Transducers

The transducer may be defined as any device that convert the energy from one form to another, Most of the transducers either convert electrical energy in to mechanical displacement and convert some non electrical physical quantities like temperature, Light, Pressure , Force , Sound etc to an electrical signals. In an electronics instrument system the function of transducers is of two types.

1. To detect or sense the pressure, magnitude and change in physical quantity being measured.
2. To produce a proportional electrical signal.

Classification of Transducers

The Classification of Transducers is done in many ways. Some of the criteria for the classification are based on their area of application, Method of energy conversion, Nature of output signal, According to Electrical principles involved, Electrical parameter used, principle of operation, & Typical applications.

The transducers can be classified broadly

- On the basis of transduction form used
- Primary and secondary transducers
- Active and passive transducers
- Transducers and inverse transducers.

Primary and Secondary Transducers:

Transducers, on the basis of methods of applications, may be classified into primary and secondary transducers. When the input signal is directly sensed by the transducer and physical phenomenon is converted into the electrical form directly then such a transducer is called the primary transducer.

For example, consider a thermistor used for the measurement of temperature fall in this category. The thermistor senses the temperature directly and causes the change in resistance with the change in temperature. When the input signal is sensed first by some detector or sensor and then its output being of some form other than input signals is given as input to a transducer for conversion into electrical form, then such a transducer falls in the category of secondary transducers.

For example, in case of pressure measurement, bourdon tube is a primary sensor which converts pressure first into displacement, and then the displacement is converted into an output voltage by an LVDT. In this case LVDT is secondary transducer.

Active and Passive Transducers

Transducers, on the basis of methods of energy conversion used, may be classified into active and passive *transducers.*

Self-generating type transducers i.e. the transducers, which develop *their* output *the form of electrical voltage* or *current without* any auxiliary *source*, are called the active transducers. Such transducers draw energy from the system under measurement. Normal such transducers give very small output and, therefore, use of amplifier becomes essential.

Transducers, in which electrical parameters i.e. resistance, inductance or capacitance changes with the change in input signal, are called the passive *transducers.* These transducers require external power source for energy conversion. In such transducer electrical parameters *i.e.* resistance, inductance or capacitance causes a change in voltages current or frequency of the external power source. These transducers may draw sour energy from the system under measurement. Resistive, inductive and capacitive transducer falls in this category.

Transducers and Inverse Transducers

Transducer, as already defined, is a device that converts a non-electrical quantity into an electrical quantity. Normally a transducer and associated circuit have a non-electrical input and an electrical output, for example a thermo-couple, photoconductive cell, pressure gauge, strain gauge etc.

An inverse transducer is a device that converts an electrical quantity into a non-electrical quantity. It is a precision actuator having an electrical input and a low-power non-electrical output.

For examples a piezoelectric crystal and transnational and angular moving-coil elements can be employed as inverse transducers. Many data-indicating and recording devices are basically inverse transducers. An ammeter or voltmeter converts electric current into mechanical movement and the characteristics of such an instrument placed at the output of a measuring system are important. A most useful application of inverse transducers is in feedback measuring systems.

On The Basis Of Transduction Form Used

Capacitance transducers

1. **Variable capacitance pressure gage -**

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

Applications: Measurement of **Displacement, pressure**

2. **Capacitor microphone**

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

Applications: **Speech, music, noise**

3. **Dielectric gage**

Principle of operation: Variation in capacitance by changes in the dielectric. Applications: **Liquid level, thickness**

Inductance transducers

1. **Magnetic circuit transducer**

Principle of operation: Self inductance or mutual inductance of ac-excited coil is varied by changes in the magnetic circuit.

Applications: **Pressure, displacement**

2. Reluctance pickup

Principle of operation: Reluctance of the magnetic circuit is varied by changing the position of the iron core of a coil.

Applications: **Pressure, displacement, vibration, position**

3. Differential transformer

Principle of operation: The differential voltage of two secondary windings of a transformer is varied by positioning the magnetic core through an externally applied force.

Applications: **Pressure, force, displacement, position**

4. **Eddy current gage**

Principle of operation: Inductance of a coil is varied by the proximity of an eddy current plate.

Applications: **Displacement, thickness**

5. Magnetostriction gage

Principle of operation: Magnetic properties are varied by pressure and stress.

