LECTURE NOTES

for

INTELLIGENT INSTRUMENTATION

(Module I, II & IV)

8th Semester (Elective – IV)

INTELLIGENT INSTRUMENTATION (3-1-0)

Module-I (10 Hours)

SCIENCE OF MEASUREMENT

Units and Standards — Calibration techniques — Classification of errors — error analysis — statistical
methods — odds and uncertainty — static and dynamic characteristics of transducers.

Module-II (10 Hours)

VARIABLE RESISTANCE , VARIABLE INDUCTANCE AND CAPACITANCE TRANSDUCERS

Potentiometer — strain gauge — resistance thermometer — hot wire anemometer — LVDT — variable
reluctance transducers for measurement of dip and acceleration - Variable capacitive transducers —electromagnetic,
thermo-elastic, capacitor microphone.

Module-III (10 Hours)

PIEZOELECTRIC AND OPTICAL TRANSDUCERS:

Piezoelectric transducer — IC sensors — Piezo-resistive sensors, photoelectric, Hall-effect, Optical transducer-
Principles — types and characteristics of fibres — fibre optic transducers for the measurement of force,
temperature, flow and pressure.

INTERFACING CONVENTIONAL TRANSDUCERS WITH PC

Transducers with frequency output — digital transducers, interfacing with PC.

Module-IV (8 Hours)

SMART INSTRUMENTS

Smart/intelligent transducer — comparison with conventional transducers — self diagnosis and remote
calibration features — smart transmitter with HART communicator —Micro Electro Mechanical Systems —
sensors, actuators — principles and applications, nonlinearity compensation.

Text Books:

1. Barney G.C.V., Intelligent Instrumentation: Prentice Hall of India Pvt. Ltd., New Delhi, 1988.
2. D. Patranabis- Principle of Industrial Instrumentation,TMH,2000

References Books:

1. Doebelin, E.O., Measurement systems, McGraw Hill, Fourth edition, Singapore, 1990.
2. Chapman, P. Smart Sensors, ISA publication, 1995.

MODULE-I

- **QUANTITIES, UNITS AND STANDARDS :-**

Definitions:-

A quantity is a quantifiable or assignable property ascribed to phenomena, bodies, or substances. Examples are speed of a car and mass of an electron. A physical quantity is a quantity that can be used in the mathematical equations of science and technology.

A unit is a particular physical quantity, defined and adopted by convention, with which other particular quantities of the same kind are compared to express their value. The value of a physical quantity is the quantitative expression of a particular physical quantity as the product of a number and a unit, the number being its numerical value. Thus, the numerical value of a particular physical quantity depends on the unit in which it is expressed. For example, the value of the height h of a light pole is h = 16 m. Here h is the physical quantity, its value expressed in the unit "meter," unit symbol m, is 16 m, and its numerical value when expressed in meters is 16.

Basic Units and Derived Units:-

In all conversations, the physical quantities are presented with their proper values compared to the standard, the units. The general unit of a physical quantity is defined as its dimension. A unit system can be developed by choosing, for each basic dimension of the system, a specific unit. For example, the internationally established (SI) units are the meter for length, the kilogram for mass, and the second for time, abbreviated as the mks system of units. Such a unit is called a basic unit. The corresponding physical quantity is called a basic quantity.

All units that are not basic are called derived units. In the mks system the derived units for force and energy are a convenient size in an engineering sense, and all the practical units fit in as the natural units to form a comprehensive unit system.

If we define the dimensions of length, mass, and time as [L], [M], and [T], respectively, then

physical quantities may be expressed as $[L]^x[M]^y[T]^z$. For instance, the dimension of acceleration is $[L][T]^{-2}$ and that of force is $[L][M][T]^{-2}$. In the mks system of units, the systematic unit of acceleration is therefore 1 m/s^2 and that of force is 1 kgm/s^2.

Systems of units in which the mass is taken as a basic unit are called absolute systems of units, whereas those in which the force rather than the mass is taken as a basic unit are called gravitational systems of units. The metric engineering system of units is a gravitational system of units and is based on the meter, kilogram-force, and second as basic units.

Standards:-

The international system of units (SI) is the internationally agreed on system of units for expressing the values of physical quantities. In this system four basic units are added to the customary three basic units (meter, kilogram, second) of the MKS absolute system of units. The four added basic units are ampere as the electric current, the Kelvin as the unit of thermodynamic temperature, the candela as the unit of luminous intensity, and the mole as the unit of amount of substance. Thus in SI units the meter, kilogram, second, ampere, Kelvin, candela, and mole constitute the seven basic units.

There are two auxiliary units in the SI units: the radian, which is the unit of a plane angle, and the steradian, which is the unit of a solid angle.
Many countries established standardization institutions and standard laboratories where they keep the standard units that are calibrated against the world standards and kept as national standards. All other standards in the country are calibrated against these national standards and used as secondary standards.
In this course we will use notations in accordance with the current International Standards. Units for engineering quantities are printed in upright roman characters, with a space between the numerical value and the unit, but no space between the decimal prefix and the unit, e.g. 275 kV.
Compound units have a space, dot or / between the unit elements as appropriate, e.g. 1.5 N m, 300 m/s, or 9.81 $m.s^{-2}$.
Variable symbols are printed in italic typeface, e.g. V. For ac quantities, the instantaneous value is printed in lower case italic, peak value in lower case italic with caret (^), and rms value in upper case, e.g. i, î, I. Symbols for the important electrical quantities with their units are given in Table 1.

Table 1 Symbols for standard quantities and units

Symbol	Quantity	Unit	Unit symbol
A	geometric area	square meter	m^2
B	magnetic flux density	tesla	T
C	Capacitance	farad	F
E	electric field strength	volt per meter	V/m
F	mechanical force	Newton	N
Fm	magnetomotive force (mmf)	Ampere	A or A.t
G	conductance	Siemens	S
H	magnetic field strength	ampere per metre	A/m
I	electric current	ampere	A
J	electric current density	ampere per square metre	A/m^2
J	moment of inertia	kilogram metre squared	$kg.m^2$
L	self-inductance	henry	H
M	mutual inductance	henry	H
N	number of turns		
P	active or real power	watt	W
Q	electric charge	coulomb	C
Q	reactive power	volt ampere reactive	VAR
R	electrical resistance	ohm	Ω
Rm	Reluctance	ampere per weber	A/Wb

S	apparent power	volt ampere	V.A
T	mechanical torque	newton meter	N.m
V	electric potential or voltage	volt	V
W	energy or work	joule	J
X	Reactance	ohm	Ω
Y	Admittance	Siemens	S
Z	Impedance	ohm	Ω
f	Frequency	hertz	Hz
i or j	square root of -1		
l	Length	Meter	m
m	Mass	Kilogram	kg
n	rotational speed	revolution per minute	rpm
p	Number of machine poles		
t	Time	Second	s
v	linear velocity	meter per second	m/s
ε	Permittivity	farad per meter	F/m
η	Efficiency		
θ	Angle	radian or degree	rad or °
λ	power factor		
Λ	Permeance	weber per ampere	Wb/A
μ	Permeability	henry per meter	H/m
ρ	Resistivity	ohm meter	Ω.m
σ	Conductivity	siemens per meter	S/m
ϕ	phase angle	radian	rad
Φ	magnetic flux	weber	Wb
Ψ	magnetic flux linkage	weber or weber-turn	Wb or Wb.t
ω	angular velocity or angular frequency	radian per second	rad/s

➢ STATIC CHARACTE RISTICS:-

The static characteristics of an instrument are, in general, considered for instruments which are used to measure an unvarying process condition. All the static performance characteristics are obtained by one form or another of a process called calibration. There are a number of related definitions (or characteristics), which are described below, such as accuracy, % precision, repeatability, resolution, errors, sensitivity, etc.

l. Instrument: A device or mechanism used to determine the present value of the quantity under measurement.
2. **Measurement:** The process of determining the amount, degree, or capacity by comparison (direct or indirect) with the accepted standards of the system units being used.
3. Accuracy: The degree of exactness (closeness) of a measurement compared to the expected (desired) value.
4. Resolution: The smallest change in a measured variable to which an instrument will respond.
5. Precision: A measure of the consistency or repeatability of measurements, i.e. successive readings does not differ. (Precision is the consistency of the instrument output for a given value of input).
6. Expected value: The design value, i.e. the most probable value that calculations indicate one should expect to measure.
7 . Error: The deviation of the true value from the desired value.
8. Sensitivity: The ratio of the change in output (response) of the instrument to a change of input or measured variable.

➢ DYNAMIC CHARACTERISTICS:-

Instruments rarely respond instantaneously to changes in the measured variables. Instead, they exhibit slowness or sluggishness due to such things as mass, thermal capacitance, fluid capacitance or electric capacitance. In addition to this, pure delay in time is often encountered where the instrument waits for some reaction to take place. Such industrial instruments are nearly always used for measuring quantities that fluctuate with time. Therefore, the dynamic and transient behavior of the instrument is as important as the static behavior.

The dynamic behavior of an instrument is determined by subjecting its primary element (sensing element) to some unknown and predetermined variations in the measured quantity. The three most common variations in the measured quantity are as follows:

l. Step change in which the primary element is subjected to an instantaneous and finite change in measured variable.
2. Linear change, in which the primary element is following a measured variable, changing linearly with time.
3, Sinusoidal change, in which the primary element follows a measured variable, the magnitude of which changes in accordance with a sinusoidal function of constant amplitude
.
The dynamic characteristics of an instrument are (i) speed of response, (ii) Fidelity, (iii) lag, and (iv) dynamic error.

(i) **Speed of Response:** It is the rapidity with which an instrument responds to changes in the measured quantity.
(ii) **Fidelity:** It is the degree to which an instrument indicates the changes in the measured variable without dynamic error (faithful reproduction).
(iii) **Lag:** It is the retardation or delay in the response of an instrument to changes in the measured variable.
(iv) **Dynamic Error:** It is the difference between the true values of a quantity changing with time and the value indicated by the instrument, if no static error is assumed.
When measurement problems are concerned with rapidly varying quantities, the dynamic relations between the instruments input and output are generally Defined by the use of differential equations

➢ STATIC ERROR:-

The static error of a measuring instrument is the numerical difference between the true value of a quantity and its value as obtained by measurement, i.e. repeated measurement of the same quantity give different indications.
Static errors are categorized as gross errors or human errors, systematic errors and Random errors.

1. **Gross Errors**
   This error is mainly due to human mistakes in reading or in using instruments or errors in recording observations. Errors may also occur due to incorrect adjustments of instruments and computational mistakes. These errors cannot be treated mathematically. The complete elimination of gross errors is not possible, but one can minimize them .Some errors are easily detected while others may be elusive. One of the basic gross errors that occur frequently is the improper use of an Instrument the error can be minimized by taking proper care in reading and recording the measurement parameter. In general, indicating instruments change ambient conditions to some extent when connected into a complete circuit.

2. **Systematic Errors**

These errors occur due to shortcomings of, the instrument, such as defective or worn parts, or ageing or effects of the environment on the instrument.
These errors are sometimes referred to as bias, and they influence all measurements of a quantity alike. A constant uniform deviation of the operation of an instrument is known as a systematic error.
There are basically three types of systematic errors
(i) Instrumental, (ii) Environmental, and (iii) Observational

(i) Instrumental Errors
Instrumental errors are inherent in measuring instruments, because of their mechanical structure. For example, in the D'Arsonval movement friction in the bearings of various moving components, irregular spring tensions, stretching of the spring or reduction in tension due to improper handling or over loading of the instrument. Instrumental errors can be avoided by
(a) Selecting a suitable instrument for the particular measurement applications.
(b) Applying correction factors after determining the amount of instrumental error.
(c) Calibrating the instrument against a standard.

(ii) Environmental Errors
Environmental errors are due to conditions external to the measuring device, including conditions in the area surrounding the instrument, such as the effects of change in temperature, humidity, barometric pressure or of magnetic or electrostatic fields.

These errors can also be avoided by (i) air conditioning, (ii) hermetically sealing certain components in the instruments, and (iii) using magnetic shields.

(iii) Observational Errors
Observational errors are errors introduced by the observer. The most common error is the parallax error introduced in reading a meter scale, and the error of estimation when obtaining a reading from a meter scale These errors are caused by the habits of individual observers. For example, an observer may always introduce an error by consistently holding his head too far to the left while reading a needle and scale reading.
In general, systematic errors can also be subdivided into static and dynamic Errors. Static errors are caused by limitations of the measuring device or the physical laws governing its behavior.
Dynamic errors are caused by the instrument not responding fast enough to follow the changes in a measured variable

1. ERROR IN MEASUREMENT

Measurement is the process of comparing an unknown quantity with an accepted standard quantity. It involves connecting a measuring instrument into the system under consideration and observing the resulting response on the instrument. The measurement thus obtained is a quantitative measure of the so-called "true value" (since it is very difficult to define the true value, the term "expected value" is used). Any measurement is affected by many variables; therefore the results rarely reflect the expected value. For example, connecting a measuring instrument into the circuit under consideration always disturbs (changes) the circuit, causing the measurement to differ from the expected value. Some factors that affect the measurements are related to the measuring instruments themselves.
Other factors are related to the person using the instrument. The degree to which a measurement nears the expected value is expressed in terms of the error of measurement. Error may be expressed either as absolute or as percentage of error.
Absolute error may be defined as the difference between the expected value of the variable and the measured value of the variable, or

$$e = Yn - Xn$$

Where e=absolute errors;
Yn=expected value;
Xn=measured value;
Therefore %error = (absolute value/expected value)*100=(e/Yn)*100
Therefore %error= $\left(\frac{Y_n - X_n}{Y_n}\right) * 100$
It is more frequently expressed as an accuracy rather than error.
Therefore A=1-$mod\left(\frac{Y_n - X_n}{Y_n}\right)$
Where A is the relative accuracy
Accuracy is a=100%-%error
a=A*100% (where a=%accuracy)

➢ TEST SIGNALS:-

The dynamic characteristic (or) analysis is classified with respect to time and frequency as time domain analysis and frequency domain analysis

(a).In time domain analysis the i/p is applied to the system and the behaviour of the system is studied as a function of time.

