar form with magnitude $|z|$ and phase angle θ.

A test circuit is as shown in the Fig. 5.26 (a). Two equal value resistors are arranged in two arms of the bridge as shown.

As the resistors between nodes 1-2 and 2-3 are of same value, the voltages across R_{12} and R_{23} will be equal say E_{12} and E_{23} respectively. If same current I flows through another branch, we can use equal deflection method to obtains magnitude of unknown impedance z_x. We can adjust the value of varibale standard resistors, such that equal voltages are obtained across $R_{STANDARD}$ and z_x given by E_{14} and E_{43} respectively. Then the unknown impedance z_x will have magnitude equal to the value of $R_{STANDARD}$ required to achieve the above explained condition.



(a) $R_{12} = R_{23} = R$

(b) Vector diagram

Fig. 5.26 Direct reading method using vector impedance meter

5.11 Q Meter

The Q factor is called **quality factor** or the **storage factor.** It is defined as the ratio of power stored in the element to the power dissipated in the element. It is the magnification provided by the circuit. It is also defined as the ratio of reactance to resistance of a reactive element. Thus for inductive reactance it is the ratio of X_L to R while for capacitance reactance it is the ratio of X_C to R.

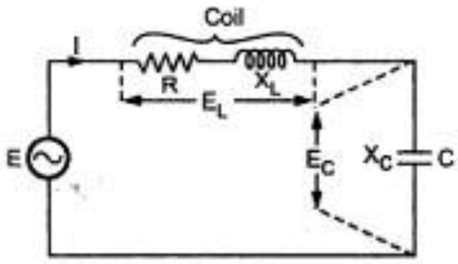
The Q meter is an instrument which is designed to measure some of the electrical properties of the coils and capacitors. It is a useful laboratory instrument.

5.11.1 Working Principle of Q Meter

The working of the Q meter is based on the characteristics of a series resonant circuit. The series resonant circuit has a characteristics that the voltage across the coil or capacitor is equal to the applied voltage times the Q factor of the circuit.

Thus if a fixed voltage is applied to the circuit, the voltmeter across the capacitor can be calibrated to read the Q value directly.

A series resonant circuit is shown in the Fig. 5.28 (a) while the voltage and current relationships at the resonance is shown in the Fig. 5.28 (b).



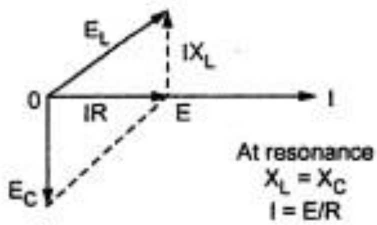


Fig. 5.28 Series resonant circuit

At the resonance,

$$X_C = X_L \quad \ldots (1)$$

$$E_C = IX_C = IX_L \quad \ldots (2)$$

$$E = IR \quad \ldots (3)$$

Where E = applied voltage

I = circuit current

E_C = voltage across capacitor

X_C = capacitive reactance

X_L = inductive reactance

R = resistance of coil

$$\therefore \quad 1.5 \times 10^6 = \frac{1}{2\pi\sqrt{L(500+36.66)\times 10^{-12}}}$$

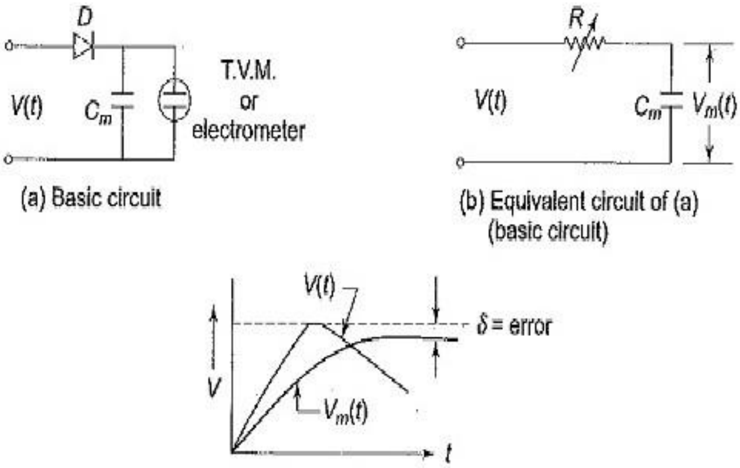
$$L\,(550 + 36.66\,)\times 10^{-12} = 1.1257 \times 10^{-14}$$

$$\therefore \quad L = \mathbf{19.19\ \mu H}$$

Peak Reading Voltmeter Circuit:

Sometimes it is enough if the Peak Reading Voltmeter Circuit of an impulse voltage wave is measured; its waveshape might already be known or fixed by the source itself. This is highly useful in routine impulse testing work. The methods are similar to those employed for a.c. voltage crest value measurements.

The instrument is normally connected to the low voltage arms of the potential dividers described in Sec. 7.2.7. The basic circuit along with its equivalent circuit and the response characteristic is shown in Fig. 7.41. The circuit consists of only rectifiers.



(a) Basic circuit
(b) Equivalent circuit of (a) (basic circuit)
(c) Waveforms of input and meter voltages showing error δ (diode reverse resistance

Diode D conducts for positive voltages only. For negative pulses, the diode has to be connected in reverse. When a voltage impulse v(t) appears across the low voltage arm of the potential divider, the capacitor C_m is charged to the peak value of the pulse. When the amplitude of the signal starts decreasing the diode becomes reverse biased and prevents the discharging of the capacitor C_m.

The voltage developed across C_m is measured by a high impedance voltmeter (an electrostatic voltmeter or an electrometer). As the diode D has finite forward resistance, the voltage to which C_m is charged will be less than the actual peak of the signal, and is modified by the R-C network of the diode resistance and the measuring capacitance C_m. The error is shown in Fig. 7.41c. The error can be estimated if the waveform is known.

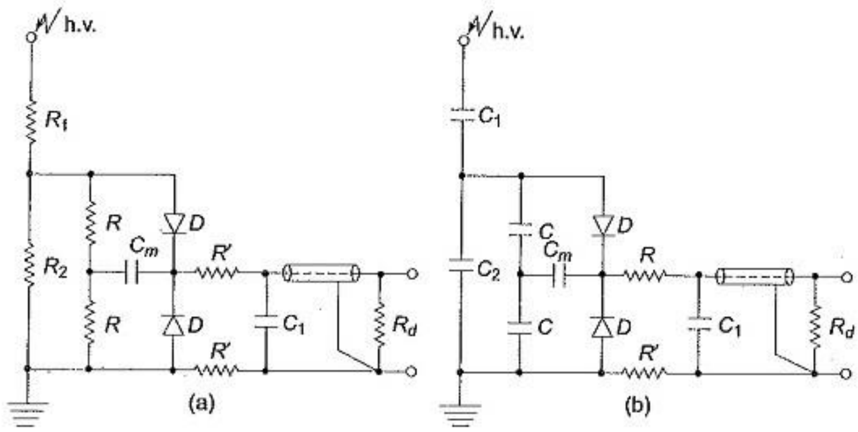
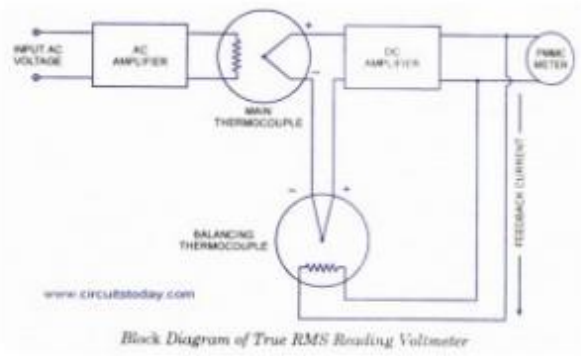


Fig. 7.42 *Peak reading voltmeter for either polarity with (a) resistance divider, and (b) capacitance divider*

The actual forward resistance of the diode D (dynamic value) is difficult to estimate, and hence the meter is calibrated Using an oscilloscope. Peak voltmeters for either polarity employing resistance dividers and capacitance dividers are shown in Fig. 7.42. In this arrangement, the voltage of either polarity is transferred into a proportional positive measuring signal by a resistive or capacitive voltage divider and a diode circuit.

An active network with feedback circuit is employed in commercial instruments, so that the fast rising pulses can also be measured. Instruments employing capacitor dividers require discharge resistance across the low voltage arm to prevent the build-up of d.c. charge.

True RMS Reading Voltmeter



RMS Reading Voltmeter

RMS value of the sinusoidal waveform is measured by the **average reading voltmeter** of which scale is calibrated in terms of rms value. This method is quite simple and less expensive. But sometimes rms value of the non-sinusoidal waveform is required to be measured. For such a measurement a true rms reading voltmeter is required. True rms reading voltmeter gives a meter indication by sensing heating power of waveform which is proportional to the square of the rms value of the voltage.

Thermo-couple is used to measure the heating power of the input waveform of which heater is supplied by the amplified version of the input waveform. Output voltage of the thermocouple is proportional to the square of the rms value of the input waveform. One more thermo-couple, called the balancing thermo-couple, is used in the same thermal environment in order to overcome the difficulty arising out of non-linear behaviour of the thermo-couple. Non-linearity of the input circuit thermo-couple is cancelled by the similar non-linear effects of the balancing thermo-couple. These thermo-couples form part of a bridge in the input circuit of a dc amplifier, as shown in block diagram.