Applications: **Force, pressure, sound**

Voltage and current transducers

1. Hall effect pickup

Principle of operation: A potential difference is generated across a semiconductor plate (germanium) when magnetic flux interacts with an applied current.

Applications: **Magnetic flux,**
Current

2. Ionization chamber

Principle of operation: Electron flow induced by ionization of gas due to radioactive radiation.

Applications: **Particle counting, radiation**

3. Photoemissive cell

Principle of operation: Electron emission due to incident radiation on photoemissive surface.

Applications: **Light and radiation**

4. Photomultiplier tube

Principle of operation: Secondary electron emission due to incident radiation on photosensitive cathode.

Applications: **Light and radiation, photo-sensitive relays**

In addition to the above, Transducers, on the basis of nature of output signal, may be classified into analog and digital transducers. Analog transducer converts input signal into output signal, which is a continuous function of time such as thermistor, strain gauge, LVDT, thermo-couple etc.

Digital transducer converts input signal into the output signal of the form of pulse e.g. it gives discrete output. These transducers are becoming more and more popular now-a-days because of advantages associated with digital measuring instruments and also due to the effect that digital signals can be transmitted over a long distance without causing much distortion due to amplitude variation and phase shift. Sometimes an analog transducer combined with an ADC (analog-digital convertor) is called a digital *transducer*.

Basic Requirements of a Transducer

In a measurement system the transducer is the input element with the critical function of transforming some physical quantity to a proportional electrical signal. The following is the summary of the factors influencing the choice of a transducer for measurement of a physical quantity:

1. **Operating principle**
2. **Sensitivity**
3. **Operating Range**
4. **Accuracy**
5. **Cross Sensitivity**

Situations where the actual quantity is measured in one plane and the transducer is subjected lo variations in another plane. More than one promising transducer design has had to be abandoned because the sensitivity to variations of the measured quantity in a plane perpendicular to the required plane has been such as to give completely erroneous results when the transducer has been used in practice.

6. **Errors**

The transducer should maintain the expected input-out relationship as described by its transfer function so as to avoid errors.

7. **Transient and Frequency Response**

The transducer should meet desired time domain specifications like peak overshoot, rise time, settling time and small dynamic error. It should ideally have a flat frequency response curve. In practice, however, there will be cutoff frequencies and higher cut off frequency should he high in order to have a wide bandwidth.

8. Loading Effects

The transducer should have high input impedance and a low output impedance to avoid loading effects.

9. Environmental Compatibility

It should be assured that the transducer selected to work under specified environmental conditions maintains its input/ output relationship and does not break down. For example, the transducer should remain operable under its temperature range. It should be able to work in corrosive environments, should be able to withstand pressures and shocks and other interactions to which it is subjected to.

10. Insensitivity to Unwanted Signals

The transducer should be minimally sensitive to unwanted signals and highly sensitive to desired signals.

11. Usage and Ruggedness

The ruggedness both of mechanical and electrical intensities of transducer versus its size and weight must be considered while selecting a suitable transducer.

12. Electrical aspects

The Electrical aspects that need consideration while selecting a transducer include the length and type of cable required. Attention also must be paid to signal to noise ratio in case the transducer is to be used in conjunction with amplifiers.

13. Stability and Reliability

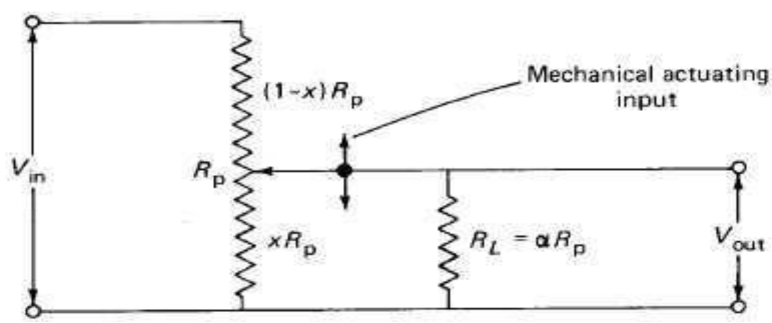
The transducers should exhibit a high degree of stability during its operation and storage life. Reliability should be assured in case of failure of transducer in order that the functioning of the instrumentation system continues unaffected.