(b) In frequency, domain analysis the i/p is a sinusoidal one and the behaviour of the system is studied as a function of frequency.

The standard test signals used for time domain analysis are as follows.

(i) Step input

(ii) Ramp input

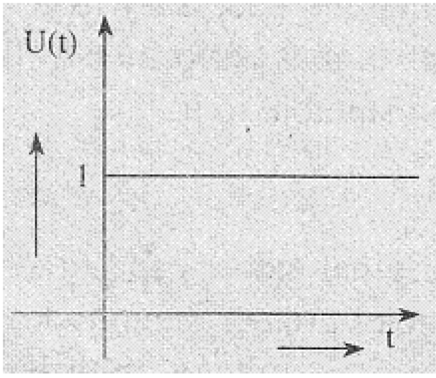
(iii) Parabolic input

(iv) Impulse input.

(i) Step Input

The continuous time step input u (t) is defined as, u (t) = $\begin{cases} 1 \ for \ t \geq 0 \\ 0 \ for \ t < 0 \end{cases}$’

Discrete time step input u[n] is defined as, u [n] = $\begin{cases} 1 \ for \ n \geq 0 \\ 0 \ for \ n < 0 \end{cases}$



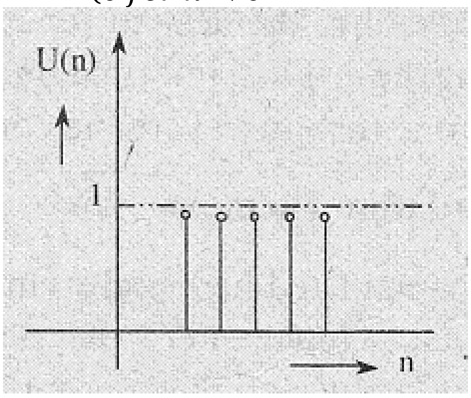
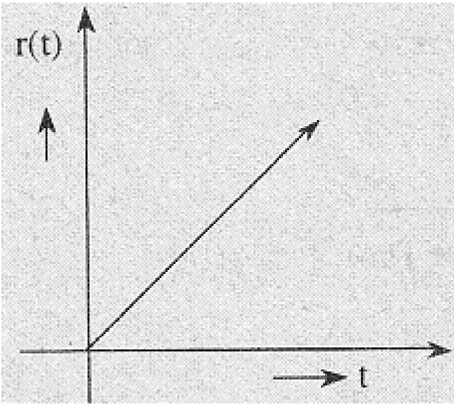


Fig1(a): Continuous time step input u (t) **Fig1(b):** Discrete time step input u[n]

Therefore, a unit step input represents a signal which changes its level from 0 to I in zero time and it reveals a great deal about how quick, the system responds to an abrupt change in the input signal

(ii) Ramp Input

The ramp input is defined in continuous time as r (t) = $\begin{cases} t \ for \ t \geq 0 \\ 0 \ for \ t < 0 \end{cases}$ and in discrete time defined as r [n] = $\begin{cases} n \ for \ n \geq 0 \\ 0 \ for \ n < 0 \end{cases}$



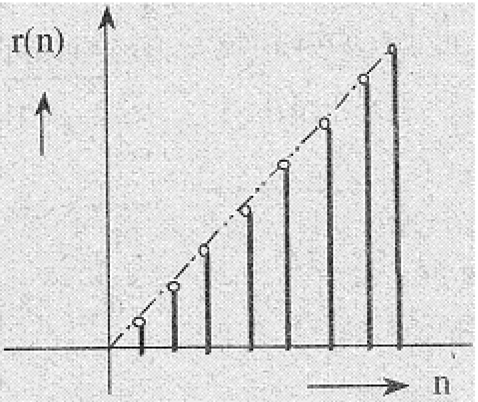


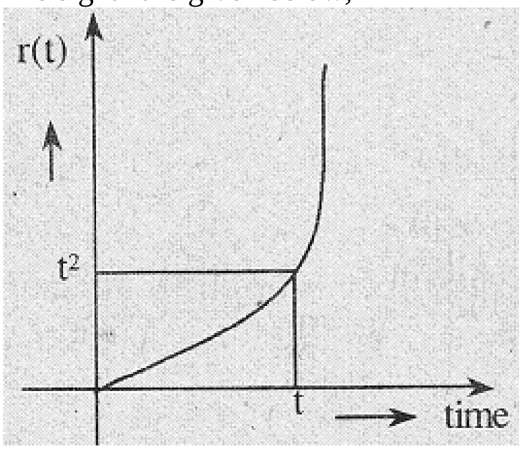
Fig 2(a) : Continuous time ramp input r (t) Fig2(b): Discrete time ramp input r[n]

(iii) Parabolic Input

The parabolic input is defined as r (t) =$\begin{cases} t^2 \; for \; t \geq 0 \\ 0 \; for \; t < 0 \end{cases}$ and the discrete time is defined as,

r [n] =$\begin{cases} n^2 \; for \; n \geq 0 \\ 0 \; for \; n < 0 \end{cases}$

The signal are given below,



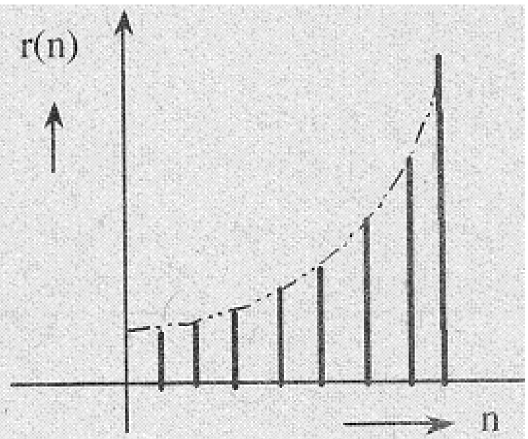


Fig 3(a): Continuous time parabolic input r (t). **Fig3(b):** Discrete time parabolic input r[n]

This signal is also called as acceleration input since the input signal is proportional to represents a constant acceleration.

(iv) Impulse Input

It is also called as a δ (delta) function. The continuous time impulse input is given by, square of time and $(t) = 0 \; for \; t \neq 0$.

And discrete time impulse input is given by, δ (n) =$\begin{cases} 1 \; for \; n = 0 \\ 0 \; for \; n \neq 0 \end{cases}$

The unit impulse is defined as the signal which has a zero value everywhere except at t=0.where the magnitude is finite.

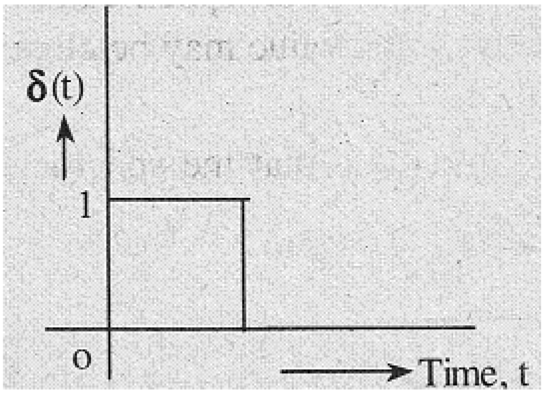


Fig 4: unit impulse signal δ (t)

In frequency domain analysis, the system behavior is studied through the sinusoidal signal because the time varying signals such as step, ramp, and parabolic inputs can be expressed in terms of sinusoidal signal of differential amplitudes and frequencies.

(v) Sinusoidal signal

A continuous time sinusoidal signal is given as

$X(t)=A\sin(\omega t+\varphi)$

Where A= amplitude

ω = frequency in radians/sec.

φ = phase angle in radians.

A sinusoidal signal is an example of a periodic signal, the period of which is $T=\frac{2\pi}{\omega}$

The discrete time version of a sinusoidal signal is given by,

$X[n]=A\sin(\omega n+\varphi)$

Where, ω = angular frequency in radians/cycle.

ANALYSIS OF MEASUREMENT DATA

A statistical analysis of measurement data is common practice because it allows an analytical determination of the uncertainty of the final test result. The outcome 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 interpretations meaningful, a large number of measurements are usually required. 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.

Table 3.1. Deviations around mean

d_1 = 12.8 - 12.65 = 0.15 mA
d_2 = 12.2 - 12.65 = -0.45 mA
d_3 = 12.5 - 12.65 = -0.15 mA
d_4 = 13.1 - 12.65 = 0.45 mA
d_5 = 12.9 - 12.65 = 0.25 mA
d_6 = 12.4 - 12.65 = -0.25 mA

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. The arithmetic mean is given by:

$$\bar{x} = \frac{x_1 + x_2 + x_3 + \cdots + x_n}{n} = \frac{\sum x}{n}$$

where $\bar{x}$ = arithmetic mean, $x_1 \ldots x_n$ = readings taken, and n = number of readings.

Example

A set of independent current measurements was taken by six observers and recorded as 12.8 mA, 12.2 mA, 12.5 mA, 13.1 mA, 12.9 mA, and 12.4 mA. Calculate the arithmetic mean.

$$\bar{x} = \frac{12.8 + 12.2 + 12.5 + 13.1 + 12.9 + 12.4}{6} = 12.65mA$$

Deviation from the Mean

In addition to knowing the mean value of a series of measurements, it is often informative to have some idea of their range about the mean. Deviation is the departure of a given reading from the arithmetic mean of the group of readings. If the deviation of the first reading x_1 is called d_1, and that of the second reading, x_2 is called d_2 and so on, then the deviations from the mean can be expressed as

$$d_1 = x_1 - \bar{x}\,;\; d_2 = x_2 - \bar{x}\,;\; \ldots;\; d_n = x_n - \bar{x}$$

Average Deviation

The average deviation is an indication of the precision at the instruments used in making the measurements. Highly precise instruments will yield a low average deviation between readings. By definition average deviation is the sum of the absolute values of the deviations divided by the number of readings. The absolute value of the deviation is the value without respect to sign. Average deviation may be expressed as

$$D = \frac{|d_1| + |d_2| + |d_3| + \cdots + |d_n|}{n} = \frac{\sum d}{n}$$

Example

The average deviation for the data given in the above example:

$$D = \frac{0.15 + 0.45 + 0.15 + 0.45 + 0.25 + 0.25}{6} = 0.283mA$$

Standard Deviation

The range is an important measurement. It indicates figures at the top and bottom around the average value. The findings farthest away from the average may be removed from the data set without affecting generality. However, it does not give much indication of the spread of observations about the mean. This is where the standard deviation comes in.

In statistical analysis of random errors, the root-mean-square deviation or standard deviation is a very valuable aid. By definition, the standard deviation σ of a finite number of data is the square root of the sum of all the individual deviations squared, divided by the number of readings minus one. Expressed mathematically:

$$\sigma = \sqrt{\frac{d_1^2 + d_2^2 + d_3^2 + \cdots + d_n^2}{n-1}} = \sqrt{\frac{\sum d_i^2}{n-1}}$$

Another expression for essentially the same quantity is the variance or mean square deviation, which is the same as the standard deviation except that the square root is not extracted. Therefore

variance (V) = mean square deviation = σ^2

The variance is a convenient quantity to use in many computations because variances are additive. The standard deviation however, has the advantage of being of the same units as the variable making it easy to compare magnitudes. Most scientific results are now stated in terms of standard deviation.

Probability of Errors

Normal Distribution of Errors

A practical point to note is that, whether the calculation is done on the whole "population" of data or on a sample drawn from it, the population itself should at least approximately fall into a so called "normal (or Gaussian)" distribution.

For example, 50 readings of voltage were taken at small time intervals and recorded to the nearest 0.1 V. The nominal value of the measured graphically in the form of a block diagram or histogram in which the number of observations is plotted against each observed voltage reading. The histogram and the table data are given in Figure . The figure shows that the largest number of readings (19) occurs at the central value of 100.0 V while the other readings are placed more or less symmetrically on either side of the central value. If more readings were taken at smaller increments, say 200 readings at 0.05-V intervals, the distribution of observations would remain approximately symmetrical about the central value and the shape of the histogram would be about the same as before. With more and more data taken at smaller and smaller increments, the contour of the histogram would finally become a smooth curve as indicated by the dashed line in the figure. This bell shaped curve is known as a Gaussian curve. The sharper and narrower the curve, the more definitely an observer may state that the most probable value of the true reading is the central value

Tabulation of Voltage Readings

Voltage reading (volts)	# of reading
99.7	1
99.8	4
99.9	12
100.0	19
100.1	10
100.2	3
100.3	1

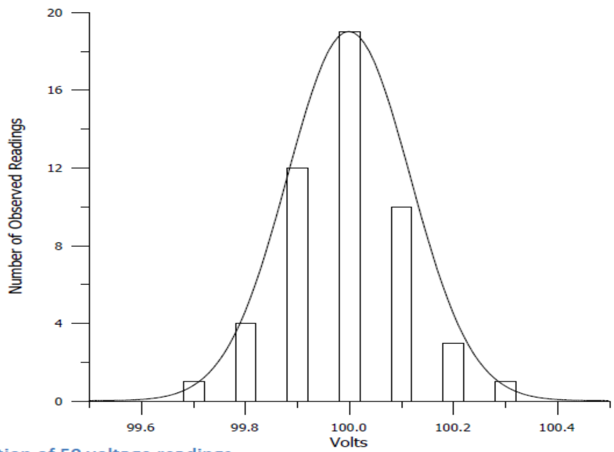


Figure Distribution of 50 voltage readings or mean reading.