AC waveform to be measured is applied to the heating element of the main thermocouple through an ac amplifier. Under absence of any input waveform, output of both thermo-couples are equal so error signal, which is input to dc amplifier, is zero and therefore indicating meter connected to the output of dc amplifier reads zero. But on the application of input waveform, output of main thermo-couple upsets the balance and an error signal is produced, which gets amplified by the dc amplifier and fedback to the heating element of the balancing thermo-couple. This feedback current reduces the value of error signal and ultimately makes it zero to obtain the balanced bridge condition. In this balanced condition, feedback current supplied by the dc amplifier to the heating element of the balance thermo-couple is equal to the ac current flowing in the heating element of main thermo-couple. Hence this direct current is directly proportional to the rms value of the input ac voltage and is indicated by the meter connected in the output of the dc amplifier.

4.3 Basic Block Diagram of DVM

Any digital instrument requires analog to digital converter at its input. Hence first block in a general DVM is ADC as shown in the Fig. 4.1.

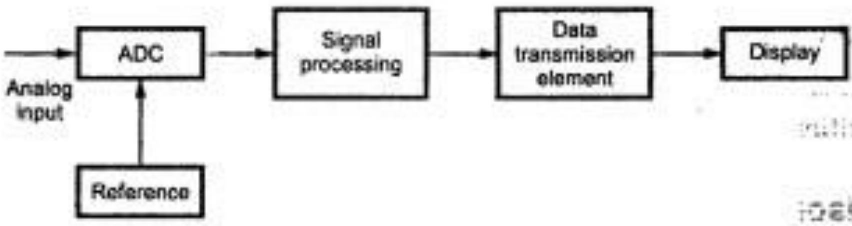


Fig. 4.1 Basic block diagram of DVM

Every ADC requires a reference. The reference is generated internally and reference generator circuitry depends on the type of ADC technique used. The output of ADC is decoded and signal is processed in the decoding stage. Such a decoding is necessary to drive the seven segment display. The data from decoder is then transmitted to the display. The data transmission element may be latches, counters etc. as per the requirement. A digital display shows the necessary digital result of the measurement.

4.4 Classification of Digital Voltmeters

The digital voltmeters are classified mainly based on the technique used for the analog to digital conversion. Depending on this, the digital voltmeters are mainly classified as,

i) Non-integrating type and ii) Integrating type

The non-integrating type digital voltmeters are further classified as,

a) Potentiometric type : These are subclassified as,

1) Servo potentiometric type
2) Successive approximation type
3) Null balance type

b) Ramp type : These are subclassified as,

1) Linear type
2) Staircase type

The integrating type digital voltmeters are classified as,

a) Voltage to frequency converter type
b) Potentiometric type
c) Dual slope integrating type

4.5 Successive Approximation Type DVM

The potentiometer used in the servo balancing type DVM is a linear divider but in successive approximation type a digital divider is used. The digital divider is nothing but a digital to analog (D/A) converter. The servomotor is replaced by an electronic logic.

The basic principle of measurement by this method is similar to the simple example of determination of weight of the object. The object is placed on one side of the balance and the approximate weight is placed on other side. If weight placed is more, the weight is removed and smaller weight is placed. If this weight is smaller than the object, another small weight is added, to the weight present. If now the total weight is higher than the object, the added weight is removed and smaller weight is added. Thus by such successive procedure of adding and removing, the weight of the object is determined. The successive approximation type DVM works exactly on the same principle.

In successive approximation type DVM, the comparator compares the output of digital to analog converter with the unknown voltage. Accordingly, the comparator provides logic high or low signals. The digital to analog converter successively generates the set pattern of signals. The procedure continues till the output of the digital to analog converter becomes equal to the unknown voltage.

The Fig. 4.2 shows the block diagram of successive approximation type DVM.

The capacitor is connected at the input of the comparator. The output of the digital to analog converter is compared with the unknown voltage, by the comparator. The output of the comparator is given to the logic control and sequencer. This unit generates the sequence of code which is applied to digital to analog converter. The position 2 of the switch S_1 receives the output from digital to analog converter. The unknown voltage is available at the position 1 of the switch S_1. The logic control also drives the clock which is used to alternate the switch S_1 between the positions 1 and 2, as per the requirement.

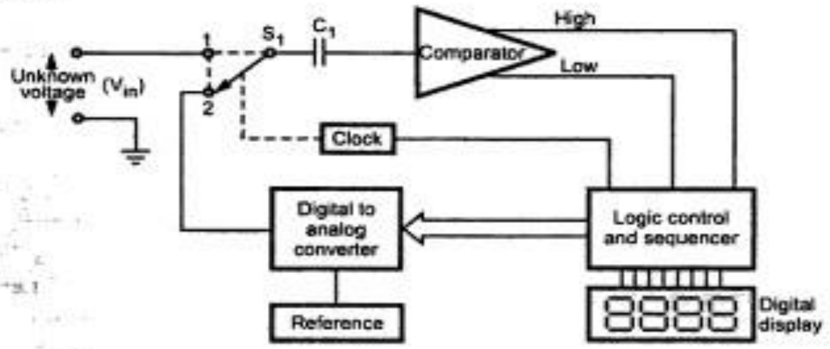


Fig. 4.2 Successive approximation type DVM

Consider the voltage to be measured is 3.7924 V. The set pattern of digital to analog converter is say 8-4-2-1. At the start, the converter generates 8 V and switch is at the position 2. The capacitor C_1 charges to 8 V. The clock is used to change the switch position. So during next time interval, switch position is 1 and unknown input is applied to the capacitor. As capacitor is charged to 8 V which is more than the input voltage 3.7924 V, the comparator sends HIGH signal to the logic control and sequencer circuit. This HIGH signal resets the digital to analog converter which generates its next step of 4 V. This again generates HIGH signal. This again resets the converter to generate the next step of 2 V.

Now 2 V is less than the input voltage. The comparator generates LOW signal and sends it to logic control and sequence circuit. During the generation of LOW signal, the generated signal by the converter is retained. Thus the 2 V step gets stored in the converter. In addition to this, next step of 1 V is generated. Thus the total voltage level becomes, stored 2 + generated 1 i.e. 3 V. This is again less than the input and generates LOW signal. Due to low signal, this gets stored. After this 0.8 V step is generated for the second digit approximation.

4.5.1 Advantages

The advantages of successive approximation DVM are,

1. Very high speed of the order of 100 readings per second possible.
2. The method of ADC is inexpensive.
3. The resolution upto 5 significant digits is possible.
4. The accuracy is high.

UNIT – IV TRANSDUCERS

Definition of Transducers, Classification of Transducers, Advantages of Electrical Transducers, Characteristics and Choice of Transducers; Principle of Operation of Resistive, Inductive, Capacitive Transducers, LVDT, Strain Gauge and Its Principle of Operation, Gauge Factor, Thermistors, Thermocouples, Synchros, Piezoelectric Transducers, Photovoltaic, Photo Conductive Cells, Photo Diodes.

INTRODUCTION:-

The primary objective of process control is to control the physical parameters such as temperature, pressure, flow rate, force, level etc. The system used to maintain these parameters constant, close to some desired specific value is called **process control system.** These parameters may change because of internal and external disturbances hence a constant corrective action is required to keep these parameters constant or within the specified range.

The Fig. 9.1 shows the general arrangement of a process loop. It consists of four elements,

1. Process 2. Measurement 3. Controller 4. Control element.

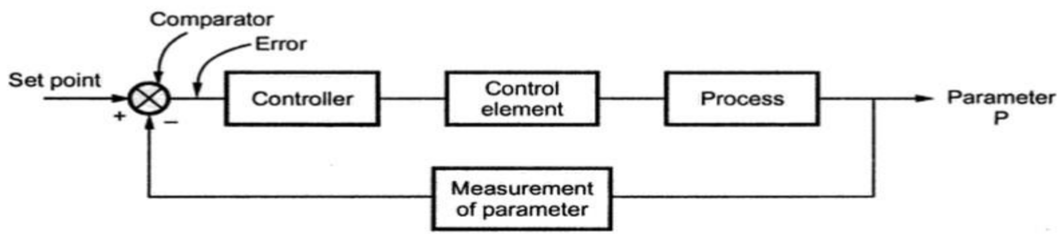


Fig. 9.1 Process control loop

For the proper feedback, it is necessary to measure the value of the actual parameter P. Most of the controllers are electronic in nature and hence require electrical input. Hence feedback signal required is in electrical form in most of the practical process loops. But actual parameter is temperature, pressure, level etc. Hence a device is required in the feedback path which will not only measure the output parameter but will produce proportional analog signal in the electric form. Many times the device is required to measure the physical parameter and produce the proportional signal which is also nonelectric such as pneumatic pressure. So in broad sense a transducer converts one form of energy to another form. But the electrical transducer produces an electrical signal proportional to the nonelectrical quantity to be measured. But as we are interested in the electrical instrumentation, a transducer can be defined as,

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.**

Actually, electrical transducer consists of two parts which are very closely related to each other. These two parts are sensing or detecting element and transduction element. The sensing or detecting element is commonly known as **sensor**.

Definition states that **sensor** is a device that produces a measurable response to a change in a physical condition.

The transduction element transforms the output of the sensor to an electrical output, as shown in the Fig. 9.2.