14. Static Characteristics

Apart from low static error, the transducers should have a low nonlinearity, low hysteresis, high resolution and a high degree of repeatability. The transducer selected should be free from load alignment effects. It should not need frequent calibration, should not have any component limitations, and should be preferably small in size,

Resistive Transducer

The variable resistance transducers are one of the most commonly used types of transducers. The variable resistance transducers are also called as resistive



transducers or resistive sensors. They can be used for measuring various physical quantities like temperature, pressure, displacement, force, vibrations etc. These transducers are usually used as the secondary transducers, where the output from the primary mechanical transducer acts as the input for the variable resistance transducer. The output obtained from it is calibrated against the input quantity and it directly gives the value of the input.

Principle of Working of Variable Resistance Transducer

The variable resistance transducer elements work on the principle that the resistance of the conductor is directly proportional to the length of the conductor and inversely proportional to the area of the conductor. Thus if L is the length of the conductor (in m) and A is its area (in m square), its resistance (in ohms) is given by:

$$R = \rho L/A$$

Where ρ is called as resistivity of the material and it is constant for the materials and is measured in ohm-m

Strain Gauges

Strain gauges are devices whose resistance changes under the application of force or strain. They can be used for measurement of force, strain, stress, pressure, displacement, acceleration etc.

It is often easy to measure the parameters like length, displacement, weight etc that can be felt easily by some senses. However, it is very difficult to measure the dimensions like force, stress and strain that cannot be really sensed directly by any instrument. For such cases special devices called strain gauges are very useful.

There are some materials whose resistance changes when strain is applied to them or when they are stretched and this change in resistance can be measured easily. For applying the strain you need force, thus the change in resistance of the material can be calibrated to measure the applied force. Thus the devices whose resistance changes due to applied strain or applied force are called as the strain gauges.

Principle of Working of Strain Gauges

When force is applied to any metallic wire its length increases due to the strain. The more is the applied force, more is the strain and more is the increase in length of the wire. If L_1 is the initial length of the wire and L_2 is the final length after application of the force, the strain is given as:

$$\varepsilon = (L_2 - L_1)/L_1$$

Further, as the length of the stretched wire increases, its diameter decreases. Now, we know that resistance of the conductor is the inverse function of the length. As the length of the conductor increases its resistance decreases. This change in resistance of the conductor can be measured easily and calibrated against the applied force. Thus strain gauges can be used to measure force and related parameters like displacement and stress. The input and output relationship of the strain gauges can be expressed by the term gauge factor or gauge gradient, which is defined as the change in resistance R for the given value of applied strain ε.

Consider a wire strain gage, as illustrated above. The wire is composed of a uniform conductor of electric resistivity r with length *l* and cross-section area *A*. Its resistance *R* is a function of the geometry given by

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

The resistance change rate is a combination effect of changes in length, cross-section area, and resistivity.

$$dR = \frac{\rho}{A} dl - \frac{\rho l}{A^2} dA + \frac{l}{A} d\rho$$
$$\Rightarrow \frac{dR}{R} = \frac{dl}{l} - \frac{dA}{A} + \frac{d\rho}{\rho}$$

When the strain gage is attached and bonded well to the surface of an object, the two are considered to deform together. The strain of the strain gage wire along the longitudinal direction is the same as the strain on the surface in the same direction.

$$\varepsilon_l = \frac{dl}{l}$$

However, its cross-sectional area will also change due to the Poisson's ratio. Suppose that the wire is cylindrical with initial radius *r*. The normal strain along the radial direction is

$$\varepsilon_r = \frac{dr}{r} = -\nu \cdot \varepsilon_l = -\nu \frac{dl}{l}$$

The change rate of cross-section area is twice as the radial strain, when the strain is small.

$$\begin{aligned} \frac{dA}{A} &= (1+\varepsilon_r)^2 - 1 = 2\varepsilon_r + \varepsilon_r^{\ 2} \approx 2\varepsilon_r \\ &= -2\nu \frac{dl}{l} \end{aligned}$$

The resistance change rate becomes

$$\begin{aligned} \frac{dR}{R} &= \frac{dl}{l} - \frac{dA}{A} + \frac{d\rho}{\rho} = (1+2\nu)\frac{dl}{l} + \frac{d\rho}{\rho} \\ &= (1+2\nu)\varepsilon_l + \frac{d\rho}{\rho} \end{aligned}$$

For a given material, the sensitivity of resistance versus strain can be calibrated by the following equation.