For unbiased experiments all observations include small disturbing effects, called random errors. Random errors undergo a Normal (Gaussian) law of distribution shown in Figure 6 . They can be positive or negative and there is equal probability of positive and negative random errors. The error distribution curve indicates that:

- Small errors are more probable than large errors.
- Large errors are very improbable.
- There is an equal probability of plus and minus errors so that the probability of a given error will be symmetrical about the zero value.

$$\Pr obabilityof\,error = \frac{1}{\sqrt{2\pi\sigma}}\exp(-\frac{x^2}{2\sigma})$$

Area Under the Probability Curve

Deviation ±σ	Fraction of total area
0.6745	0.5000
1.0	0.6828
2.0	0.9546
3.0	0.9972

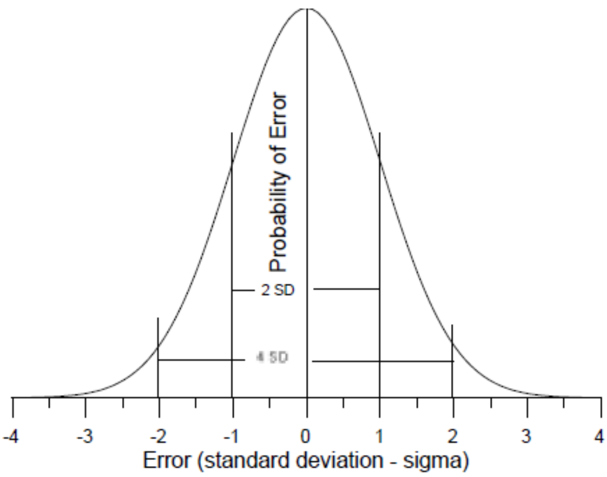


Figure 6: the error distribution curve for a normal distribution

Reading, x	Deviation	
	d	d^2
101.	-0.1	0.01
101.7	0.4	0.16
101.3	0.0	0.00
101.0	-0.3	0.09
101.5	0.2	0.04
101.3	0.0	0.00
101.2	-0.1	0.01
101.4	0.1	0.01
101.3	0.0	0.00
101.1	-0.2	0.04
$\Sigma x=1013.0$	$\Sigma\lvert d\rvert=1.4$	$\Sigma d^2=0.36$

The error distribution curve in Figure 3.8 is based on the Normal (Gaussian) law and shows a symmetrical distribution of errors. This normal curve may be regarded as the limiting form of the histogram in which the most probable value of the true voltage is the mean value of 100.0V. Table 3.2 lists the readings, deviations and deviation squares of readings from the mean value. The reason why the standard deviation is such a useful measure of the scatter of the observations is illustrated in the figure. If the observations follow a “normal” distribution, a range covered by one standard deviation above the mean and one standard deviation below it (i.e. $\bar{x} \pm 1$ SD) includes about 68% of the observations. A range of 2 standard deviations above and below ($\bar{x} \pm 2$ SD) covers about 95% of the observations. A range of 3 standard deviations above and below ($\bar{x} \pm 3$ SD) covers about 99.72% of the observations.

Range of a Variable

If we know the mean and standard deviation of a set of observations, we can obtain some useful information by simple arithmetic. By putting 1, 2, or 3 standard deviations above and below the mean we can estimate the ranges that would be expected to include about 68%, 95% and 99.7% of observations. Ranges for $\pm$ SD and $\pm$ 2 SD are indicated by vertical lines. The table in the inset (next to the figure) indicates the fraction of the total area included within a given standard deviation range.

Acceptable range of possible values is called the confidence interval. Suppose we measure the resistance of a resistor as (2.65 ± 0.04) kΩ. The value indicated by the color code is 2.7 kΩ. Do the two values agree? Rule of thumb: if the measurements are within 2 SD, they agree with each other. Hence, $\pm$ 2 SD around the mean value is called the range of the variable.

Probable Error

The table also shows that half of the cases are included in the deviation limits of $\pm 0.6745\sigma$. The quantity *r* is called the *probable error* and is defined as

$$probable\ error\ r = \pm 0.6745\sigma$$

This value is *probable* in the sense that there is an even chance that any one observation will have a random error no greater than ±r. Probable error has been used in experimental work to some extent in the past, but standard deviation is more convenient in statistical work and is given preference.

Example

Ten measurements of the resistance of a resistor gave 101.2 Ω, 101.7 Ω, 101.3 Ω, 101.0 Ω, 101.5 Ω, 101.3 Ω, 101.2 Ω, 101.4 Ω, 101.3 Ω, and 101.1 Ω. Assume that only random errors are present. Calculate the arithmetic mean, the standard deviation of the readings, and the probable error.

SOLUTION: With a large number of readings a simple tabulation of data is very convenient and avoids confusion and mistakes.

Arithmetic mean, $\bar{x} = \dfrac{\sum x}{n} = \dfrac{1013.0}{10}$ = 101.3 Ω

Standard deviation, $\sigma = \sqrt{\dfrac{d^2}{n-1}} = \sqrt{\dfrac{0.36}{9}}$ = 0.2 Ω

Probable error=0.6745*σ =0.6745*0.2=0.1349Ω

Uncertainties in Reading Analog Displays

The uncertainty in analog displays depends upon the organization of display screen and capabilities of the reader. In analog multi meters it is accepted as ± ½ scale divisions (the least count). In oscilloscope displays, it depends upon the thickness of the trace and it is around ±½ mm. For both analog and digital displays, it is recommended to take the measurement as close to full scale as possible to minimize the effect of the reading error. The following example illustrates the uncertainties in analog meter readings.

Example

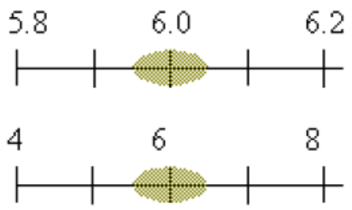


Figure for example

An analog voltmeter is used to measure a voltage. It has 100 divisions on the scale. The voltage read is 6 volts and the meter has two ranges as 0 – 10 volts and 0 – 100 volts. Find the uncertainty in the measured value in both ranges.

Uncertainty = ± ½ V_{FSD} / # of divisions, where V_{FSD} is the voltage measured at full-scale deflection of the meter.

On 10 V range, uncertainty = ± ½ 10 / 100 = ± 0.05 V yielding V = 6 ± 0.05 volt.

On 100 V range, uncertainty = ± ½ 100 / 100 = ± 0.5 V yielding V = 6 ± 0.5 volt.

Relative uncertainty: on 10 V range, 0.05/6 = 1/120 = 0.0083;

on 100 V range, 0.5/6 = 1/12 = 0.083

Percentage uncertainty: on 10 V range, (0.05/6)x100 = 0.83%, and

on 100 V range, (0.5/6)x100 = 8.3%

MODULE – II

- **POTENTIOMETER :--**

A potentiometer is an instrument designed to measure an unknown voltage by comparing it with a known voltage. The known voltage may be supplied by a standard cell or any other known voltage.

A potentiometer is a modified resistor. Unlike a typical resistor, which has two terminals, a potentiometer is a three terminal device. A potentiometer is an instrument for measuring the potential(voltage) in a circuit. Before the introduction of the moving coil and digital volt meters, potentiometers were used in measuring voltage, hence the '-meter' part of their name. The method was described by Johann Christian Poggendorff around 1841 and became a standard laboratory measuring technique.

In this arrangement, a fraction of a known voltage from a resistive slide wire is compared with an unknown voltage by means of a galvanometer. The sliding contact or wiper of the potentiometer is adjusted and the galvanometer briefly connected between the sliding contact and the unknown voltage. The deflection of the galvanometer is observed and the sliding tap adjusted until the galvanometer no longer deflects from zero. At that point the galvanometer draws no current from the unknown source, and the magnitude of voltage can be calculated from the position of the sliding contact.

Potentiometers can be divided into four main categories—thermocouple, constant current, constant resistance and microvolt potentiometers.
Potentiometers are variable resistance devices that can be used to set voltages. They can have linear or logarithmic characteristics and can be constructed using carbon film tracks, or wire wound if longevity and accuracy is required. A wiper or slider can traverse the track to give a variable voltage. A potentiometer is connected between a supply voltage and ground. Using a linear potentiometer the wiper can be used to obtain a voltage proportional to its position on the track making a voltage divider. In Fig. 1.1b the output voltage is proportional to shaft rotation, and in Fig. 1.1c the output voltage is proportional to linear displacement. Linear potentiometers are used to convert mechanical movement into electrical voltages. Logarithmic devices are used in volume controls (the ear, for instance, has a logarithmic response) or similar applications, where a logarithmic output is required.

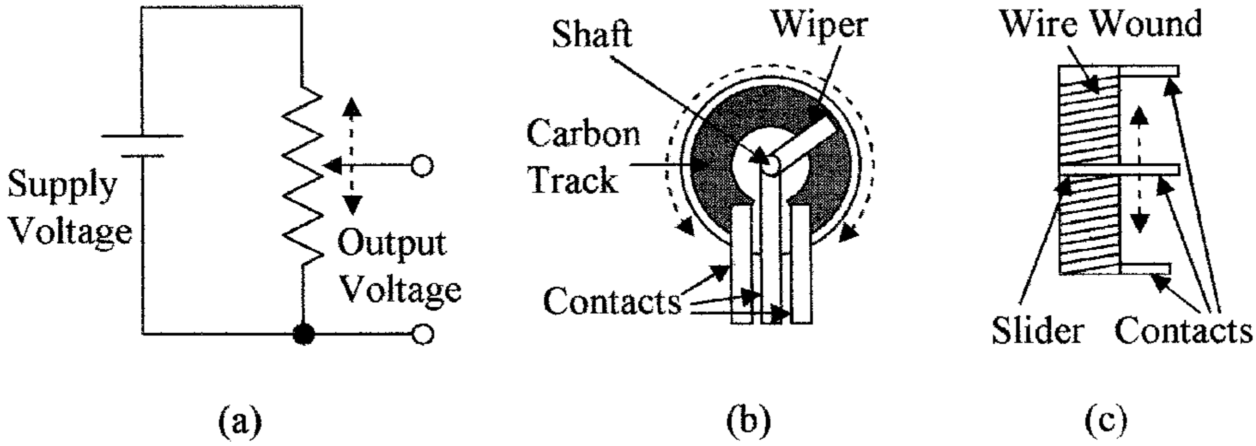


Fig. 1.1(a) voltage divider potentiometer, **(b)** rotational carbon potentiometer, and **(c)** wire-wound slider type potentiometer.

- **STRAIN GAUGE :--**

A strain gauge is used to measure the strain in a work piece. The work piece must be finite in length. For pieces of smaller length strain measurement at a point is better, provided a suitable-sized gauge is available of the purpose. The length over which the average measurement is made is called the 'base length.' A suitable gauge indicates a minimum deformation known as the 'deformation sensitivity' of the base length.

Strain gauges can be made of resistance materials or semiconductor materials. In the former type the strain gauge, generally, consists of a wire of diameter between 0.0008 to 0.0025 cm made of suitable material and of appropriate length.

Other than resistance strain gauges, semiconductor strain gauges are becoming more popular. They may be classified as bonded semiconductor type or the diffused semiconductor type. A typical semiconductor strain gauge is formed by the semiconductor technology i.e., the semiconducting wafers or filaments of length varying from 2 mm to 10 mm and thickness of 0.05 mm are bonded on suitable insulating substrates (for example Teflon). The gold leads are usually employed for making electrical contacts. The electrodes are formed by vapour deposition. The assembly is placed in a protective box as shown in the figure below.

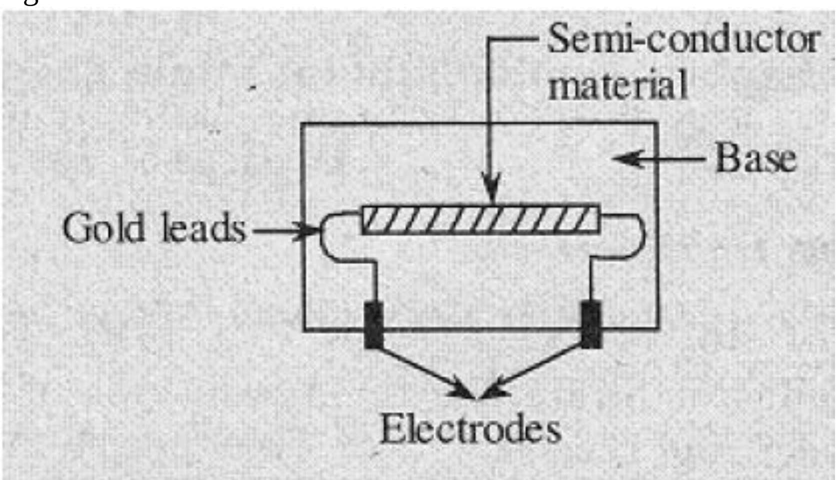


Fig. **1.2** Semiconductor Strain Gauge.

Elements used by the strain sensitive gauge are the semiconductor strain materials such as silicon and germanium. When the strain is applied to the semiconductor element a large of change in resistance occur which can be measured with the help of a wheatstone bridge. The strain can be measured with high degree of accuracy due to relatively high change in resistance. A temperature compensated semiconductor strain gauge can be used to measure small strains of the order of 10-6 i.e., micro-strain. This type of gauge will have a gauge factor of 130 ± 10% for a semiconductor material of dimension 1 x 0.5 x 0.005 inch having the resistance of 350 Ω.

Advantages of Semiconductor Strain Gauge :--

1. The gauge factor of semiconductor strain gauge is very high, about ±130.
2. They are useful in measurement of very small strains of the order of 0.01 micro-strains due to their high gauge factor.
3. Semiconductor strain gauge exhibits very low hysteresis i.e., less than 0.05%.
4. The semiconductor strain gauge has much higher output, but it is as stable as a metallic strain gauge.
5. It possesses a high frequency response of 1012 Hz.
6. It has a large fatigue life i.e., 10 x 106 operations can be performed.
7. They can be manufactured in very small sizes, their lengths ranging from 0.7 to 7.0 mm.

- **RESISTANCE THERMOMETER:--**

Every aspect of our lives, both at home and at work, is influenced by temperature. Temperature measuring devices have been in existence for centuries.

Every type of metal has a unique composition and has a different resistance to the flow of electrical current. This is termed the resistively constant for that metal. For most metals the change in electrical resistance is directly proportional to its change in temperature and is linear over a range of temperatures. This constant factor called the temperature coefficient of electrical resistance (short formed TCR) is the basis of resistance temperature detectors. The RTD can actually be regarded as a high precision wire wound resistor whose resistance varies with temperature. By measuring the resistance of the metal, its temperature can be determined.
Several different pure metals (such as platinum, nickel and copper) can be used in the manufacture of an RTD. A typical RTD probe contains a coil of very fine metal wire, allowing for a large resistance change without a great space requirement. Usually, platinum RTDs are used as process temperature monitors because of their accuracy and linearity.
To detect the small variations of resistance of the RTD, a temperature transmitter in the form of a Wheatstone bridge is generally used. The circuit compares the RTD value with three known and highly accurate resistors.