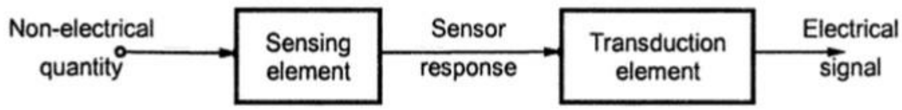


Fig. 9.2 Transducer elements in cascade

The common range of an electrical signal used to represent analog signal in the industrial environment is 0 to 5 V or 4 to 20 mA. In industrial applications, now-a-days, 4 to 20 mA range is most commonly used to represent analog signal. A current of 4 mA represents a zero output and current of 20 mA represents a full scale value i.e. 5 V in case of voltage representation. The zero current condition represents open circuit in the signal transmission line. Hence the standard range is offset from zero.

Many a times, the transducer is a part of a circuit and works with other elements of that circuit to produce the required output. Such a circuit is called signal conditioning circuit.

CLASSIFICATION OF TRANSDUCERS:

A transducer is a device that receives energy from one system and transmits it to another in different form. Basically there are two types of transducers; namely **electrical and mechanical.** The **mechanical** transducers are those primary sensing elements that respond to changes in the physical condition of a system and gives output in different form. For example, when a bimetallic strip is subjected to a temperature change then the output is the mechanical displacement of the strip. The mechanical transducers are distinguished from the electrical transducers on the basis of the output signal generated. The mechanical transducers generate output signal which is mechanical by nature. The **electrical** transducers respond to non-electrical quantities but generate output signal which is electrical by nature. It is practically always possible to use either mechanical or electrical transducer for the measurement of any physical parameter. **But it is observed that for each measurand, an electrical transducers are prefered over the mechanical transducers.**

The various advantages of electrical transducers are,

1. Electrical signals can be easily attenuated or amplified and can be brought upto a level suitable for various devices, with the help of static devices FGK.
2. The power requirement of transducers is very small. The electrical systems can be controlled with a small level of power.
3. The electrical output of the transducer can be easily used, transmitted and processed for the purpose of measurement.
4. The reduced effects of friction and other mechanical nonlinearities.
5. Due to the integrated circuit technology, the electrical and electronic systems are compact, having less weight and portable.
6. The data transmission through mechanical means is eliminated. Thus no mechanical wear and tear and no possibility of mechanical failures exist.
7. The reduced effects of mass inertia problems.

In general the **electrical** transducers are classified according to their structures, application area, method of energy conversion, output signal nature etc. Thus the electrical transducers are classified.

i) As active and passive transducers,

ii) On the basis of transduction principle used,

iii) As analog and digital transducers,

iv) As primary and secondary transducers, and

v) As transducer and inverse transducer.

CHARACTERISTICS OF TRANSDUCERS:

1. **Accuracy :** It is defined as the closeness with which the reading approaches an accepted standard value or ideal value or true value, of the variable being measured.
2. **Ruggedness :** The transducer should be mechanically rugged to withstand overloads. It should have overload protection.
3. **Linearity :** The output of the transducer should be linearily proportional to the input quantity under measurement. It should have linear input - output characteristic.
4. **Repeatability :** The output of the transducer must be exactly the same, under same environmental conditions, when the same quantity is applied at the input repeatedly.
5. **High output :** The transducer should give reasonably high output signal so that it can be easily processed and measured. The output must be much larger than noise. Now-a-days, digital output is preferred in many applications.
6. **High stability and reliability :** The output of the transducer should be highly stable and reliable so that there will be minimum error in measurement. The output must remain unaffected by environmental conditions such as change in temperature, pressure, etc.
7. **Sensitivity :** The sensitivity of the electrical transducer is defined as the electrical output obtained per unit change in the physical parameter of the input quantity. For example, for a transducer used for temperature measurement, sensitivity will be expressed in mV/℃. A high sensitivity is always desirable for a given transducer.
8. **Dynamic range :** For a transducer, the operating range should be wide, so that it can be used over a wide range of measurement conditions.
9. **Size :** The transducer should have smallest possible size and shape with minimal weight and volume. This will make the measurement system very compact.

10. **Speed of response :** It is the rapidity with which the transducer responds to changes in the measured quantity. The speed of response of the transducer should be as high as practicable.

CHOICE OF TRANSDUCERS:

Picking the right transducer for a given measurement application involves considering the transducer's characteristics, desired system performance, and input requirements. Because there are so many kinds of transducers, proper selection requires careful consideration.

1. **Nature of measurement** : The selection of transducer will naturally depend upon the nature of quantity to be measured. For example, for temperature measurement, temperature sensors will be used; for measuring stress or strain, strain gauges will be utilized.
2. **Loading effect** : If the transducer in any way affects or changes the value of the parameter under measurement, errors may be introduced. The transducer is selected to have minimum loading effect to keep the errors to minimum.
3. **Environmental considerations** : A careful study be made of the conditions under which a transducer is expected to give satisfactory output. The troublesome aspects of the transducer location are the temperature changes, shock and vibration, and electromagnetic interference.

To minimize the errors due to temperature changes, some transduces are temperature compensated. For operation of transducer beyond 300°F, such temperature compensation becomes extremely difficult to design, and special materials are used for the transducer internal construction and bonding.

It is often very difficult to eliminate completely the errors due to shock and vibration. To have these errors as minimum as possible, transducers should be selected with a minimum movable mass in the sensing mechanism. Proper **damping** may extend the range of a transducer's usefulness under high shock and vibration conditions.

Transducers are often required to operate in the presence of varying strong electromagnetic fields. Transducers with low output impedance, high output voltage, and short cable length are less susceptible to such interferences.

Other considerations for transducer environments include :

i) Simplicity of mounting and cable installation,

ii) Convenient size, shape and weight,

iii) Resistance of corrosion,

iv) Accessibility of the transducer for later repairs.

4. **Measuring system compatibility** : The transducer selected and the electrical system used for measurement should be compatible. The output impedance of the transducer and the impedance imposed by the measuring system must be such that one does not adversely affect the other.

5. **Cost and availability** : General factors involved in selection are cost, availability, basic simplicity, reliability, and low maintenance.

While selecting transducers of comparatively equal merits for a given application, the one that is most simple in operation and contains minimum number of moving parts would usually be selected.

Transducers are selected which do not require excessive repair or continuous calibration checking.

The selection of a transducer for a given application is normally a compromise between a number of factors discussed above.

PASSIVE TRANSDUCERS:

In electrical circuits, there are combinations of three passive elements : resistor, inductor and capacitor. These three passive elements are described with the help of the primary parameters such as resistance, self or mutual inductance and capacitance respectively. Any change in these parameters can be observed only if they are externally powered. We have studied that the passive transducers do not generate any electrical signal by themselves and they require some external power to generate an electrical signal. The transducers based on variation of parameters such as resistance, self or mutual inductance capacitance, due to an external power are known as **passive transducers**. Hence resistive transducer, inductive transducer and capacitive transducer are the basic passive transducers.

RESISTIVE TRANSDUCERS:

In general, the resistance of a metal conductor is given by,

$$R = \frac{\rho L}{A}$$

where ρ = Resistivity of conductor (Ω m)

L = Length of conductor (m)

A = Area of cross-section of conductor (m^2)

The electrical resistive transducers are designed on the basis of the methods of variation of any one of the quantities in above equation; such as change in length, change in area of cross-section and change in resistivity.

The resistive transducers can be used either as primary transducers or secondary transducers. The methods based on measurement of the resistance change are most widely used in various industrial applications as,

i) Both a.c. and d.c. voltages and currents are suitable for the measurement of resistance change.
ii) The speed of response of the resistive transducers is high.
iii) They are available in various sizes with wide range of resistance value.
iv) High resolution in measurements can be achieved as large variety of electrical circuits are available.

The resistance change due to the change in the length of the conductor is used in translational or rotational potentiometers to measure linear or rotational displacement. The change in resistance of conductor or semiconductor due to the strain applied is the working principle of the strain gauge which is used to measure various physical quantities such as pressure, displacement and force. The change in resistivity of conductor due to the temperature variations causes change in resistance. This principle is used to measure temperature.

Table 9.1 explains the range of electrical quantities that can be measured using the resistive transducers either as primary transducer or secondary transducer.

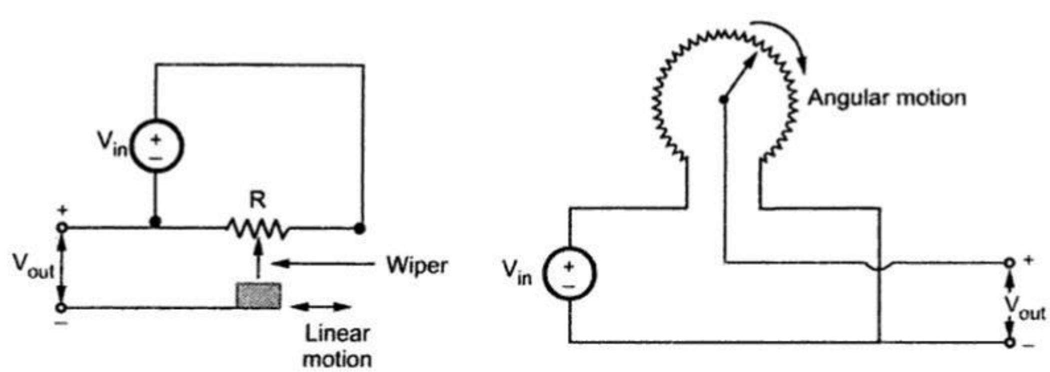
Effect	As a primary transducer	As a secondary transducer
Change in length	Linear displacement, angular displacement, thickness.	Temperature, presure, weight, force, level, flowrate, velocity, acceleration, density.
Change in area of cross-section	High pressure strain.	Temperature, pressure, weight, force, level, flow rate, acceleration density.
Change in resistivity	Temperature, magnetic displacement, humidity.	Thermal conductivity, low pressure and vacuum, displacement.