$$\begin{aligned} S &\triangleq \frac{dR/R}{\varepsilon_l} \\ &= 1 + 2\nu + \frac{d\rho/\rho}{\varepsilon_l} \end{aligned}$$

When the sensitivity factor *S* is given, (usually provided by strain gage vendors) the average strain at the point of attachment of the strain gage can be obtained by measuring the change in electric resistance of the strain gage.

$$\varepsilon_l = \frac{dR/R}{S} \approx \frac{\Delta R}{SR}$$

Materials Used for the Strain Gauges

Earlier wire types of strain gauges were used commonly, which are now being replaced by the metal foil types of gauges. The metals can be easily cut into the zigzag foils for the formation of the strain gauges. One of the most popular materials used for the strain gauges is the copper-nickel-manganese alloy. Some semiconductor materials can also be used for making the strain gauges.

Types of Strain Gauges based on principle of working

1. **Mechanical**: It is made up of two separate plastic layers. The bottom layer has a ruled scale on it and the top layer has a red arrow or pointer. One layer is glued to one side of the crack and one layer to the other. As the crack opens, the layers slide very slowly past one another and the pointer moves over the scale. The red crosshairs move on the scale as the crack widens. Some mechanical strain gauges are even cruder than this. The piece of plastic or glass is sticked across a crack and observed its nature.

2. **Electrical**: The most common electrical strain gauges are thin, rectangular-shaped strips of foil with maze-like wiring patterns on them leading to a couple of electrical cables. When the material is strained, the foil strip is very slightly bent out of shape and the maze-like wires are either pulled apart (so their wires are stretched slightly thinner) or pushed together (so the wires are pushed together

and become slightly thicker). Changing the width of a metal wire changes its electrical resistance. This change in resistance is proportional to the stress applied. If the forces involved are small, the deformation is elastic and the strain gauge eventually returns to its original shape.

3. **Piezoelectric**: Some materials such as quartz crystals and various types of ceramics are effectively "natural" strain gauges. When pushed and pulled, they generate tiny electrical voltages between their opposite faces. This phenomenon is called piezoelectricity. By measuring the voltage from a piezoelectric sensor we can easily calculate the strain. Piezoelectric strain gauges are the most sensitive and reliable devices.

Electrical Strain Gauge: A strain gauge takes advantage of the physical property of electrical conductance. It does not depend on merely the electrical conductivity of a conductor, but also the conductor's geometry. When an electrical conductor is stretched within the limits of its elasticity such that it does not break or permanently deform, it will become narrower and longer. Similarly, when it is compressed, it will broaden and shorten. The change in the resistance is due to variation in the length and cross sectional area of gauge wire.

Gauge Factor:

The characteristics of the strain gauges are described in terms of its sensitivity (gauge factor).

Gauge factor is defined as unit change in resistance for per unit change in length of strain gauge wire given as

$$G.F. = (\Delta R/R_G)/\varepsilon$$

Where,

ΔR - the change in resistance caused by strain, *RG* - is the resistance of the undeformed gauge, and

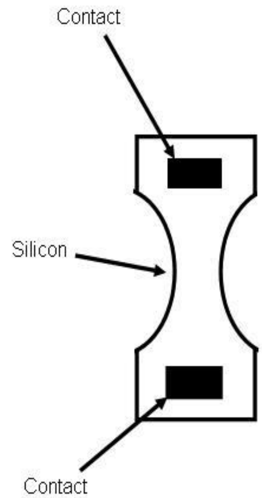
ε – Strain.

Types of strain gauge based on construction

Optical sensors are sensitive and accurate, but are delicate and not very popular in industrial applications. They use interference fringes produced by optical flats to measure strain. Optical sensors operate best under laboratory conditions.

The photoelectric gauge uses a light beam, two fine gratings, and a photocell detector to generate an electrical current that is proportional to strain. The gage length of these devices can be as short as 1/16 inch, but they are costly and delicate.