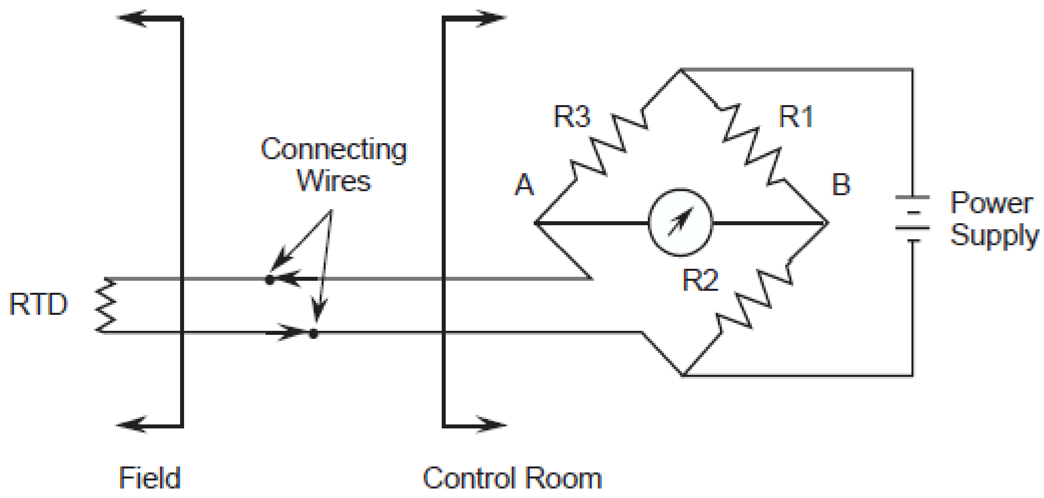


Fig. 1.3 RTD using a thermocouple.

A Wheatstone bridge consisting of an RTD, three resistors, a voltmeter and a voltage source is illustrated in Fig. 1.3. In this circuit, when the current flow in the meter is zero (the voltage at point A equals the voltage at point B) the bridge is said to be in null balance. This would be the zero or set point on the RTD temperature output. As the RTD temperature increases, the voltage read by the voltmeter increases. If a voltage transducer replaces the voltmeter, a 4-20 mA signal, which is proportional to the temperature range being monitored, can be generated.

As in the case of a thermocouple, a problem arises when the RTD is installed some distance away from the transmitter. Since the connecting wires are long, resistance of the wires changes as ambient temperature fluctuates. The variations in wire resistance would introduce an error in the transmitter. To eliminate this problem, a three-wire RTD is used.

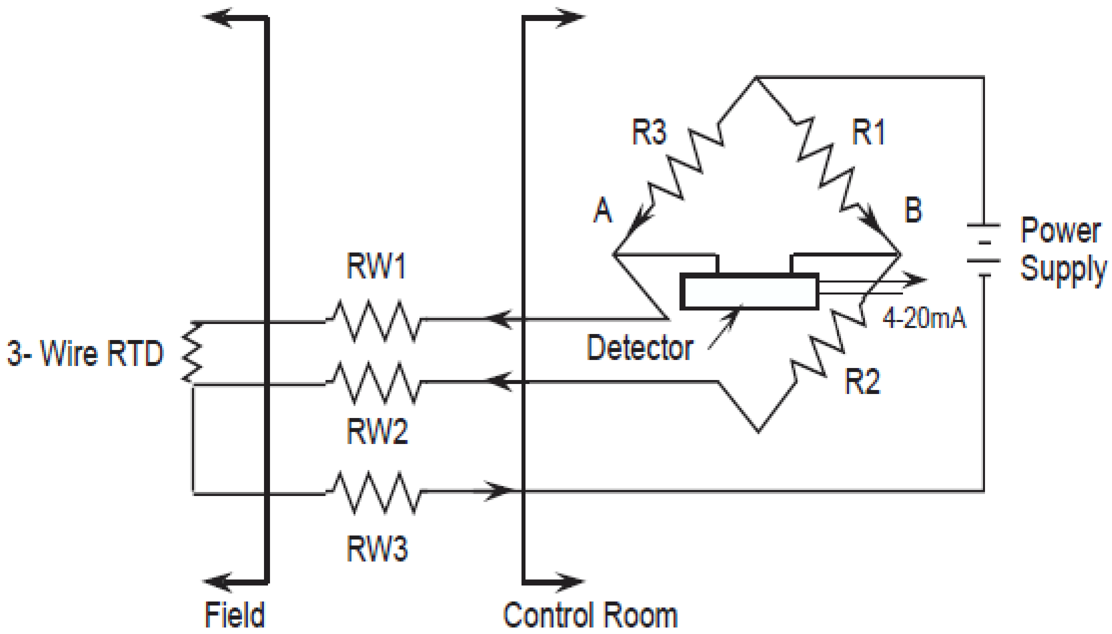


Fig. 1.4 Three wired RTD.

Advantages:--

• The response time compared to thermocouples is very fast – in the order of fractions of a second.
• An RTD will not experience drift problems because it is not self powered.
• Within its range it is more accurate and has higher sensitivity than a thermocouple.
• In an installation where long leads are required, the RTD does not require special extension cable.
• Unlike thermocouples, radioactive radiation (beta, gamma and neutrons) has minimal effect on RTDs since the parameter measured is resistance, not voltage.

Disadvantages:--

• Because the metal used for a RTD must be in its purest form, they are much more expensive than thermocouples.
• In general, an RTD is not capable of measuring as wide a temperature range as a thermocouple.
• A power supply failure can cause erroneous readings
• Small changes in resistance are being measured, thus all connections must be tight and free of corrosion, which will create errors.
• Among the many uses in a nuclear station, RTDs can be found in the reactor area temperature measurement and fuel channel coolant temperature.

Failure Modes:--

• An open circuit in the RTD or in the wiring between the RTD and the bridge will cause a high temperature reading.
• Loss of power or a short within the RTD will cause a low temperature reading.

- **HOT-WIRE ANEMOMETER:--**

Hot wire anemometers use a very fine wire (on the order of several micrometers) electrically heated up to some temperature above the ambient. Air flowing past the wire has a cooling effect on the wire. As the electrical resistance of most metals is dependent upon the temperature of the metal (tungsten is a popular choice for hot-wires), a relationship can be obtained between the resistance of the wire and the flow speed.

Several ways of implementing this exist, and hot-wire devices can be further classified as CCA (constant current anemometer), CVA (constant voltage anemometer) and CTA (constant-temperature anemometer). The voltage output from these anemometers is thus the result of some sort of circuit within the device trying to maintain the specific variable (current, voltage or temperature) constant, following Ohm's law.

The Hot-Wire Anemometer is the most well known thermal anemometer, and measures a fluid velocity by noting the heat convected away by the fluid. The core of the anemometer is an exposed hot wire either heated up by a constant current or maintained at a constant temperature (refer to the schematic below). In either case, the heat lost to fluid convection is a function of the fluid velocity.

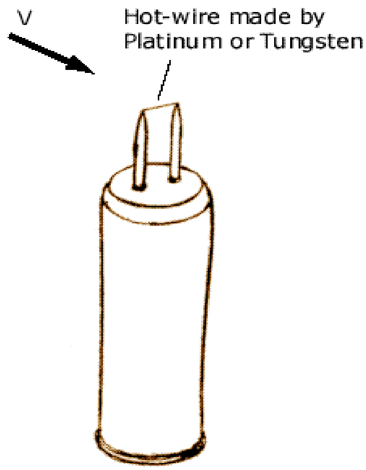


Fig. 1.5 Typical Hot-Wire Anemometer

By measuring the change in wire temperature under constant current or the current required to maintain a constant wire temperature, the heat lost can be obtained. The heat lost can then be converted into a fluid velocity in accordance with convective theory.

Typically, the anemometer wire is made of platinum or tungsten and is 4 ~ 10 µm (158 ~ 393 µin) in diameter and 1 mm (0.04 in) in length. Typical commercially available hot-wire anemometers have a flat frequency response (< 3 dB) up to 17 kHz at the average velocity of 9.1 m/s (30 ft/s), 30 kHz at 30.5 m/s (100 ft/s), or 50 kHz at 91 m/s (300 ft/s). Due to the tiny size of the wire, it is fragile and thus suitable only for clean gas flows. In liquid flow or rugged gas flow, a platinum hot-film coated on a 25 ~ 150 mm (1 ~ 6 in) diameter quartz fiber or hollow glass tube can be used instead, as shown in the schematic below.

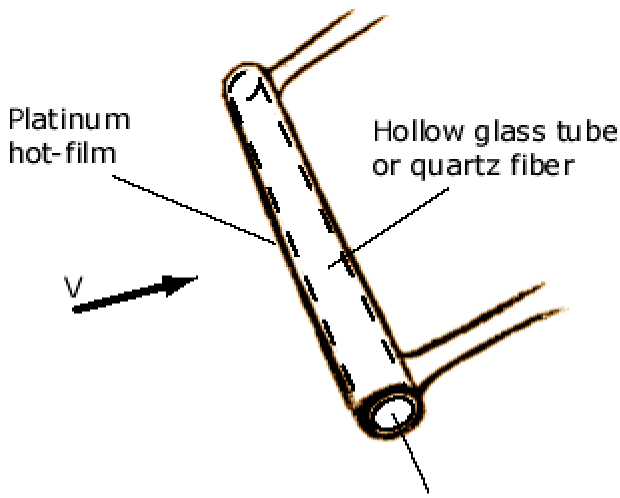


Fig. 1.5 Cooling water or coolant flow through.

- **<u>Pros:--</u>**

Excellent spatial resolution.
High frequency response, >10 KHz(upto 400 KHz).

- **<u>Cons:--</u>**

Fragile, can be used only in clean gas flows.
Needs to be recalibrated frequently due to dust accumulation(unless the flow is very clean).
High cost.

➢ LINEAR VARIABLE DIFFERENTIAL TRANSFORMER(LVDT) :--

Linear Variable Differential Transformer (LVDT) consists of one primary winding *(P)* and two secondary windings (51 and S2).with equal number of turns wound on a cylindrical former. The two secondary windings are connected in series opposition and are placed identically on either side of primary winding to which an AC excitation voltage is connected. A movable soft iron core is placed within the cylindrical former. When the displacement to be measured is applied to the arm of the core, the LVDT converts this displacement into an electrical signal. The construction of LVDT is illustrated in figures below.

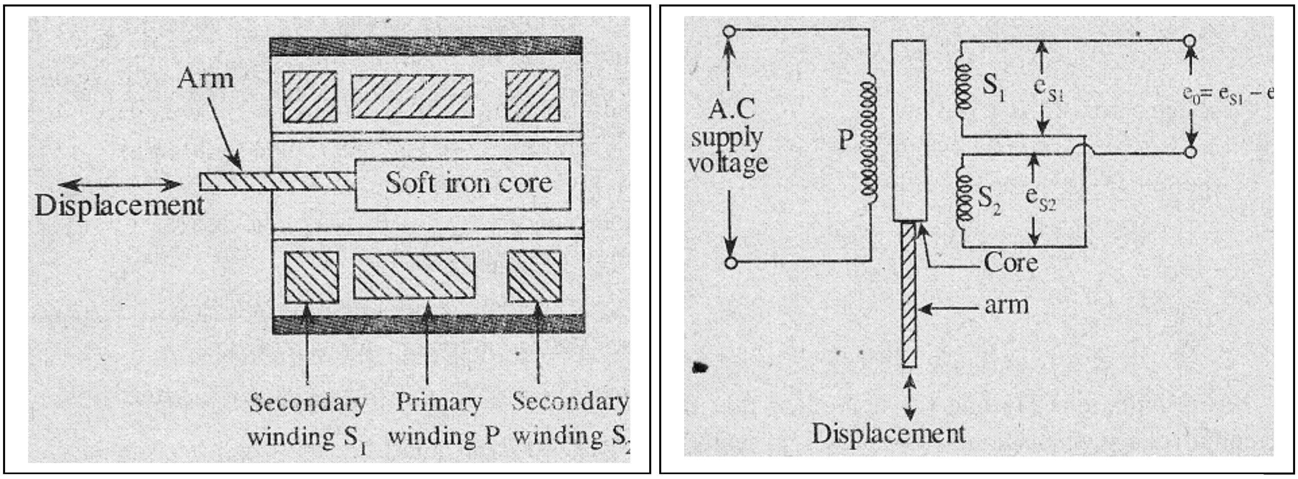


Fig. 1.6 Construction and circuit diagram of LVDT.

Principle of LVDT depends on mutual inductance. When the primary winding is supplied with A.C. supply voltage, it generates alternating magnetic field. Due to this magnetic field an alternating voltage will be induced in the two secondary windings. In the figures ‘es1’ is the output voltage of secondary winding S1 and es2 is the output voltage of secondary winding S2 In order to get single differential output voltage two secondary windings are connected in series opposition. Thus the differential output voltage is given by,

e0=es1-es2

When the core is placed symmetrically with respect to two secondary windings an equal amount of voltage will be induced in both windings. Therefore *esl - es2* and the output voltage is '0'. Hence, this position is known as null position. Now if the core is moved towards up from null position, more magnetic field links with secondary winding S1, and small field links with secondary winding S2. Therefore more voltage will be induced in S1 and less in S2 i . e . , *e s 1* will be larger than *e s 2* . Hence the differential output voltage is e0=es1-es2 and is in phase with primary voltage.

But when the core is moved towards down from null position more magnetic field links with secondary winding S2 and small field links with secondary winding S1. Therefore more voltage will be induced in *S2* and less in S1, i.e.,*es2* will be larger than *es1*. Hence, the differential output voltage is *e0 = es2 – es1* and is 180° out of phase with primary voltage. Thus the output voltage *e0* position of the core and hence the displacement applied to the arm of the core.

Merits:-

1. LVDT has good linearity i.e.. it produces linear output voltages.
2. It can measure displacements of very high range usually from 1.25mm to 250mm.
3. It has high sensitivity.