Table 8.1 Resistance transducers and measurands

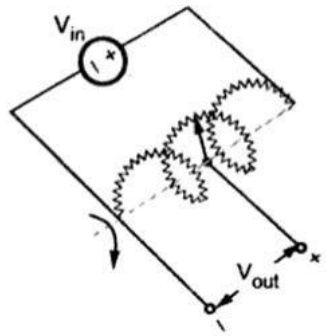
Let us discuss some of the resistive transducers which are most commonly used in the industrial applications.

8.7 Potentiometric Resistance Transducer

A potentiometric resistance transducer (or simply potentiometer) is generally used to measure linear or angular displacement. A resistance potentiometer consists a wire wound resistive element along with a sliding contact which is called as **wiper.** A wire is made up of platinum or nickel alloy with diameter as small as 0.01 mm. The resistive element is made up of cement, hot moulded carbon or carbon film. The wire is wound on an insulating former. The linear and rotary potentiometers are as shown in the Fig. 8.12.



(a) Linear V_{in} **(b) Rotary**



(c) Helipot

Fig. 8.12 Resistance potentiometers

Using resistance potentiometers mechanical displacement is converted into an electrical output. Linear or angular displacement is applied to the sliding contact and then the corresponding change in resistance is converted into voltage or current. Note that the resistance potentiometers shown in the Fig. 8.12 may be excited by either a.c. voltage or d.c. voltage. To measure combination of linear (translational) and angular (rotational) motion, the helipots are used. As the resistive element in such potentiometer is in the form of helix, it is called **helipot.**

8.7.1 Advantages and Disadvantages of Resistance Potentiometers

The **advantages** of resistance potentiometers are as follows.

i) Simple in construction and operation.

ii) Best suitable for measurements in the systems with least requirements.

iii) High electrical efficiency and provides sufficient output for further control operations.

iv) Useful for displacement measurements of large amplitudes.

v) Inexpensive.

The **disadvantages** of resistance potentiometers are as follows,

i) In linear potentiometers, large force is required to move wiper.

ii) Suffer from mechanical wear and misallignment of wiper.

iii) Limited resolution and high electronic noise in output.

INDUCTIVE TRANSDUCERS:

Inductive transducer is a simple and most popular type of displacement transducer in which variation of inductance as a function of displacement is achieved by variation in self inductance or mutual inductance.

In general the value of self inductance of an inductor is given by,

$$L = \frac{N^2}{S} \quad .....(1)$$

where, N = Number of the coil

S = Reluctance of the coil (A/Wb)

But the reluctance S is given by

$$S = \frac{l}{\mu a} \quad .... (2)$$

Hence self inductance L is given by,

$$L = \frac{N^2 \mu a}{l} \quad ....(3)$$

where N = Number of turns of coil.

μ = Permeability of core (H/m)

a = Area of magnetic circuit through which flux is passing (m^2)

l = Length of the magnetic circuit (m)

Thus the variation in the self inductance may be due to

i) Change in number of turns

ii) Change in reluctance

iii) Change in permeability.

The mutual inductance between the two coils is given by

$$M = k\sqrt{L_1 \cdot L_2} \quad .... (4)$$

where M = mutual inductance between two coils.

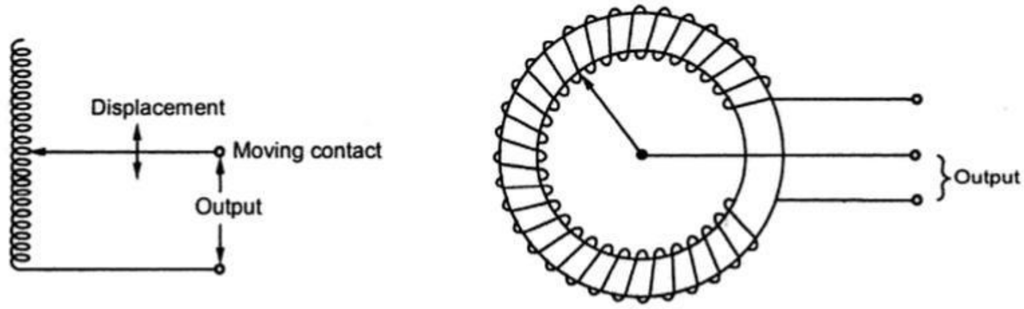
k = coefficient of coupling

The mutual inductance between two coils can be varied by varying either self inductances of the coils or coefficient of coupling.

In general, inductive transducers are used for the measurement of physical quantities such as displacement, force, pressure, velocity, position, vibration etc. Let us study few types of inductive transducers.

9.8.1 Transducer Based on Principle of Change in Self Inductance with Number of Turns

From the expression of the self inductance it is clear that L is directly proportional to N^2 i.e. square of the number of turns. This property can be used to measure linear as well as angular displacement as shown in the Fig. 9.13.



(a) Linear displacement (b) Angular displacement

Fig. 9.13 Inductive transducer based on change in self inductance

In both the cases, as number of turns changes, the value of self inductance changes and hence the output voltage also changes.

9.8.2 Variable Permeability Inductive Transducer

The value of self inductance of a coil also depends on the permeability μ. The transducer based on variable permeability is as shown in the Fig. 9.14.

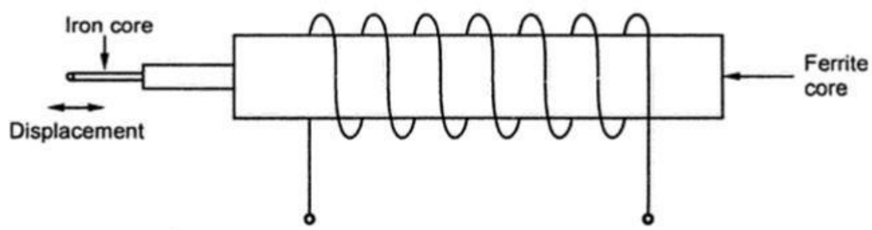


Fig. 9.14 Variable permeability inductive transducer.

In this transducer, the displacement to be measured is applied to the rod which moves in and out of ferrite core according to the direction of the displacement. When iron core moves in, the effective permeability increases, while when iron core moves

9.8.3 Variable Reluctance Inductive Transducer

The self inductance L is inversely proportional to the reluctance S. A variable reluctance type inductive transducer is as shown in the Fig. 9.15. It is a self generating type transducer.

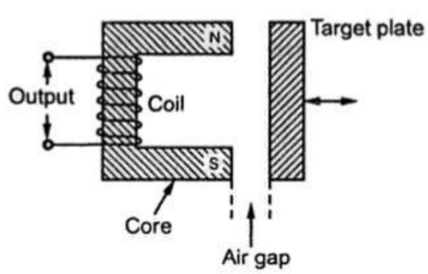


Fig. 9.15 Variable reluctance inductive transducer

A coil is wound by C shaped ferromagnetic core with a target plate placed above core with a small air gap. The size of this air gap determines the reluctance of the magnetic circuit, which inturn decides the self inductance. The displacement to be measured is applied to the target plate. According to the displacement, the target plate moves which chages the air gap and hence the self inductance. Thus for different air gaps we get different values of inductance hence we get different output voltage.

9.8.4 Eddy Current Type Inductive Transducer

An eddy current type inductive transducer is as shown in the Fig. 9.16. It is a self generating type transducer.

A non-ferrous plate moves in a direction perpendicular to the lines of flux of a magnet. The eddy currents are generated in a plate which are proportional to the velocity of the plate. These currents set up a magnetic field in a direction opposing the magnetic field producing these currents. Thus the output is proportional to the change in eddy current or the acceleration of the plate. As the air gap between the magnet and the plate remains constant, the transducer characteristics are linear.

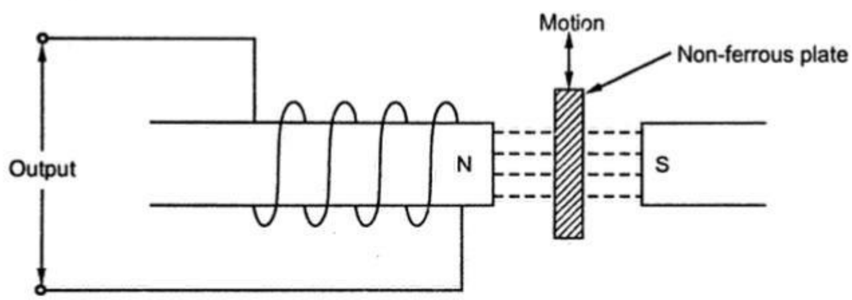


Fig. 9.16 Eddy current type inductive transducer

9.9 Linear Variable Displacement Transducer (LVDT)

Displacement is a vector quantity representing a change in position of a body or a point with respect to a reference. It can be linear or angular (rotational) motion. With the help of displacement transducer, many other quantities, such as force, stress, pressure, velocity, and acceleration can be found. In case of linear displacement, the magnitude of measurement may range from a few micrometer to a few centimeters. A majority of displacement transducers detect the static or dynamic displacement by means of suitable mechanical links coupled to the point or body whose displacement is to be measured.

The main electrical displacement transducers work on the principle of :

1. Variable resistance : transducer is strain gauge.
2. Variable inductance : transducer is linear variable differential transformer
3. Variable capacitance : transducer is parallel plate capacitor with variable gap
4. Synchros and resolvers : used to measure angular displacement.