Semiconductor strain gauges: For measurements of small strain, semiconductor strain gauges, so called piezo-resistors, are often preferred over foil gauges. Semiconductor strain gauges depend on the piezo-resistive effects of silicon or germanium and measure the change in resistance with stress as opposed to strain. The semiconductor bonded strain gauge is a wafer with the resistance element diffused into a substrate of silicon. The wafer element usually is not provided with a backing, and bonding it to the strained surface requires great care as only a thin layer of epoxy is used to attach it. The size is much smaller and the cost much lower than for a metallic foil sensor. The same epoxies that are used to attach foil gages are used to bond semiconductor gages. The advantages are higher unit resistance and sensitivity whereas, greater sensitivity to temperature variations and tendency to drift are disadvantages in comparison to metallic foil sensors. Another disadvantage of semiconductor strain gages is that the resistance-to-strain relationship is nonlinear. With software compensation this can be avoided.



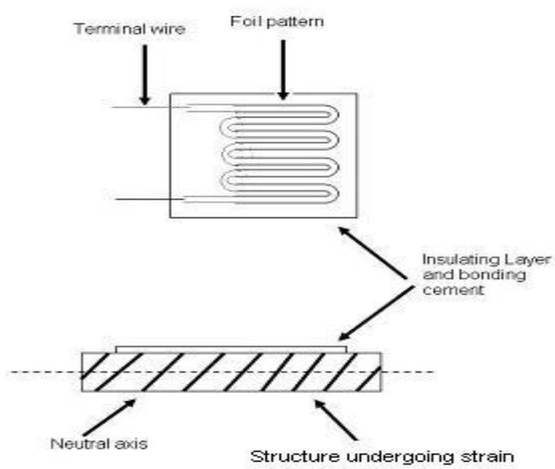
Thin-film strain gauge: These gauges eliminate the need for adhesive bonding. The gauge is produced by first depositing an electrical insulation (typically a ceramic) onto the stressed metal surface, and then depositing the strain gauge onto this insulation layer. Vacuum deposition or sputtering techniques are used to bond the materials molecularly. Because the thin-film gauge is molecularly bonded to the specimen, the installation is much more stable and the resistance values experience less drift. Another advantage is that the stressed force detector can be a metallic diaphragm or beam with a deposited layer of ceramic insulation.

Diffused semiconductor strain gauges: This is a further improvement in strain gage technology as they eliminate the need for bonding agents. By eliminating bonding agents, errors due to creep and hysteresis also are eliminated. The diffused semiconductor strain gage uses photolithography masking techniques and solid-state diffusion of boron to molecularly bond the resistance elements. Electrical leads are directly attached to the pattern. The diffused gauge is limited to moderate-temperature applications and requires temperature compensation. Diffused semiconductors often are used as sensing elements in pressure transducers. They are small, inexpensive, accurate and repeatable, provide a wide pressure range, and generate a strong output signal. Their limitations include sensitivity to ambient temperature variations, which can be compensated for in intelligent transmitter designs.

Types of strain gauge based on mounting

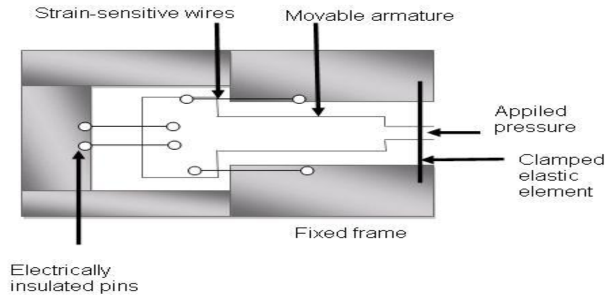
Bonded strain gauge

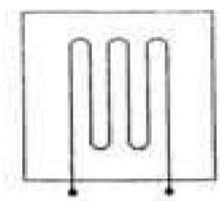
A bonded strain-gage element, consisting of a metallic wire, etched foil, vacuum-deposited film, or semiconductor bar, is cemented to the strained surface.



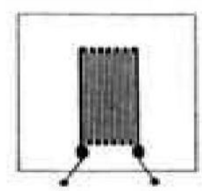
Unbonded Strain Gauge

The unbonded strain gage consists of a wire stretched between two points in an insulating medium such as air. One end of the wire is fixed and the other end is attached to a movable element.





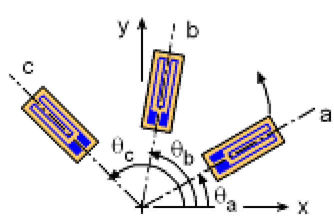
Wire Type Strain Gauges



Metal Foil type of Strain Gauges

ROSETTES

In addition to single element strain gauges, a combination of strain gauges called rosettes is available in many combinations for specific stress analysis.