4. Since it produces high output, it does not require amplifier devices.
5. It has low hysteresis.
6. It consume less power (about < 1w)

Demerits

1. It is sensitive to stray magnetic fields.
2. Performance of LVDT is affected by variations in temperature.
3. It has limited dynamic response.
4. To provide high differential output, it requires large displacements.

- **ACCELEROMETER :--**

Accelerometer sense speed changes by measuring the force produced by the change in velocity of a known mass (seismic mass). These devices can be made with a cantilevered mass and a strain gauge for force measurement or can use capacitive measurement techniques. Accelerometers are now commercially available, made using micromachining techniques. The devices can be as small as 500 μm × 500 μm, so that the effective loading by the accelerometer on a measurement is very small. The device is a small cantilevered seismic mass that uses capacitive changes to monitor the position of the mass. Piezoelectric devices are also used to measure acceleration. The seismic mass produces a force on the piezoelectric element during acceleration which causes a voltage to be developed across the element.

Accelerometers are used in industry for the measurement of changes in velocity of moving equipment, in the automotive industry as crash sensors for air bag deployment, and in shipping crates where battery operated recorders are used to measure shock during the shipment of expensive and fragile equipment.

An accelerometer is a sensor that measures the physical acceleration experienced by an object due to inertial forces or due to mechanical excitation. In aerospace applications accelerometers are used along with gyroscopes for navigation guidance and flight control. Conceptually, an accelerometer behaves as a damped mass on a spring. When the accelerometer experiences acceleration, the mass is displaced and the displacement is then measured to give the acceleration.

In these devices, piezoelectric, piezoresistive and capacitive techniques are commonly used to convert the mechanical motion into an electrical signal. Piezoelectric accelerometers rely on piezoceramics (e.g. lead zirconate titanate) or single crystals (e.g. quartz, tourmaline). They are unmatched in terms of their upper frequency range, low packaged weight and high temperature range. Piezoresistive accelerometers are preferred in high shock applications. Capacitive accelerometers performance is superior in low frequency range and they can be operated in servo mode to achieve high stability and linearity.

Modern accelerometers are often small micro electro-mechanical systems (MEMS), consisting of little more than a cantilever beam with a proof-mass (also known as seismic-mass) realized in single crystal silicon using surface micromachining or bulk micromachining processes.

Working principle of accelerometer:-

The principle of working of an accelerometer can be explained by a simple mass (m) attached to a spring of stiffness (k) that in turn is attached to a casing, as illustrated in fig 2.1. The mass used in accelerometers is often called the seismic-mass or proof-mass. In most cases the system also includes a dashpot to provide a desirable damping effect.

The dashpot with damping coefficient (c) is normally attached to the mass in parallel with the spring. When the spring mass system is subjected to linear acceleration, a force equal to mass times acceleration acts on the proof-mass, causing it to deflect. This deflection is sensed by a suitable means and converted into an equivalent electrical signal. Some form of damping is required, otherwise the system would not stabilize quickly under applied acceleration.

To derive the motion equation of the system Newton"s second law is used, where all real forces acting on the proof-mass are equal to the inertia force on the proof-mass. Accordingly

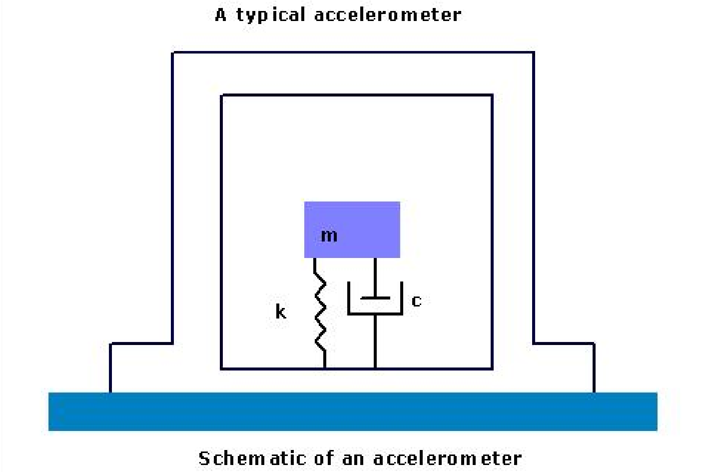


Fig. 1.7 A typical accelerometer

a dynamic problem can be treated as a problem of static equilibrium and the equation of motion can be obtained by direct formulation of the equations of equilibrium. This damped mass-spring system with applied force constitutes a classical second order mechanical system.

From the stationary observer’s point of view, the sum of all forces in the z direction is,

$$Fapplied - Fdamping - Fspring = m\ddot{x}$$

$$m\ddot{x} + kx + \dot{c}x = F \quad \text{... (2.1)}$$

Where ,

m = mass of the proof-mass
x = relative movement of the proof-mass with respect to frame
c = damping coefficient
k = spring constant
F = force applied

Types of Accelerometer:-

There are several different principles upon which an analog accelerometer can be built. Two very common types utilize capacitive sensing and the piezoelectric effect to sense the displacement of the proof mass proportional to the applied acceleration.

Capacitive:-

Accelerometers that implement capacitive sensing output a voltage dependent on the distance between two planar surfaces. One or both of these "plates" are charged with an electrical current. Changing the gap between the plates changes the electrical capacity of the system, which can be measured as a voltage output. This method of sensing is known for its high accuracy and stability. Capacitive accelerometers are also less prone to noise and variation with temperature, typically dissipate less power, and can have larger bandwidths due to internal feedback circuitry.

Piezoelectric:-

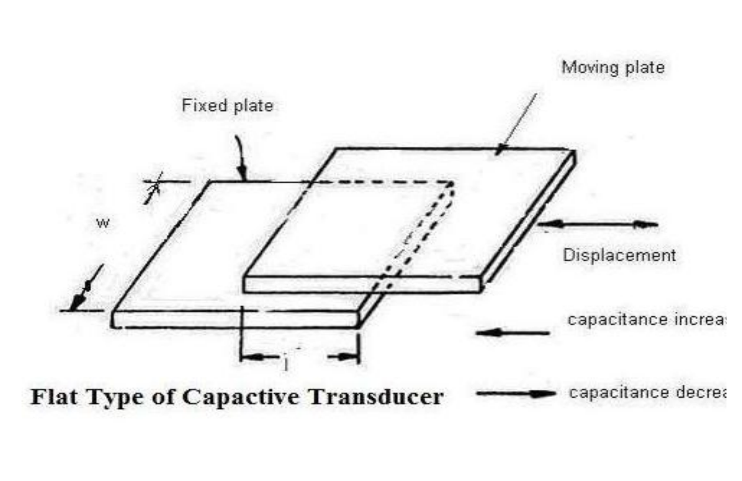
Piezoelectric sensing of acceleration is natural, as acceleration is directly proportional to force. When certain types of crystal are compressed, charges of opposite polarity accumulate on opposite sides of the crystal. This is known as the piezoelectric effect. In a piezoelectric accelerometer, charge accumulates on the crystal and is translated and amplified into either an output current or voltage.

Piezoelectric accelerometers only respond to AC phenomenon such as vibration or shock. They have a wide dynamic range, but can be expensive depending on their quality. Piezo-film based accelerometers are best used to measure AC phenomenon such as vibration or shock, rather than DC phenomenon such as the acceleration of gravity. They are inexpensive, and respond to other phenomenon such as temperature, sound, and pressure

- **VARIABLE CAPACITIVE TRANSDUCER:--**

The capacitive transducer or sensor is nothing but the capacitor with variable capacitance. The capacitive transducer comprises of two parallel metal plates that are separated by the material such as air, which is called as the dielectric material. In the typical capacitor the distance between the two plates is fixed, but in variable capacitance transducers the distance between the two plates is variable.

In the instruments using capacitance transducers the value of the capacitance changes due to change in the value of the input quantity that is to be measured. This change in capacitance can be measured easily and it is calibrated against the input quantity, thus the value if the input quantity can be measured directly.



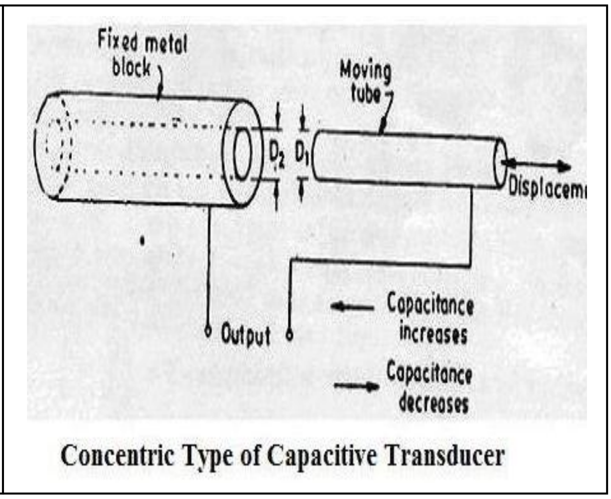


Fig. 1.8 Different types of capacitive transducer

<u>Principle of Working:-</u>

The capacitance C between the two plates of capacitive transducers is given by:
$C = \varepsilon_o \times \varepsilon_r \times A/d$
Where, 'C' is the capacitance of the capacitor or the variable capacitance transducer ε_o is the absolute permittivity ε_r is the relative permittivity.
The product of ε_o & ε_r is also called as the dielectric constant of the capacitive transducer. A is the area of the plates. D is the distance between the plates
It is clear from the above formula that capacitance of the capacitive transducer depends on the area of the plates and the distance between the plates. The capacitance of the capacitive transducer also changes with the dielectric constant of the dielectric material used in it.
Thus the capacitance of the variable capacitance transducer can change with the change of the dielectric material, change in the area of the plates and the distance between the plates. Depending on the parameter that changes for the capacitive transducers, they are of three types as mentioned below.

1) Changing Dielectric Constant type of Capacitive Transducers:- In these capacitive transducer the dielectric material between the two plates changes, due to which the capacitance of the transducer also changes. When the input quantity to be measured changes the value of the dielectric constant also changes so the capacitance of the instrument changes. This capacitance, calibrated against the input quantity, directly gives the value of the quantity to be measured. This principle is used for measurement of level in the hydrogen container, where the change in level of hydrogen between the two plates results in change of the dielectric constant of the capacitance transducer. Apart from level, this principle can also be used for measurement of humidity and moisture content of the air.

2) Changing Area of the Plates of Capacitive Transducers:- The capacitance of the variable capacitance transducer also changes with the area of the two plates. This principle is used in the torquemeter, used for measurement of the torque on the shaft. This comprises of the sleeve that has teeth cut axially and the matching shaft that has similar teeth at its periphery.

3) Changing Distance between the Plates of Capacitive Transducers:- In these capacitive transducers the distance between the plates is variable, while the area of the plates and the dielectric constant remain constant. This is the most commonly used type of variable capacitance transducer. For measurement of the displacement of the object, one plate of the capacitance transducer is kept fixed, while the other is connected to the object. When the object moves, the plate of the capacitance transducer also moves, this results in change in distance between the two plates and the change in the capacitance. The changed capacitance is measured easily and it calibrated against the input quantity, which is displacement. This principle can also be used to measure pressure, velocity, acceleration etc.

Advantages:

- Very little force is required to operate them and hence they are very useful in small systems.
- They are extremely sensitive.
- They have a good frequency response and can measure both the static as well as dynamic changes.
- A resolution of 2.5 x 10^-3 mm may be obtained with these transducers.

Disadvantages:

- The metallic part of the capacitor must be insulated from each other.
- Their performance is severely affected by dirt and other contaminants because they change the dielectric constant.
- They are sensitive to temperature variations and there are possibilities of erratic or distorted signals due to long lead length.

ELECTROMAGNETIC MICROPHONE:--

Electromagnetic microphones are also called dynamic microphones. They convert mechanical motion (as produced by, e.g., an acoustic wave) into an electrical signal. An electrical current is induced (and voltage is produced) if: (i) a static conductor is situated in a changing magnetic field, or (ii) a conductor moves in a static magnetic field. This phenomenon is characterized by Faraday’s law of electromagnetic induction

• The direction of motion (perpendicular to the lines of flux) controls the direction of current flow in the conductor (e.g. a wire).
• Back and forth movements result in an alternating current (AC) related in frequency and amplitude to the wire’s motion.

The diaphragm is attached to the coil. When the diaphragm vibrates in response to incoming sound waves, the coil moves backwards and forwards past the magnet. This creates a current in the coil which is channeled from the microphone along wires.
Moving-coil microphones use the same dynamic principle as in a loudspeaker, only reversed. A small movable induction coil, positioned in the magnetic field of a permanent magnet, is attached to the diaphragm.

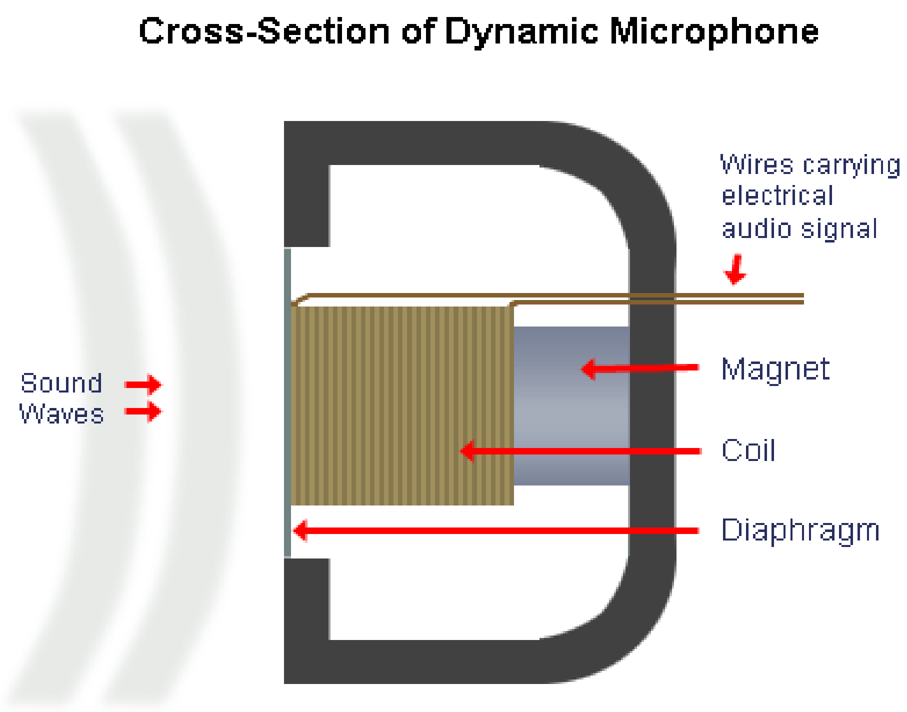


Fig. 1.9 Dynamic Microphone

When sound enters through the windscreen of the microphone, the sound wave moves the diaphragm. When the diaphragm vibrates, the coil moves in the magnetic field, producing a varying current in the coil through electromagnetic induction. A single dynamic membrane does not respond linearly to all audio frequencies. Some microphones for this reason utilize multiple membranes for the different parts of the audio spectrum and then combine the resulting signals. Combining the multiple signals correctly is difficult and designs that do this are rare and tend to be expensive. There are on the other hand several designs that are more specifically aimed towards isolated parts of the audio spectrum. The AKG D 112, for example, is designed for bass response rather than treble. In audio engineering several kinds of microphones are often used at the same time to get the best result.