A simple and more popular type of displacement transducer is the variable inductance type wherein the inductance is varied according to the displacement. This is achieved either by varying the mutual inductance between the two coils (linear variable differential transformer) or by varying self inductances (variable reluctance sensor).

The very fine resolution, high accuracy, and good stability make LVDT most suitable as a position - measuring device. LVDT forms the basic sensing element in the measurement of pressure, load, and acceleration. It is also a basic element of electronic comparators, thickness - measuring units, and level indicators.

9.9.1 Construction and Working of LVDT

As illustrated in the Fig. 9.17, the linear variable differential transformer consists of a single primary winding P_1 and two secondary windings S_1 and S_2 wound on a hollow cylindrical former. The secondaries have an equal number of turns but they are connected in series opposition so that the e.m.f.s induced in the coils oppose each other. The primary winding is connected to an a.c. source, whose frequency may range from 50 Hz to 20 kHz. A movable soft iron core slides inside the hollow former. The position of the movable core determines the flux linkage between the a.c. excited primary winding and each of the two secondary windings. The core made up of nickel-iron alloy is slotted longitudinally to reduce eddy current losses. The displacement to be measured is applied to an arm attached to the core. With the core in the center, or reference, position, the induced e.m.f.s in the secondaries are equal, and since they oppose each other, the output voltage will be zero volt.

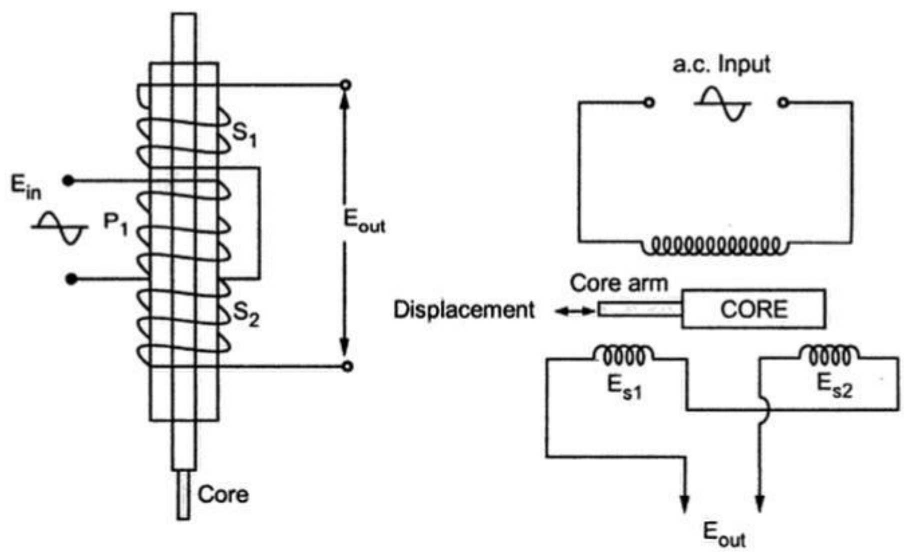


Fig. 9.17 Linear variable differential transformer

When an externally applied force moves the core to the left-hand position, more magnetic flux links the left-hand coil than the right-hand coil. The e.m.f. induced in the left-hand coil, E_{s1}, is therefore larger than the induced e.m.f. of the right-hand coil, E_{s2}. The magnitude of the output voltage is then equal to the difference between the two secondary voltages and it is in phase with the voltage of the left-hand coil.

Similarly, when the core is forced to move to the right, more flux links the right-hand coil than the left-hand coil and the resulting output voltage, which is the difference between E_{s2} and E_{s1}, is now in phase with the e.m.f. of the right-hand coil.

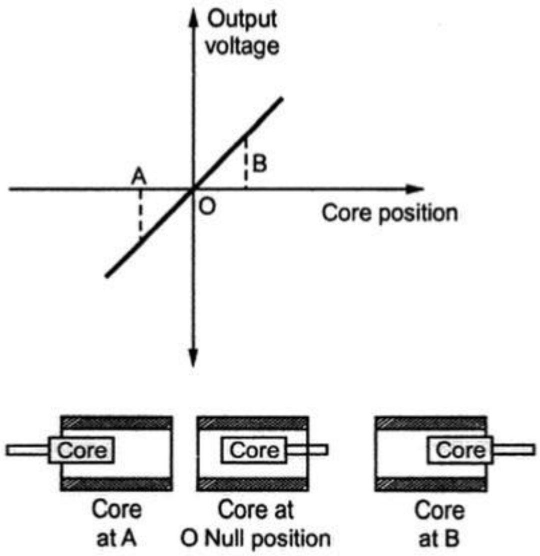


Fig. 9.18 Output voltage of LVDT at different core positions

Thus the LVDT output voltage is a function of the core position. The amount of a voltage change in either secondary winding is proportional to the amount of movement of the core. By noting which output is increasing or decreasing, the direction of motion can be determined. The output a.c. voltage inverts in phase as the core passes through the central null position. Further as the core moves from the center, the greater is the difference in value between E_{s1} and E_{s2} and consequently the greater the output voltage. Therefore the amplitude of the output voltage is a function of the distance the core moves, while the polarity or phase indicates the direction of the motion.

The amount of output voltage of an LVDT is a linear function of the core displacement within a limited range of motion.

9.9.2 Advantages and Disadvantages of LVDT

Advantages of LVDT

1. **Linearity :** The output voltage of LVDT is almost linear for displacement upto 5 mm.
2. **Infinite resolution :** The change in output voltage is continuous, stepless. The effective resolution depends more on the equipment used for the measurement rather than on the LVDT.
3. **High output :** LVDT gives reasonably high output, and hence requires less amplification afterwards.

CAPACITIVE TRANSDUCERS:

The capacitive transducers work on the fundamental principle of electrical capacitance. The capacitance C of a system depends on the dielectric medium used and properties of a capacitive system.

The important capacitances used in the capacitive transducers are,

1. **Parallel plate capacitor :** The capacitance of a parallel plate capacitor is given by,

$$C = \frac{\varepsilon A}{d} \text{ F}$$

where $\varepsilon = \varepsilon_0 \varepsilon_r$, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

ε_r = Relative permittivity of material

A = Cross-sectional common area of plates

d = Plate separation

The arrangement is shown in the Fig. 8.42.

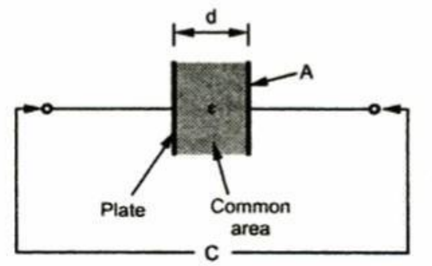


Fig. 8.42 Parallel plate capacitor

By using simple methods, the capacitance of the capacitor can be varied and change in its value can be used for transduction in a transducer.

2. **Composite capacitor :** This capacitance consists of more than one dielectric medium in between the plates as shown in the Fig. 8.43.

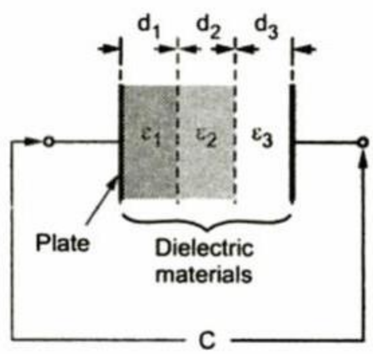


Fig. 8.43 Composite capacitor

It consists of three layers of dielectrics having relative permittivities ε_1, ε_2 and ε_3. The layers having thicknesses d_1, d_2 and d_3. The capacitance of a system is given by,

$$C = \frac{\varepsilon_0 A}{\frac{d_1}{\varepsilon_1} + \frac{d_2}{\varepsilon_1} + \frac{d_3}{\varepsilon_2}}$$

The system creates the effect of three capacitances connected in series.

Fig. 9.20 Composite capacitor

3. **Cylindrical capacitor :** In this system, the plates are cylindrical separated by a dielectric as shown in the Fig. 9.21.

Let r = Outer radius of inner cylinder

R = Inner radius of outer cylinder

Then its capacitance is given by,

$$C = \frac{2\pi\varepsilon l}{ln\left(\frac{R}{r}\right)} \text{ F}$$

and l is length of the cylinders.

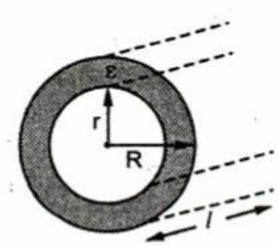


Fig. 9.21 Cylindrical capacitance

9.10.1 Variation in Capacitance

To have capacitive system to be used as a sensor, it is necessary to change the value of capacitance proportional to the action to be measured or detected. Such a variation of capacitance is achieved in four ways.

1. Change of distance :

The capacitance C depends on separation between the plates. Thus by varying the distance of separation, C can be varied. The system is shown in the Fig. 9.22 (a) in which distance is varied by keeping one plate fixed and other plate moving. As the distance increases from d to d′ the capacitance decreases from C to C′.

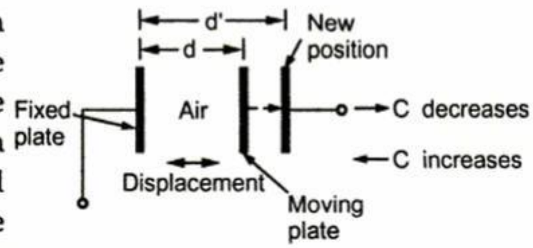


Fig. 9.22 (a) Change in separation

Another method of varying the distance is employing cantilever spring plate as shown in the Fig. 9.22 (b).