Strain Gauge Rosette at Arbitrary Angles

Since a single gage can only measure the strain in only a single direction, two gauges are needed to determine strain in the ε_x and ε_y. However, there is no gage that is capable of measuring shear strain.

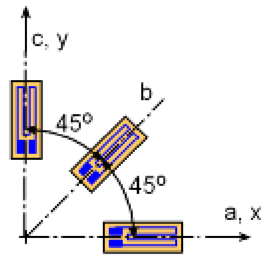
There is a clever solution to finding shear strain. Three gauges are attached to the object in any three different angles. Recall, any rotated normal strain is a function of the coordinate strains, ε_x, ε_y and γ_{xy}, which are unknown in this case. Thus, if three different gages are all rotated, that will give three equations, with three unknowns, ε_x, ε_y and γ_{xy}. These equations are,

$$\varepsilon_a = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2}\cos 2\theta_a + \frac{\gamma_{xy}}{2}\sin 2\theta_a$$
$$\varepsilon_b = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2}\cos 2\theta_b + \frac{\gamma_{xy}}{2}\sin 2\theta_b$$
$$\varepsilon_c = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2}\cos 2\theta_c + \frac{\gamma_{xy}}{2}\sin 2\theta_c$$

Any three gages used together at one location on a stressed object is called a strain rosette.

Strain Rosette - 45^o

To increase the accuracy of a strain rosette, large angles are used. A common rosette of three gauges is where the gages are separated by 45^o, or θ_a = 0^o, or θ_b = 45^o, or θ_c = 90^o. The three equations can then be simplify to



Strain Gauge Rosette at 45°

$$\varepsilon_a = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2}$$
$$\varepsilon_b = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\gamma_{xy}}{2}$$
$$\varepsilon_c = \frac{\varepsilon_x + \varepsilon_y}{2} - \frac{\varepsilon_x - \varepsilon_y}{2}$$

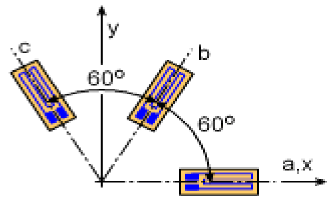
Solving for ε_x, ε_y and γ_{xy} gives,

$$\varepsilon_x = \varepsilon_a \qquad \varepsilon_y = \varepsilon_c \qquad \gamma_{xy} = 2\varepsilon_b - (\varepsilon_a + \varepsilon_c)$$

Strain Rosette - 60°

Similarly, if the angles between the gages are 60°, or$\theta_a = 0^\circ$, or $\theta_b = 60^\circ$, or $\theta_c = 120^\circ$., the unknown strains, for ε_x, ε_y and γ_{xy} will be,

$$\varepsilon_x = \varepsilon_a$$
$$\varepsilon_y = \frac{2\varepsilon_b + 2\varepsilon_c - \varepsilon_a}{3}$$
$$\gamma_{xy} = \frac{2\varepsilon_b - 2\varepsilon_c}{\sqrt{3}}$$



Strain Gage Rosette at 60^{o}

Applications of the Strain Gauges

The strain gauges are used for two main purposes:

1) Measurement of strain: Whenever any material is subjected to high loads, they come under strain, which can be measured easily with the strain gauges. The strain can also be used to carry out stress analysis of the member.

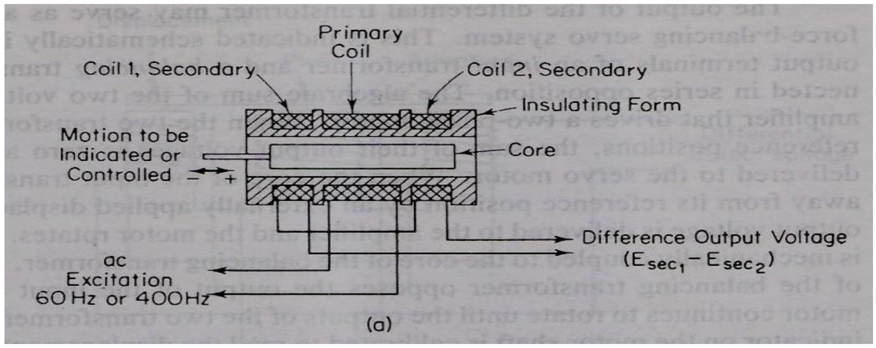
2) Measurement of other quantities: The principle of change in resistance due to applied force can also be calibrated to measure a number of other quantities like force, pressure, displacement, acceleration etc since all these parameters are related to each other. The strain gauges can sense the displacements as small as 5 µm. They are usually connected to the mechanical transducers like bellows for measuring pressure and displacement and other quantities.