Advantages :-

- Relatively cheap
- Rugged.
- Can be easily miniaturized.

Disadvantages :-

- The uniformity of response to different frequencies does not match that of the ribbon or condenser microphones

.

Capacitor Microphone:--

Also called condenser or electrostatic microphone as capacitors were historically called as condensers.

Here, the diaphragm acts as one plate of a capacitor, and the vibrations produce changes in the distance between the plates. There are two types, depending on the method of extracting the audio signal from the transducer: DC-biased microphones, and radio frequency (RF) or high frequency (HF) condenser microphones. With a DC-biased microphone, the plates are biased with a fixed charge (*Q*). The voltage maintained across the capacitor plates changes with the vibrations in the air, according to the capacitance equation ($C = {}^{Q}\!/_{V}$), where Q = charge in coulombs, C = capacitance in farads and V = potential difference in volts. The capacitance of the plates is inversely proportional to the distance between them for a parallel-plate capacitor.
The assembly of fixed and movable plates is called an "element" or "capsule".

A nearly constant charge is maintained on the capacitor. As the capacitance changes, the charge across the capacitor does change very slightly, but at audible frequencies it is sensibly constant. The capacitance of the capsule (around 5 to 100 pF) and the value of the bias resistor (100 MΩ to tens of GΩ) form a filter that is high-pass for the audio signal, and low-pass for the bias voltage. Note that the time constant of an RC circuit equals the product of the resistance and capacitance. Within the time-frame of the capacitance change (as much as 50 ms at 20 Hz audio signal), the charge is practically constant and the voltage across the capacitor changes instantaneously to reflect the change in capacitance. The voltage across the capacitor varies above and below the

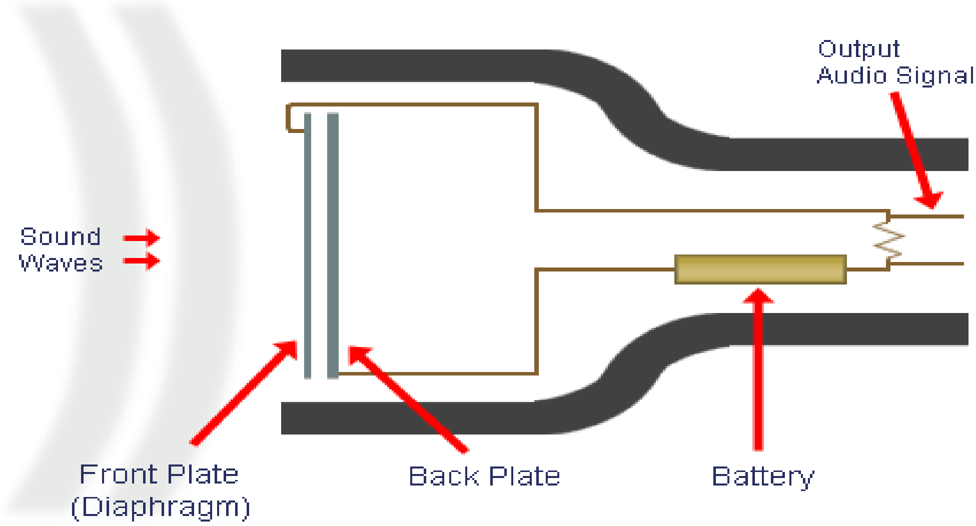


Fig. 1.10 Condenser Microphone.

bias voltage. The voltage difference between the bias and the capacitor is seen across the series resistor. The voltage across the resistor is amplified for performance or recording. In most cases, the electronics in the microphone itself contribute no voltage gain as the voltage differential is quite significant, up to several volts for high sound levels. Since this is a very high impedance circuit, current gain only is usually needed, with the voltage remaining constant.

Advantages:-

- Best overall frequency response
- Best Transient Response

Disadvantages:-

- Expensive
- May pop and crack when miked close
- Requires a battery or external power supply

Module-IV

- **INTRODUCTION:-**

The word smart has been added as prefix to many things that are perceived to possess some form of intelligence. The term smart sensor was adopted in the mid-1980s in the sensor fields to differentiate this class of sensors from conventional sensors. A conventional sensor measures a physical, biological, or chemical parameters, such as displacement, acceleration, pressure, temperature, humidity, oxygen, or carbon monoxide content, and converts them into an electrical signal, either voltage or current. However, a smart sensor with some form of intelligence, provided by an additional microcontroller unit or microprocessor, can convert this raw signal into a level or form which makes it more convenient to use. This might include signal amplification, conditioning, processing, or conversion. In addition, over time, smart functions were not only built into sensors, but applied to actuators as well. Therefore, the term *smart transducers* as used in this chapter refers to smart sensors or smart actuators. Figure 4.1 illustrates the partitioning of a smart transducer s functions.

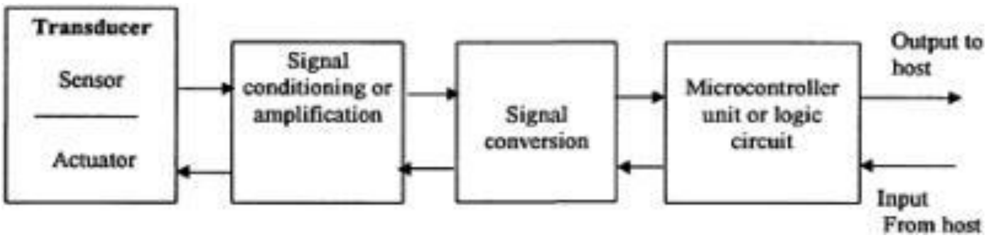


Fig. 4.1: A smart transducer

A smart transducer is either a sensor or an actuator that is instrumented or integrated with signal conditioning and conversion and a microcontroller or microprocessor to provide intelligent functions. Its output is migrating from an analog to a digital format for added capability to communicate with a host or a network.

As sensors and actuators become more complex they provide support for various modes of operation and interfacing. Some applications require additionally fault-tolerance and distributed computing. Such high-level functionality can be achieved by adding an embedded microcontroller to the classical sensor/actuator, which increases the ability to cope with complexity at a fair price.

In the machine vision field, a single compact unit which combines the imaging functions and the complete image processing functions is often called a smart sensor.

They are often made using CMOS, VLSI technology and may contain MEMS devices leading to lower cost. They may provide full digital outputs for easier interface or they may provide quasi-digital outputs like pulse width modulation.

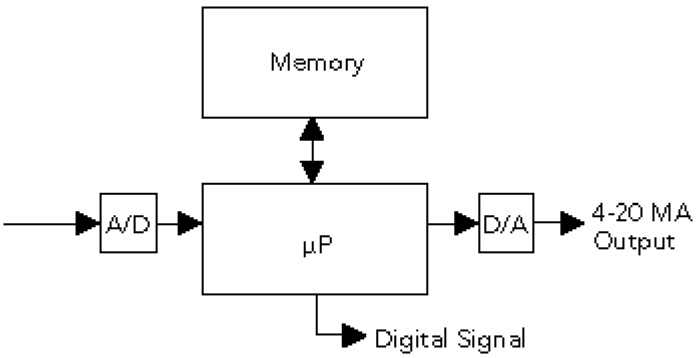
Advantages of smart transducers

1. Compact
2. Higher reliability
3. Lower cost

4. Can be done using existing cmos processes
5. Ease of use
6. electronic data storage
7. self diagnosis and remote calibration
8. self correction
9. auto display

- **SMART TRANSMITTER:-**

So far, the discussion has centered around electronic and pneumatic transmitters. The input and output of both of these types of transmitters is an analog signal -- either a mA current or air pressure, both of which are continuously variable. There is another kind of transmitter -- the "smart" transmitter.



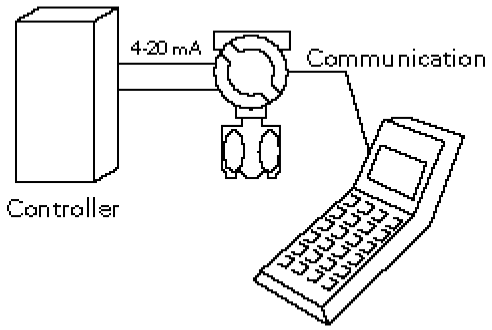


Fig. 4.2: Smart Transmitter Components and Function

The figure above illustrates functions of a smart transmitter. They can convert analog signals to digital signals (A/D), making communication swift and easy and can even send both analog and digital signals at the same time as denoted by D/A.

A smart transmitter has a number of other capabilities as well. For instance, inputs can be varied, as denoted by A/D. If a temperature transmitter is a smart transmitter, it will accept millivolt signals from thermocouples and resistance signals from resistance temperature devices (RTDs) and thermistors.

Components of the smart transmitter are illustrated in the lower figure. The transmitter is built into a housing about the size of a softball as seen on the lower left. The controller takes the output signal from the transmitter and sends it back to the final control element. The communicator is shown on the right.

The communicator is a hand-held interface device that allows digital "instructions" to be delivered to the smart transmitters. Testing, configuring , and supply or acquiring data are all accomplished through the communicator. The communicator has a display that lets the technician see the input or output information. The communicator can be connected directly to the smart transmitter, or in parallel any where on the loop.

- **SMART TRANSMITTER WITH HART COMMUNICATOR:-**

Modern field instruments, otherwise known as smart transmitters, are intelligent microprocessor-based field instruments that monitor process control variables (e.g., temperature, mass flow rate, and pressure). Such field devices are becoming more intelligent, as some processing capabilities are being distributed into the field domain from centralized control rooms. This has simultaneously increased the complexity of the smart transmitter signal chain and added additional challenges to the design of the end product. The incorporation of extra intelligence, functionality, and diagnostic capabilities, while developing a system which can operate effectively within the limited power available from the 4 mA to 20 mA loop, is the immediate challenge facing system designers. A sample solution developed by Analog Devices, Inc., and registered with the HART® Communication Foundation focuses on such a design.

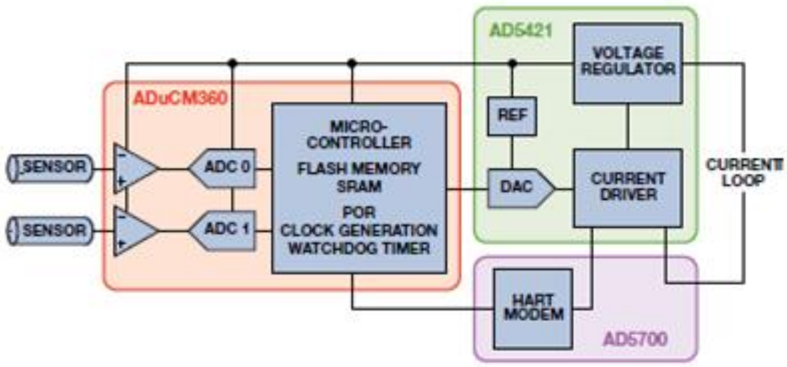


Fig. 4.3. Smart transmitter signal chain.

The two sensors shown in Figure 4.3 are common to smart transmitter designs, whereby the primary variable is dependent on a secondary variable (e.g., temperature compensation of a primary variable).

The ADuCM360 on-chip ADC 0 measures the field instrument primary sensor: in this case, it’s a resistive bridge pressure sensor, while the ADC 1 is used to measure the secondary temperature sensor signal. This allows for temperature compensation of the primary sensor. As with the ADCs, both instrumentation amplifiers are also integrated onto the ADuCM360, along with excitation current sources, voltage reference, and other support analog circuitry. All the field instrument digital functions are provided by the low power 32-bit ARM Cortex™-M3 RISC processor. The microcontroller is, thus, a complex component, with the potential to require a lot of power, so the more processing that can be done per milliwatt, the better. Therefore, the clock frequency at which the controller is operated is adjusted to maintain the required operation and still operate within the low power budget. The same is true of the clock signal for any of the microcontroller peripherals/interfaces. Another crucial aspect for the ADuCM360 to stay within its allocated power budget is the ability to dynamically switch the power to the individual blocks. Such a power gating feature ensures that power is provided to each functional block, as and when it is required, but is switched off when that particular functional block is not in use. As well as processing the measurements, the ADuCM360 is used to control the DAC, which, in turn, controls the loop current.

This AD5421 is a complete, loop powered, digital-to-4 mA-to-20 mA converter that incorporates the reference, loop interface stage, and programmable voltage regulation circuitry necessary to extract a low power supply from the loop, to power both itself and the rest of the transmitter signal chain. The DAC also provides a number of on-chip diagnostic features, all of which can be configured and read by the microcontroller, but can also operate autonomously. As an example, if the communication between the microcontroller and the DAC fails, the on-chip watchdog timer will automatically set the DAC analog output to a 3.2 mA “alarm” current after a defined period. This indicates to the host that the field instrument failed to operate.