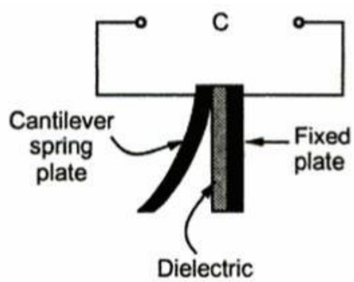


Fig. 9.22 (b) Use of cantilever spring plate

2. Change in common plate area : By keeping the one plate moving and changing its position parallel to the other plate, common plate area can be varied. This is shown in the Fig. 9.23. By varying area A, the capacitance can be varied.

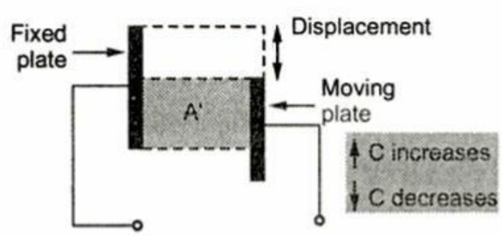
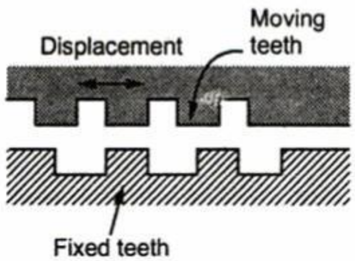
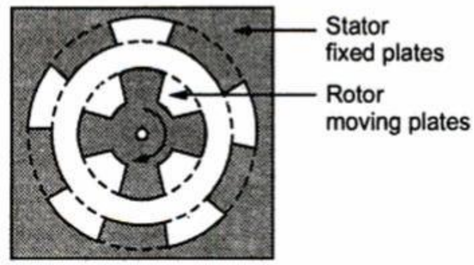


Fig. 9.23 Change in common plate area

This method is suitable in the measurements of rotational displacement. The arrangement is employed in the form of slotted rotor and stator as shown in the Fig. 9.24 (b). As the rotor plates of the capacitor are rotated, the capacitance varies proportional to the angular displacement of the rotor plates. This method can be used to measure the torques.



(a) Change in area



(b) Measurement of angular displacement

Fig. 9.24

3. Change in dielectric : By inserting a slab of variable permittivity, the capacitance can be varied. Introduction of slab of variable permittivity gives rise to a composite capacitor. This is shown in the Fig. 9.25. This method is used in capacitance type level meter.

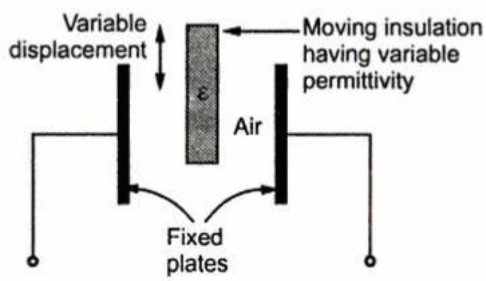


Fig. 9.25 Change in dielectric

4. Using quartz diaphragms : In some cases the two silvered quartz diaphragms are used as shown in the Fig. 9.26. Depending upon the pressure the displacement of these diaphragms vary and hence the capacitance of the system gets varied. This method is used in capacitive pressure transducers.

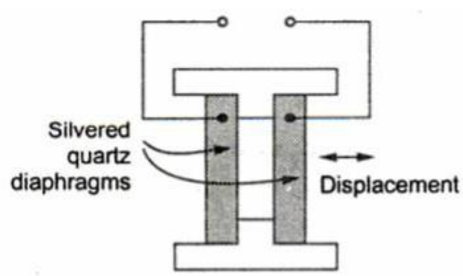


Fig. 9.26 Use of quartz diaphragms

9.10.2 Capacitance Type Level Meter

The capacitive transducer using the method of change in dielectric is used for the measurement of the liquid levels.

The Fig. 9.27 shows the capacitance type level meter.

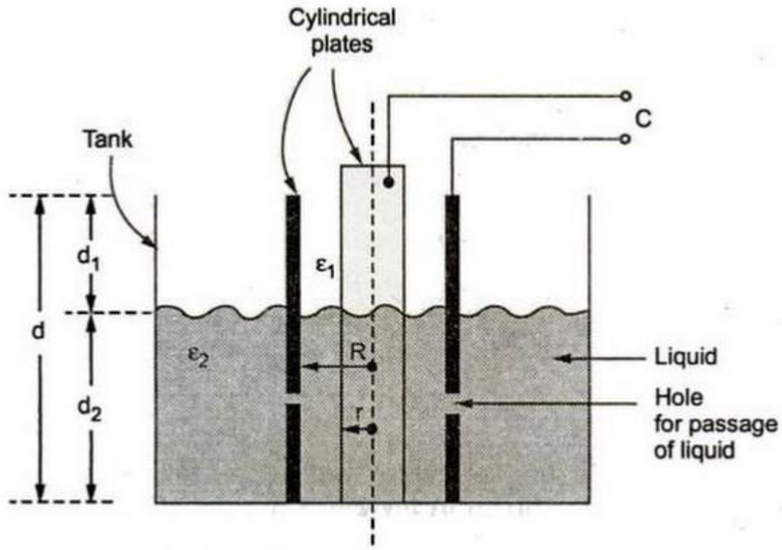


Fig. 9.27 Capacitance type level meter

It is uses concentric cylindrical capacitor. The two plates are cylindrical using the dielectric material with a permittivity ε_1. Most of the times, this dielectric is an air with $\varepsilon_r = 1$ and $\varepsilon = \varepsilon_0$. The outer cylindrical plates have holes at the bottom through which passage of liquid is possible between the plates.

Let r = Outer radius of inner cylinder
R = Inner radius of outer cylinder
d = Height of tank
d_2 = Level of liquid in tank
ε_2 = Permittivity of liquid

As the liquid level d_2 changes, the composite capacitor formed experiences change in its value. The value of the capacitance is given by,

$$C = \frac{2\pi\varepsilon_0 \left[\varepsilon_1 d_1 + \varepsilon_2 d_2\right]}{ln\left[\frac{R}{r}\right]}$$

Thus, change in the liquid level causes the change in the capacitance measured between the cylinders.

This change in capacitance is detected by some other circuit with which the electrical signal proportional to the liquid level can be obtained.

9.10.3 Capacitive Pressure Transducer

The capacitive pressure transducer is based on the principle that when the distance between the two parallel plates changes, capacitance of the parallel plate capacitor changes. The capacitive pressure transducer is as shown in the Fig. 9.28.

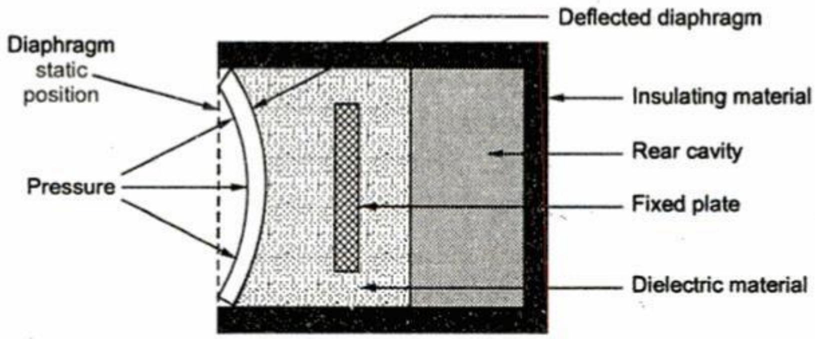


Fig. 9.28 Capacitive pressure transducer

In capacitive pressure transducer diaphragm acts as one of the plates of a two plate capacitor while other plate is fixed. The fixed plate and the diaphragm are separated by a dielectric material. When the force is applied to the diaphragm, it changes its position from initial static position obtained with no force applied. Due to this, the distance of separation between the fixed plate and the diaphragm changes, hence the capacitance also changes. The change in the capacitance can be measured by using any simple a.c. bridge. But practically the change in capacitance is measured using an oscillator circuit where capacitive transducer is part of that circuit. Hence when capacitance changes, the oscillator frequency changes accordingly. In this way, by using capacitive transducer, applied force can be measured interms of change in the capacitance.

9.10.4 Advantages and Disadvantages of Capacitive Transducers

The **advantages** of the capacitive transducers are as follows,

i) The force requirement is very small, hence the power required to operate is small and very useful in small systems.

ii) They are highly sensitive.

iii) They have good frequency response and very high input impedance, so loading effects are minimum.

iv) They are useful in the applications where stray magnetic fields affect performance of the inductive transducers.

The **disadvantages** of the capacitive transducers are as follows :

i) Proper insulation is required between the metallic parts of the capacitive transducers.

ii) The stray capacitances affect the performance of the transducer. It can be overcome by properly earthing the frame of the transducer.

iii) They show non-linear behaviour due to edge effects and stray electric fields. These can be eliminated by using guard rings.

iv) Due to long leads and the cables used, loading effect makes low frequency response poor and reduces sensitivity.

v) For low value capacitances (of the order of pico-farads) the output impedance tend to very high value which causes loading effects.

STRAIN GAUGE:

The strain gauge is a passive resistive transducer which is based on the principle of conversion of mechanical displacement into the resistance change.