- **HART PROTOCOL - AN OVERVIEW :-**

HART is an acronym for "Highway Addressable Remote Transducer". The HART protocol makes use of the Bell 202 Frequency Shift Keying (FSK) standard to superimpose digital communication signals at a low level on top of the 4-2OmA. This enables two-way field communication to take place and makes it possible for additional information beyond just the normal process variable to be communicated to/from a smart field instrument.

The HART protocol communicates at 1200 bps without interrupting the 4-2OmA signal and allows a host application (master) to get two or more digital updates per second from a field device. As the digital FSK signal is phase continuous, there is no interference with the 4- 2OrnA signal.

HART is a master/slave protocol which means that a field (slave) device only speaks when spoken to by a master. Master devices include handheld terminals as well as PC-based work places, e.g. in the control room. HART slave devices, on the other hand, include sensors, transmitters and various actuators. The variety ranges from two-wire and four-wire devices to intrinsically safe versions for use in hazardous environments.

The HART data is superimposed on the 4 to 20 mA signal via a FSK modem. This enables the devices to communicate digitally using the HART protocol, while analog signal transmission takes place at the same time (see .Coding.on page 16ff and Lit./2/).Field devices and compact handheld terminals have an integrated FSK modem,whereas PC stations have a serial interface to connect the modem externally.

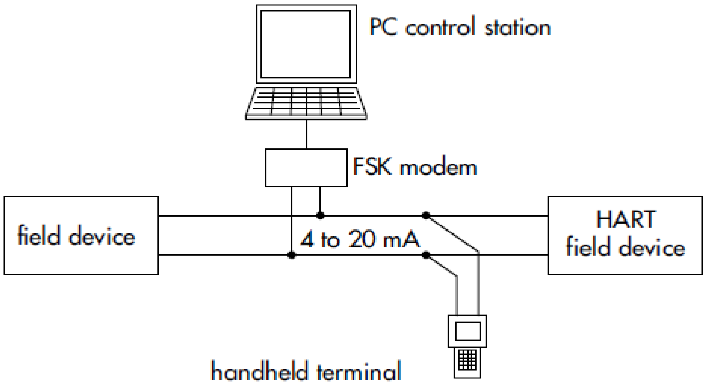


Fig. 4.4: Connection scheme of a HART host device and a HART field device

Figure 4.4 shows a typical connection scheme of a HART host device and a HART field device. HART communication is often used for such simple point-to-point connections.

The HART protocol can be used in various modes for communicating information to/from smart field in3truments and central control or monitor systems. HART provides for up to two masters (primary and secondary). This allows secondary masters such as handheld communicators to be used without interfering with communications to/from the primary master, i.e. control/monitoring system. The most commonly employed HART communication mode is master/slave communication of digital information simultaneous with transmission of the 4-2OmA signal. The HART protocol permits all digital communication with field devices in either point-to-point or multidrop network configuration.

There is an optional "burst" communication mode where single slave device can continuously broadcast a standard HART reply message.

HART COMMUNICATION LAYERS

OSI layers	HART layers
application	HART commands
presentation	
session	
transport	
network	
data link	HART protocol rules
physical layer	Bell 202

Fig. 4.5: HART communication layer

The HART protocol utilizes the OSI reference model. As is the case for most of the communication systems on the field level, the HART protocol implements only the Layers 1, 2 and 7 of the OSI model. The layers 3 to 6 remain empty since their services are either not required or provided by the application layer 7

MICRO-ELECTRO-MECHANICAL SYSTEMS

Micro-Electro-Mechanical Systems, or MEMS, is a technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of micro fabrication.

The critical physical dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, all the way to several millimeters. Likewise, the types of MEMS devices can vary from relatively simple structures having no moving elements, to extremely complex electromechanical systems with multiple moving elements under the control of integrated microelectronics.

The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality whether or not these elements can move.

The term used to define MEMS varies in different parts of the world. In the United States they are predominantly called MEMS, while in some other parts of the world they are called "Microsystems Technology" or "micro machined devices".

While the functional elements of MEMS are miniaturized structures, sensors, actuators, and microelectronics, the most notable (and perhaps most interesting) elements are the micro sensors and micro actuators.

Micro sensors and micro actuators are appropriately categorized as "transducers", which are defined as devices that convert energy from one form to another. In the case of micro sensors, the device typically converts a measured mechanical signal into an electrical signal.

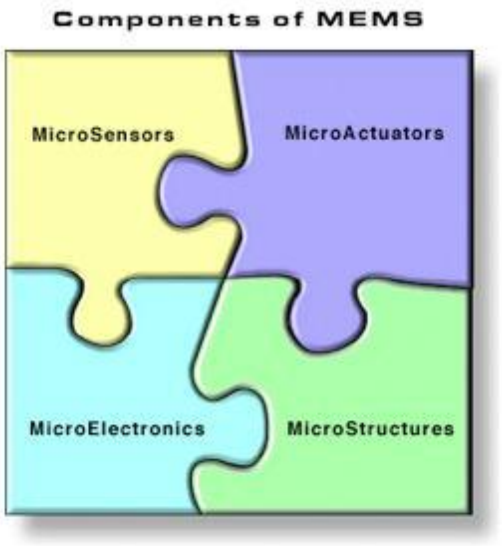


Fig. 4.6: Components of MEMS

Materials for MEMS manufacturing:

The fabrication of MEMS evolved from the process technology in semiconductor device
fabrication, i.e. the basic techniques are deposition of material layers, patterning by photolithography and etching to produce the required shapes.

1 Silicon:

Silicon is the material used to create most integrated circuits used in consumer electronics in the modern world. The economies of scale, ready availability of cheap high-quality materials and ability to incorporate electronic functionality make silicon attractive for a wide variety of MEMS applications.

Silicon also has significant advantages engendered through its material properties. In single crystal form, silicon is an almost perfect Hookean material, meaning that when it is flexed there is virtually no hysteresis and hence almost no energy dissipation. As well
as making for highly repeatable motion, this also makes silicon very reliable as it suffers very little fatigue and can have service lifetimes in the range of billions to trillions of cycles without breaking.

2 Polymers

Polymers on the other hand can be produced in huge volumes, with a great variety of material characteristics. MEMS devices can be made from polymers by processes such as injection molding, embossing or stereo lithography and are especially well suited to micro fluidic applications such as disposable blood testing cartridges.

4.3 Metals

Metals can also be used to create MEMS elements. While metals do not have some of the advantages displayed by silicon in terms of mechanical properties, when used within their limitations, metals can exhibit very high degrees of reliability.

Metals can be deposited by electroplating, evaporation, and sputtering processes. Commonly used metals include gold, nickel, aluminum, copper, chromium, titanium, tungsten, platinum, and silver.

Actuation

On-chip actuation of microsystems has been a particularly challenging aspect of MEMS development. Common macro-level actuation approaches, such as hydraulics, pneumatics, electric motors, internal combustion engines and turbines, are either too difficult to fabricate at the micro level or do not work well at that scale. Electrostatic attraction is one approach that has been widely used for actuation of microsystems. While electrostatic actuation is suitable for many applications, some systems require either lower voltages or higher output forces. Electrostatic and thermal actuation approaches are described in more detail.

Electrostatic Actuation

According to Coulomb's law, the electrostatic force acting between two charges is inversely proportional to the distance between the charges. For macro-scale objects, this force is normally negligible. However, micro-scale devices may have very small gaps, making electrostatic attraction an important source of mechanical motion. This actuation technology is especially attractive because it uses very little power. On the other hand, large voltages (typically tens to hundreds of volts) are required.

The simplest type of electrostatic actuator consists of a movable plate or beam which is pulled toward a parallel electrode under the application of a voltage difference. This type of actuator is illustrated schematically in Figure 5. The movable electrode is suspended by a mechanical spring, which is often simply a micromachined beam. When voltage is placed across the electrodes, opposite charges on each one attract each other. However, unless they touch, the electrodes only draw sufficient current to charge the actuator's effective capacitance, resulting in low power requirements. The attractive force is larger when the movable electrode is closer to the fixed electrode, with the force proportional to the reciprocal of the square of the gap.

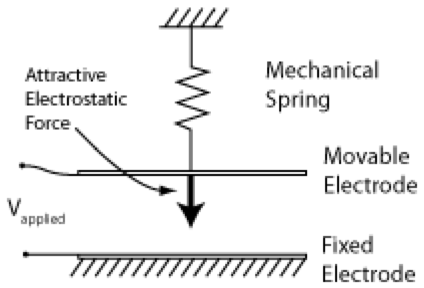


Fig. 4.7: A parallel-plate actuator consists of two parallel electrodes.

Because of this inverse relationship, these parallel-plate actuators suffer from instability for voltages beyond a threshold known as the "pull-in" voltage. For voltages beyond the pull-in voltage, the electrostatic attraction grows more quickly than the mechanical restoring force, causing the electrodes to crash into each other. Unless the electrodes are protected with a dielectric coating or mechanical stops to prevent contact, this normally results in catastrophic melting or vaporization of the actuator due to sudden current flow between the electrodes. For systems with a linear spring, the pull-in voltage is the voltage which causes the movable electrode to deflect one third of the gap. Hence, these actuators cannot be stably operated for deflections larger than this. However, many types of mechanical springs, including fixed-fixed beams, exhibit nonlinear deflection characteristics, leading to a larger usable deflection range.

Comb drive electrostatic actuators avoid the pull-in instability and remove the dependence of the force on the deflection. As with parallel-plate actuators, comb drives consist of one fixed and one movable electrode. The electrodes are shaped like interdigitated combs, however, as shown in Figure 4.7. Using straight combs, like those shown in the figure, results in an attractive force that is nearly constant over a wide range of deflection of the movable comb. The attractive force falls rapidly when the combs disengage and rises rapidly when the combs approach full engagement, but most comb drives are designed to operate entirely in the constant-force region.

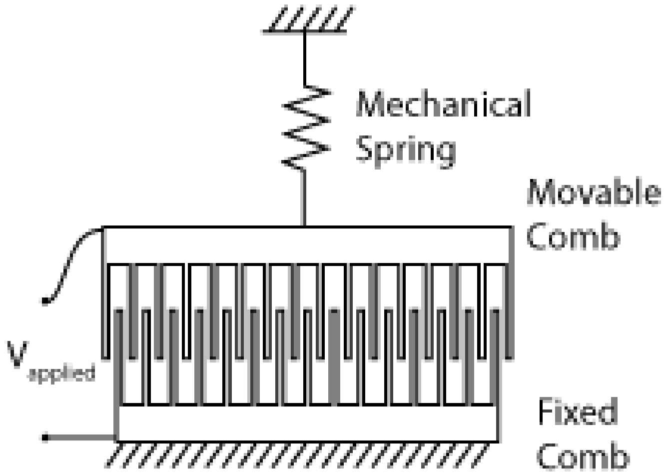


Fig. 4.7: A comb-drive actuator

Comb drives also suffer from instability when the applied voltage is too high, but this instability is not directly related to the deflection of the movable comb. As long as each comb finger is perfectly centered between two opposing comb fingers, the net transverse force acting on that finger will be zero. However, it is common for the fingers to become slightly off-center during motion. If the resulting transverse force is large enough, it will either cause bending of the fingers or it will pull the entire comb in the transverse direction. Hence, for sufficiently large applied voltage, the fingers on opposing combs can touch, which is frequently catastrophic due to melting or vaporization of the fingers.

Thermal Actuation

A change in temperature causes an object to undergo a change in length, where the change is proportional to the material's coefficient of thermal expansion. This length change is usually too small to be useful in most actuation purposes. Therefore, a method of amplifying the displacement is an essential part of thermal actuators. Figures 4.8 a to 4.8 d illustrate four examples for achieving amplification of thermal expansion in microactuators.

Bimetallic devices use two materials with different coefficients of thermal expansion that are fused together. As the temperature increases, one material expands more than the other and the actuator bends to accommodate the different deflections. An example is demonstrated in Figure 4.8a Challenges associated with bimetallic actuators include somewhat complicated fabrication and the potential for delamination of the layers.

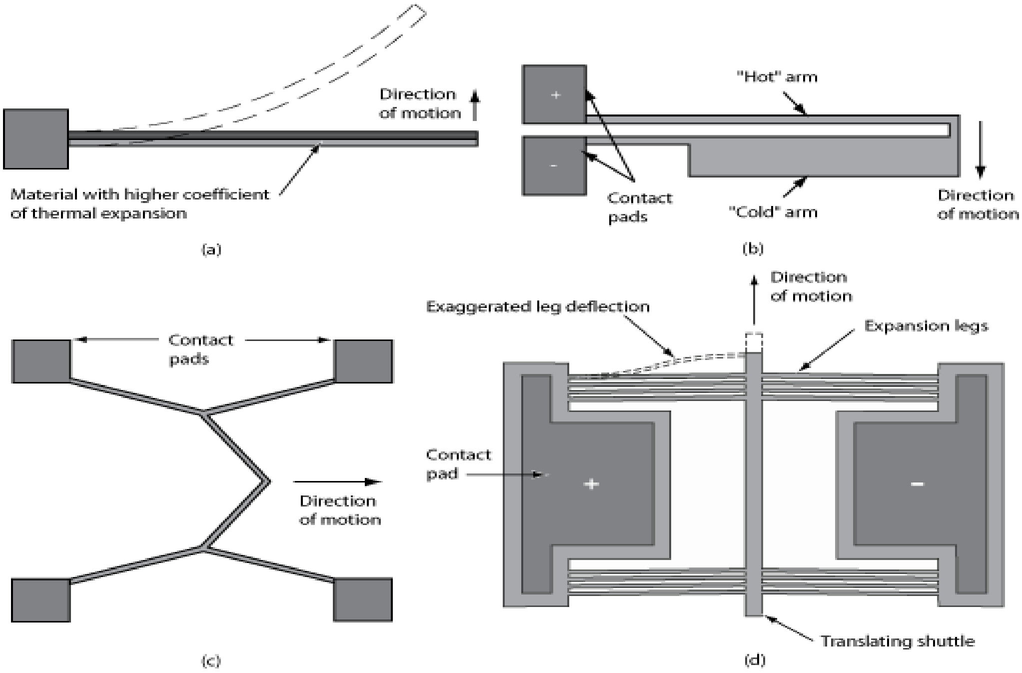


Fig. 4.8: Example thermal amplification approaches, including (a) bimetallic, (b) pseudo-bimorph, (c) geometry-based amplification, and (d) a thermomechanical in-plane microactuator (TIM).

While bimetallic actuators heat both materials to the same temperature but exploit their differences in coefficients of thermal expansion, pseudo bimorphs use a single material with a uniform coefficient of thermal expansion, but with different parts experiencing different temperature changes. This approach makes it possible to construct an actuator from a single layer of the same material. An example is the device shown in Figure 4.8 b which has one leg thinner than the other. An electric current runs through the legs, but the thin leg will have a higher electrical resistance and will heat up more than the wide leg. As the hot leg expands it will cause the actuator to rotate in the direction shown.

Another approach for amplifying the thermal expansion is to use geometric constraints that force the actuator to move in the desired direction. An example of this type of amplification is the "bent beam" actuator, illustrated in Figure 4.8c . As the thin legs heat up, the expansion causes an amplified deflection in the direction shown.

The Thermomechanical In-plane Microactuator (TIM) also exploits geometric constraints , as illustrated in Figure 4.8d. It consists of thin legs connecting both sides of a center shuttle. The leg ends not connected to the shuttle are anchored to bond pads on the substrate and are fabricated at a slight angle to bias motion in the desired direction. As voltage is applied across the bond pads, electric current flows through the thin legs. The legs have a small cross sectional area and thus have a high electrical resistance, which causes the legs to heat up as the current passes through them. The shuttle moves forward to accommodate the resulting thermal expansion. Advantages of this device include its ability to obtain high deflections and large forces, as well as its ability to provide a wide range of output forces by changing the number of legs in the design.

➢ Applications:-

Digital Micromirrors

One of the most visible commercially available microelectromechanical systems is Texas Instruments' Digital Micromirror Device (DMDTM) which is used in applications such as portable projectors, rear-projection televisions, and cinema projectors. The DMD is a rectangular array of moving micromirrors that is combined with a light source, optics, and electronics to project high quality color images [14].

Figure 4.9 shows the architecture of a single DMD pixel. A 16 micrometer square aluminum mirror is rigidly attached to a platform (the "yoke"). Flexible torsion hinges are used to connect the yoke to rigid posts. An applied voltage creates an electrostatic force that causes the mirror to rotate about the torsion hinges. The electronics and structure are designed to allow the mirror to be rotated by 10 degrees in either of two directions (the "on" and "off" positions). When tilted in the on position, the mirror directs light from the light source to the projection optics and the pixel appears bright. When the mirror is tilted in the off position, the light is directed away from the projection optics and the pixel appears dark.

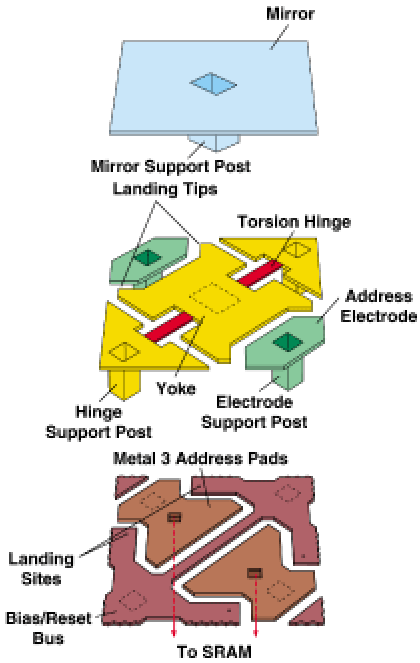


Fig. 4.9: Architecture of the Texas Instruments Digital Micromirror Device (DMD). (Illustration courtesy of Texas Instruments.)

The micromirrors can be combined in an array on a chip, and each micromirror is associated with the pixel of a projected image

The DMD architecture nicely illustrates several MEMS concepts - a few of these are:

- Multi-layer MEMS fabrication was used to make the DMD structure and electronics in layers below the mirror to create a high fill factor.
- The torsion hinges use compliance to obtain motion while avoiding rubbing parts that cause friction and wear.
- The small mass of the micromirrors allows them to move very quickly.
- Electrostatic forces were used to actuate mechanical devices, resulting in low power requirements.

MEMS in Optical Circuits

A wide variety of optical components may also be implemented in MEMS. For example, the Digital Mirror Device discussed above uses micromachined mirrors to redirect light. MEMS mirrors have also been used for optical switching applications, allowing optical communication to be routed without requiring conversion to electrical signals. Adaptive optics systems using MEMS mirrors have been built to correct distortions due to air refraction or lens anomalies.

MEMS optical waveguides are often used to route optical signals within a MEMS optical chip. These waveguides consist of a core with low loss at optical wavelengths. Using micromachining, the waveguides can be patterned on the same chip as other optical components. Both mechanically suspended and fixed waveguides have been demonstrated. Suspended waveguides can also be designed to deflect mechanically. Hence, they can also switch or attenuate a signal when the waveguide is moved in and out of alignment with other components.

Micromachined lens arrays have also been demonstrated for optical applications. Figure 4.10 shows an example of three types of micromachined lens arrays. Similarly, diffractive gratings can be made using the fine dimensional control available from micromachining. These lens arrays and gratings have been used in optical filters and switches.

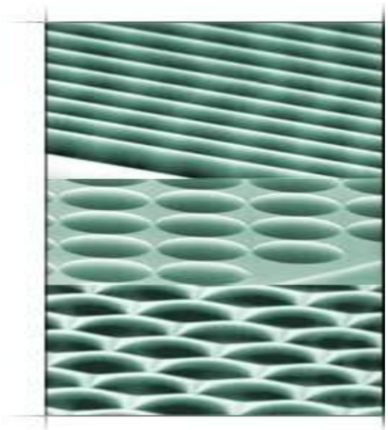


Fig. 4.10: Three types of MEMS lens arrays: cylindrical (top), circular lenses, square packed (middle), and hexagonal lense, hex packed (bottom).

Sensors

A sensor is a device that responds to a physical input (such as motion, radiation, heat, pressure, magnetic field), and transmits a resulting signal that is usually used for detection, measurement, or control. A transducer (often used as a synonym for sensor) is a device that is actuated by power from one system and converts it to a different form to another system. Advantages of MEMS sensors are their size and their ability to be more closely integrated with their associated electronics.

Piezoresistive and capacitive sensing methods are among the most commonly employed sensing methods in MEMS. Piezoresistance is the change in resistivity caused by mechanical stresses applied to a material. Materials with high piezoresistivity (such as some semiconductors which have more than an order of magnitude higher piezoresistivity than metals) are useful for transducing mechanical deformation to electrical signals. This is particularly useful in applications such as pressure sensors and accelerometers.

Capacitive sensors rely on the physical input being sensed to cause a change in capacitance. This capacitance change can be caused by changing the distance between the capacitor plates (e.g. pressure pushing two plates closer together) or by changing the dielectric (such as relative humidity sensor using a dielecric with a permittivity that changes with moisture content). The resulting change in capacitance can be very small and specialized electronics are required to detect the changes and convert them into a usable output signal.

An example of MEMS sensors include bulk micromachined pressure sensors, which have been commercially available since the 1970's. A typical design is illustrated in Figure 4.11. A cavity is etched to create a thin diaphragm which deflects under pressure. A backside port is etched in another substrate and bonded to the first. Piezoresistive pressure sensors have piezoresistive elements on the diaphragm that change resistance as the pressure increases. Another approach is to use the diaphragm as a plate in a capacitor and to detect the capacitance change as the diaphragm deflects under pressure.

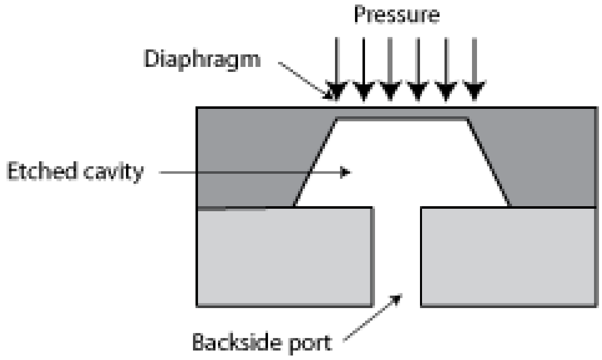


Fig. 4.11: An example of a MEMS pressure sensor.

Accelerometers are another example of commercially successful MEMS sensors. Applications include automotive airbag safety systems, mobile electronics, hard drive protection, and others. These have been successful enough that Analog Devices, a leader in MEMS sensors, had shipped over 200 million MEMS inertial sensors by April 2005. Figure 4.12 illustrates an example of a surface micromachined capacitive accelerometer. An acceleration causes a displacement of the inertial mass and the capacitance change between the comb fingers is detected.

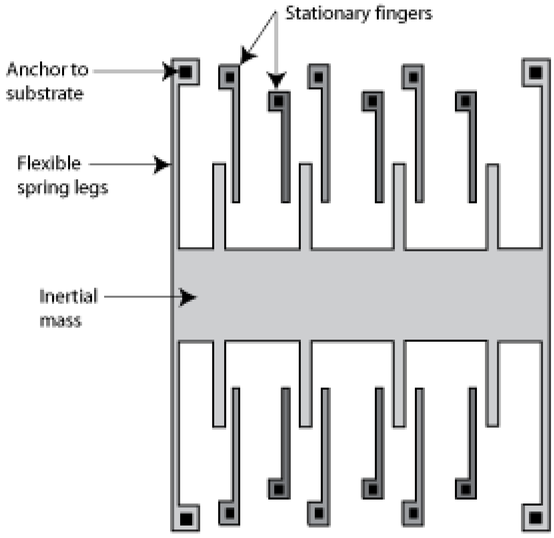


Fig. 4.12: A sketch of a capacitive MEMS accelerometer.

Other MEMS sensors include rate sensors, gyroscopes, radiation sensors, gas sensors, microphones, and mass flow sensors, to name a few.

Applications:-

RF MEMS Components

Several types of MEMS components have been designed to operate in radio-frequency communications circuits. Low-power MEMS filters, variable capacitors, and switches have all been identified as promising MEMS components of RF communications systems. MEMS filters use mechanical vibrations to filter RF signals. They have demonstrated extremely low-power operation. MEMS variable capacitors are used in tuning circuits and oscillators.

MEMS switches are especially attractive because they exhibit "nearly ideal" switch behavior . When on, their insertion loss is typically about 0.2 dB or less, and off-state isolation is normally 20 dB or better even at high frequency (20-40 GHz). In addition, MEMS switches are normally electrostatically actuated, so that they consume very little cycling power.

Two types of MEMS switches have been used. The simplest type opens and closes a contact between micromachined metal electrodes.

Capacitive switches do not suffer from this limitation. Capacitive RF switches also consist of a suspended electrode which is pulled toward a second electrode; however, a dielectric layer separates the two electrodes to prevent the flow of electrons between them. Instead, a capacitive switch works by changing the capacitance between the two electrodes. The ratio of on-state to off-state capacitance can be as high as 200. Because DC current does not flow between the electrodes, capacitive switches can often carry more power than metal contact switches. However, because capacitive impedance is a function of signal frequency, they operate in a more narrow frequency band than metal contact switches.

Inkjet Printing

In 1984, Hewlett-Packard introduced the Thinkjet printer, the one of the first desktop printers to use inkjet technology. The technology was based on micromachined inkjet print heads used to expel drops of ink onto paper in well-defined patterns.

Inkjet printing depends on ink drops being ejected through micromachined orifices to create the desired pattern. Many different techniques have been used to eject the ink drops. Fig. 4.13 illustrates a micromachined print-head that uses one method, called thermal inkjet printing by Hewlett Packard, where it was developed. In this method, a thin-film heater inside an ink-filled cavity heats a thin layer of ink. A bubble forms as the ink layer is superheated. The bubble rises out of the cavity through the micromachined orifice, carrying with it a drop of ink, which is expelled toward the paper. The size of the ink drop can be controlled by designing and fabricating an appropriately-sized cavity and orifice. Other methods for ejecting ink drops rely on mechanical pumping motions, often using piezoelectric materials. This application of micromachining has become extremely wide-spread in the printing industry; in addition, it is starting to be expanded to other industries, including automotive fuel injection, drug delivery, and other areas where precise control of fluid volume is required.

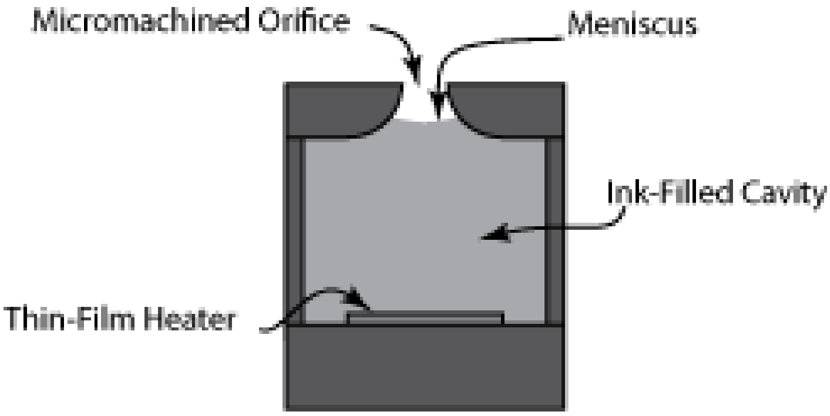


Fig. 4.13. A micromachined inkjet printhead.

Compliant Mechanisms

Achieving motion at the micro level presents some interesting challenges. Because bearings are not feasible and lubrication is problematic, friction and wear present major difficulties. Assembly of parts at this scale is difficult. The constraints introduced by the planar nature of MEMS fabrication also introduce a number of unique challenges in constructing mechanical devices.

The advantages of compliant mechanisms at the micro level include the following :

- Can be fabricated in a plane

- Require no assembly
- Require less space and are less complex
- Have less need for lubrication
- Have reduced friction and wear
- Have less clearance due to pin joints, resulting in higher precision
- Integrate energy storage elements (springs) with the other components