A knowledge of strength of the material is essential in the design and construction of machines and structures. The strength of the material is normally characterized in terms of stress, which is defined as the force experienced per unit area, and is expressed in pressure units. **Stress** as such cannot be directly measured. It is normally deduced from the changes in mechanical dimensions and the applied load. The mechanical deformation is measured with strain-gauge elements. The **strain** is defined as the change, (Δl), in length, (l), per unit length and is expressed as $\Delta l / l$ in microstrains.

The stress-strain curve for a typical metal specimen is shown in Fig. 9.29.

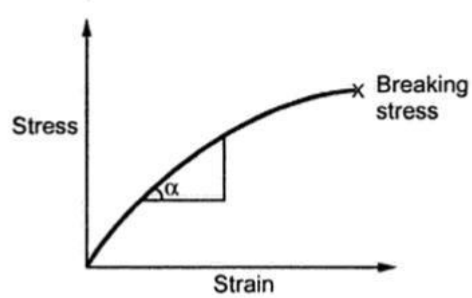


Fig. 9.29 Stress-strain curves for typical metal specimen

It is observed that the curve is linear as long as the stress is kept below the elastic limits. Strain measurements are usually carried out on the free surface of a body. Normally the strain magnitude is of the order of a few micrometers per meter, which is expressed as microstrains. Since the magnitude of strain is extremely small, it is practically difficult to measure it directly. Hence, a gauge which can yield strain directly is used. Such a gauge is known as **strain gauge**.

The desirable characteristics of the strain gauge are gauge sensitivity, range of measurement, accuracy, frequency response, and the ambient environmental conditions it can withstand. **Sensitivity** is defined as the smallest value of strain that can be measured. The maximum strain measurable and the accuracy achievable depend upon the type of gauges used and the method of gauging used.

Basically stress and strain both are directly related to the modulus of elasticity. But strain can be measured easily as compared to stress, using variable resistance transducer, the resistive transducer is commonly called **strain gauge.**

9.11.1 Principle of Operation and Construction of Strain Gauges

The basic principle of operation of an electrical resistance strain gauge is the fact that the resistance of the wire changes as a function of strain, increasing with tension and reducing with compression. The change in resistance is measured with a Wheatstone bridge. The strain gauge is bonded to the specimen and hence the gauge is subjected to the same strain as that of the specimen under test.

The materials used for fabrication of electrical strain gauges must possess some basic qualities to achieve high accuracy, excellent reproducibility, good sensitivity, long life and ability to operate under the required environmental conditions. Some of these qualities are attained by selecting materials with high specific resistance, low temperature coefficient of resistance, constant gauge factor, and constant strain sensitivity over a wide range of strain values. The bonding cement should have high insulation resistance and excellent transmissibility of strain, and must be immune to moisture effects.

The most common materials used for wire strain gauges are constantan alloys containing 45% nickel and 55% copper, as they exhibit high specific resistance, constant gauge factor over a wide strain range, and good stability over a reasonably large temperature range (from 0°C to 300°C). For dynamic strain measurements, nichrome alloys, containing 80% nickel and 20% chromium are used. They can be compensated for temperature with platinum.

Bonding cements are adhesives used to fix the strain gauge onto the test specimen. This cement serves the important function of transmitting the strain from the specimen to the gauge-sensing element. Improper bonding of the gauge can cause many errors.

Basically, the cement can be classified under two categories, viz, solvent-setting cement and chemically-reacting cement. Duco cement is an example of solvent-setting cements which is cured by solvent evaporation. Epoxies and phenolic bakelite cement are chemically-reacting cements which are cured by polymerization. Acrylic cements are contact cements that get cured almost instantaneously.

The proper functioning of a strain gauge is wholly dependent on the quality of bonding which holds the gauge to the surface of the structure undergoing the test.

9.11.2 Derivation of Gauge Factor

The gauge factor is defined as the unit change in resistance per unit change in length. It is denoted as K or S. It is also called **sensitivity** of the strain gauge.

$$S = \frac{\Delta R/R}{\Delta l/l}$$

where S = Gauge factor or sensitivity

R = Gauge wire resistance

ΔR = Change in wire resistance

l = Length of the gauge wire in unstressed condition

Δl = Change in length in stressed condition.

Derivation : Consider that the resistance wire is under tensile stress and it is deformed by Δl as shown in the Fig. 9.30.

Let ρ = Specific resistance of wire material in Ω-m

l = Length of the wire in m

A = Cross-section of the wire in m^2

When uniform stress σ is applied to this wire along the length, the resistance R changes to $R + \Delta R$ because of change in length and cross-sectional area.

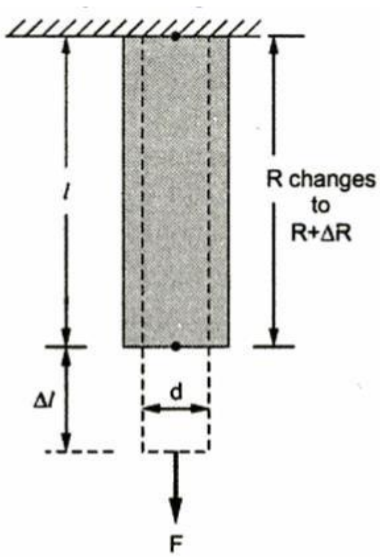


Fig. 9.30 Deformed resistance wire

Hall Effect Transducers

When a conductor is kept perpendicular to the magnetic field and a direct current is passed through it, it results in an electric field perpendicular to the directions of both the magnetic field and current with a magnitude proportional to the product of the magnetic field strength and current.

1. The voltage so developed is very small and it is difficult to detect it. But in some semiconductors such as germanium, this voltage is enough for measurement with a sensitive moving coil instrument. This phenomenon is called the **Hall Effect.**
2. Commercial hall effect transducers are made from germanium or other semiconductor materials. They find application in instruments that measure magnetic field with small flux densities.
3. Hall effect element can be used for measurement of current by the magnetic field produced due to flow of current.
4. Hall effect element may be used for measuring a linear displacement or location of a structural element in case where it is possible to change the magnetic field strength by variation in the geometry of a magnetic structure.

Advantages

1. Non-contact device
2. Small size
3. High resolution

Dis-advantages

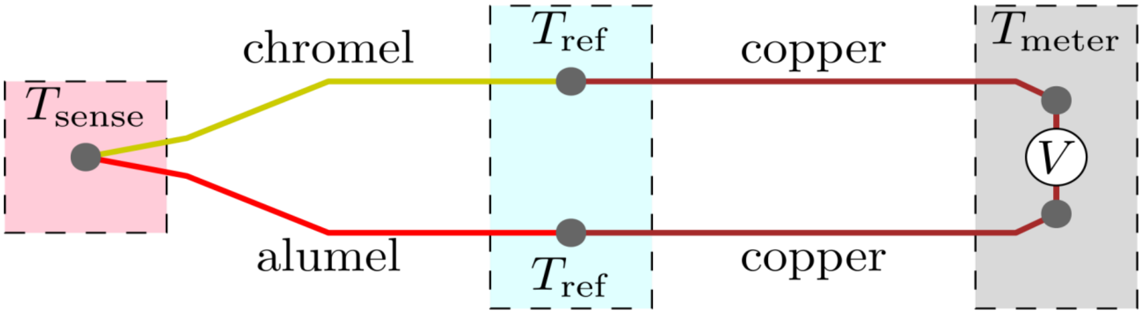
1. High sensitivity to temperature changes
2. Variation of hall coefficient from plate to plate, hence requires individual calibration in each case

Thermocouple:

A **thermocouple** is an electrical device consisting of two dissimilar electrical conductors forming electrical junctions at differing temperatures. A thermocouple produces a temperature-dependent voltage as a result of the thermoelectric effect, and this voltage can be interpreted to measure temperature. Thermocouples are a widely used type of temperature sensor

Principle of Operation of Thermocouple:

The standard configuration for thermocouple usage is shown in the figure. Briefly, the desired temperature T_{sense} is obtained using three inputs—the characteristic function $E(T)$ of the thermocouple, the measured voltage V, and the reference junctions' temperature T_{ref}. The solution to the equation $E(T_{sense}) = V + E(T_{ref})$ yields T_{sense}. These details are often hidden from the user since the reference junction block (with T_{ref} thermometer), voltmeter, and equation solver are combined into a single product.



Comparison of types[edit]

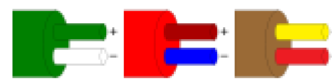
The table below describes properties of several different thermocouple types. Within the tolerance columns, *T* represents the temperature of the hot junction, in degrees Celsius. For example, a thermocouple with a tolerance of ±0.0025×*T* would have a tolerance of ±2.5 °C at 1000 °C.

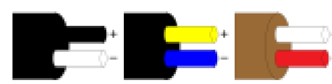
Type	Temperature range (°C)				Tolerance class (°C)		Color code		
	Continuous		Short-term		One	Two	IEC[23]	BS	ANSI
	Low	High	Low	High					
T	−185	+300	−250	+400	−40 – 125: ±0.5 125 – 350: ±0.004×*T*	−40 – 133: ±1.0 133 – 350: ±0.0075×*T*			
S	0	+1600	−50	+1750	0 – 1100: ±1.0 1100 – 1600: ±0.003×(*T* − 767)	0 – 600: ±1.5 600 – 1600: ±0.0025×*T*			Not defined
R	0	+1600	−50	+1700	0 – 1100: ±1.0 1100 – 1600: ±0.003×(*T* − 767)	0 – 600: ±1.5 600 – 1600: ±0.0025×*T*			Not defined

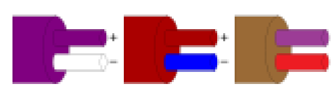
N	0	+1100	−270	+1300	−40 – 375: ±1.5 375 – 1000: ±0.004×*T*	−40 – 333: ±2.5 333 – 1200: ±0.0075×*T*			

Type	Temperature range (°C)				Tolerance class (°C)		Color code		
	Continuous		Short-term		One	Two	IEC[23]	BS	ANSI
	Low	High	Low	High					
K	0	+1100	−180	+1300	−40 – 375: ±1.5 375 – 1000: ±0.004×T	−40 – 333: ±2.5 333 – 1200: ±0.0075×T			
J	0	+750	−180	+800	−40 – 375: ±1.5 375 – 750: ±0.004×T	−40 – 333: ±2.5 333 – 750: ±0.0075×T			
E	0	+800	−40	+900	−40 – 375: ±1.5 375 – 800: ±0.004×T	−40 – 333: ±2.5 333 – 900: ±0.0075×T			
Chromel/AuFe	−272	+300	N/A	N/A	Reproducibility 0.2% of the voltage. Each sensor needs individual calibration.				

B	+200	+1700	0	+1820	Not available	600 – 1700: $\pm 0.0025 \times T$	No standard	No standard	Not defined



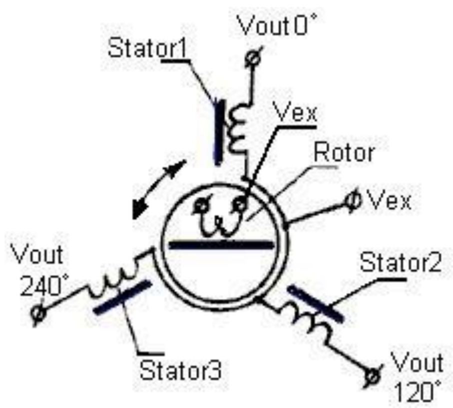




Synchros:

A synchro is, in effect, a transformer whose primary-to-secondary coupling may be varied by physically changing the relative orientation of the two windings. Synchros are often used for measuring the angle of a rotating machine such as an antenna platform.

Synchros are simply variable transformers. Each **synchro** contains a rotor, similar in appearance to the armature in a motor, and a stator, which corresponds to the field in a motor



Operation:

On a practical level, synchros resemble motors, in that there is a rotor, stator, and a shaft. Ordinarily, slip rings and brushes connect the rotor to external power. A synchro transmitter's shaft is rotated by the mechanism that sends information, while the synchro receiver's shaft rotates a dial, or operates a light mechanical load. Single and three-phase units are common in use, and will follow the other's rotation when connected properly. One transmitter can turn several receivers; if torque is a factor, the transmitter must be physically larger to source the additional current. In a motion picture interlock system, a large motor-driven distributor can drive as many as 20 machines, sound dubbers, footage counters, and projectors.

A picture of a synchro transmitter.

Photo Conductive Cell:

The **photoconductive cell** is a two terminal semiconductor device whose terminal resistance will vary (linearly) with the intensity of the incident light. For obvious reasons, it is frequently called a photoresistive device..... Both materials respond rather slowly to changes in light intensity.

Working:

In the dark, the **photoconductive** layer on the drum acts as an insulator, resisting the flow of electrons from one atom to another. But when the layer is hit by light, the energy of the photons liberates electrons and allows current to pass through.

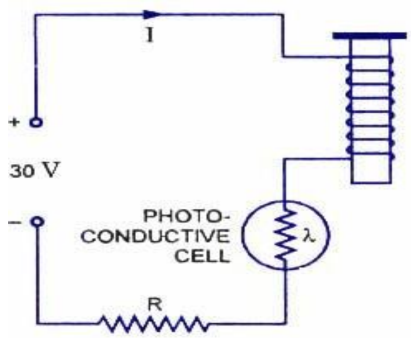


Fig:Photo Conductive Cell

Photo Diodes:

A **photodiode** is a semiconductor device that converts light into an electrical current. The current is generated when photons are absorbed in the**photodiode**. **Photodiodes** may contain optical filters, built-in lenses, and may have large or small surface areas.

Principle of Operation:

A photodiode is a p–n junction or PIN structure. When a photon of sufficient energy strikes the diode, it creates an electron-hole pair. This mechanism is also known as the inner photoelectric effect. If the absorption occurs in the junction's depletion region, or one diffusion length away from it, these carriers are swept from the junction by the built-in electric field of the depletion region. Thus holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced. The total current through the photodiode is the sum of the dark current (current that is generated in the absence of light) and the photocurrent, so the dark current must be minimized to maximize the sensitivity of the device

Applications:

P–n photodiodes are used in similar applications to other photodetectors, such as photoconductors, charge-coupled devices, and photomultiplier tubes. They may be used to generate an output which is dependent upon the illumination (analog; for measurement and the like), or to change the state of circuitry (digital; either for control and switching, or digital signal processing).

Comparison with photomultipliers:

Advantages compared to photomultipliers:

1. Excellent linearity of output current as a function of incident light
2. Spectral response from 190 nm to 1100 nm (silicon), longer wavelengths with other semiconductor materials
3. Low noise
4. Ruggedized to mechanical stress
5. Low cost
6. Compact and light weight
7. Long lifetime
8. High quantum efficiency, typically 60–80%
9. No high voltage required

Disadvantages compared to photomultipliers:

1. Small area
2. No internal gain (except avalanche photodiodes, but their gain is typically 10^2–10^3 compared to 10^5-10^8 for the photomultiplier)
3. Much lower overall sensitivity
4. Photon counting only possible with specially designed, usually cooled photodiodes, with special electronic circuits
5. Response time for many designs is slower
6. latent effect.

UNIT-5

MEASUREMENT OF NON-ELECTRICAL QUANTITIES

Measurement of strain, Gauge Sensitivity, Measurement of Displacement, Velocity, Angular Velocity, Acceleration, Force, Torque, Temperature, Pressure, Flow, Liquid level.

Measurement of strain:

Strain is used to describe the measurement of the deformation of a material. The material of a certain component or object can be elongated (tractioned) or contracted (compressed), thus experiencing strain due to the following factors:

- the effect of an applied external force (mechanical strain)
- the influence of heat and cold (thermal strain)
- internal forces from the non-uniform cooling of cast components, forging, or welding (residual strain)

Measurement of Displacement:

Measuring of displacement indicates the direction of motion. The output signal of the linear **displacement** sensor is the **measurement** of the distance an object has traveled in units of millimeters (mm), or inches (in.), and can have a negative or positive value.

Velocity:

Measuring displacement indicates the direction of motion. The output signal of the linear **displacement** sensor is the **measurement** of the distance an object has traveled in units of millimeters (mm), or inches (in.), and can have a negative or positive value.

Angular Velocity:

The **angular velocity** of a particle is the rate at which it rotates around a chosen center point: that is, the time rate of change of its angular displacement relative to the origin (i.e. in layman's terms: how quickly an object goes around something over a period of time - e.g. how fast the earth orbits the sun). It is measured in angle per unit time, radians per second in SI units, and is usually represented by the symbol omega (**ω**, sometimes **Ω**). By convention, positive angular velocity indicates counter-clockwise rotation, while negative is clockwise.

Acceleration:

acceleration is the rate of change of velocity of an object with respect to time. An object's acceleration is the net result of all forces acting on the object, as described by Newton's Second Law.[1] The SI unit for acceleration is metre per second squared ($m\ s^{-2}$).Accelerations are vector quantities (they have magnitude and direction) and add according to the parallelogram law.The vector of the net force acting on a body has the same direction as the vector of the body's acceleration, and its magnitude is proportional to the magnitude of the acceleration, with the object's mass (a scalar quantity) as proportionality constant.

Torque:

moment of force is the rotational equivalent of linear force.The concept originated with the studies of Archimedes on the usage of levers. Just as a linear force is a push or a pull, a torque can be thought of as a twist to an object. The symbol for torque is typically,the lowercase Greek letter *tau*. When being referred to as moment of force, it is commonly denoted by *M*.

In three dimensions, the torque is a pseudovector; for point particles, it is given by the cross product of the position vector (distance vector) and the force vector.

Temparature:

Temparature is a physical quantity expressing hot and cold. It is measured with a thermometer calibrated in one or more temperature scales. The most commonly used scales are the Celsius scale (formerly called *centigrade*) (denoted °C), Fahrenheit scale (denoted °F), and Kelvin scale (denoted K). The kelvin (spelled with a lower-case k) is the unit of temperature in the International System of Units(abbreviated SI), in which temperature is one of the seven fundamental base quantities. The Kelvin scale is widely used in science and technology.

Theoretically, the coldest a system can be is when its temperature is absolute zero, at which point the thermal motion in matter would be zero. However, an actual physical system or object can never attain a temperature of absolute zero. Absolute zero is denoted as 0 Kon the Kelvin scale, −273.15 °C on the Celsius scale, and −459.67 °F on the Fahrenheit scale.

Pressure:

is the force applied perpendicular to the surface of an object per unit area over which that force is distributed. Gauge pressure (also spelled *gage* pressure)is the pressure relative to the ambient pressure.

Various units are used to express pressure. Some of these derive from a unit of force divided by a unit of area; the SI unit of pressure is pascal (Pa).