INDUCTIVE TRANSDUCERS

The variable inductance transducers work generally upon of the following three principals

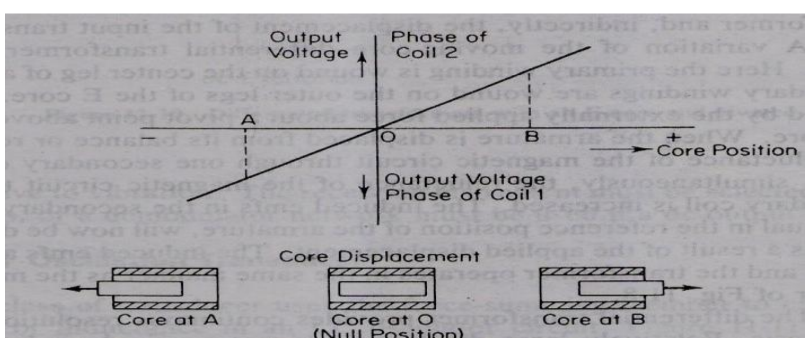
- ✓ Change of self inductance
- ✓ Change of mutual inductance
- ✓ Production of eddy current

Linear Variable Differential Transformer – LVDT Transducer



Construction of the LVDT

The differential transformer transducer measures force in terms of the displacement of the ferromagnetic core of a transformer. The basic construction of the LVDT is given in Fig, 9. The transformer consists of a single primary winding and two secondary windings which are placed on either side of the primary. The secondaries have an equal number of turns but they are connected in series opposition so that the emfs induced in the coils OPPOSE each other. The position of the movable core determines the flux linkage between the ac-excited primary winding and each of the two secondary winding.



Relative positions of the core generate the indicated output voltages as shown in Fig. The linear characteristics impose limited core movements, which are typically up to 5 mm from the null position. With the core in the center, (or *reference* position or Fig.), the induced emfs in the secondaries are equal, and since they oppose each other, the output voltage will be

0 V. When an externally applied force moves the core to the left-hand position, more magnetic flux links the left-hand coil than the right-hand coil and the Differential Output $E0 = E_{S1} - E_{S2}$ Is in-phase with Ei as $E_{S1} > E_{S2}$. The induced emf of the left hand coil is therefore larger than the induced emf of the right-hand coil. The magnitude of the output voltage is then equal to the difference between the two secondary voltages, and it is *in phase* with the voltage of the left-hand coil.Similarly, when the core is forced to move to the right, more flux links the right-hand coil than the left-hand coil and the resultant output voltage is now in phase with the emf of the right-hand coil, while its magnitude again equals the difference between the two induced emfs.Ideally the output voltage at the null position should be equal to zero. In actual practice there exists a small voltage at the null position. This may be on account of **presence of harmonics** in the **input supply voltage** and also due to **harmonics produced in the output voltage** due to use of iron Displacement core. There may be either an **incomplete magnetic or electrical** unbalance or both which result in a finite output voltage at the null position. This finite residual voltage is generally less than 1% of the maximum output voltage in the linear range. Other causes of residual voltage are **stray magnetic fields and temperature effects.**

Advantages of LVDT

- High Range: the LVDTs has a very high range for measurement of displacement This can be used for measurement of displacement ranging from 1.25 mm to 2.50 mm
- Friction and Electrical Isolation

- Immunity from External Effects
- High input and high sensitivity
- Ruggedness: The transducer can usually tolerate high degree of shock and vibration
- Low Hysteresis
- Low Power consumption

Disadvantage of LVDT

- ✓ Relatively large displacement are required for appreciable differential output
- ✓ They are sensitivity to stray magnetic fields but shielding is possible
- ✓ Many times, the transducer performance is affected by vibrations
- ✓ The receiving instrument must be selected to operate on ac signal
- ✓ The dynamic response is limited mechanically by the mass of the core and electrically by frequency of applied voltage. The frequency of the carrier of the carrier should be at least ten times the highest frequency component to be measured
- ✓ Temperature affects the performance

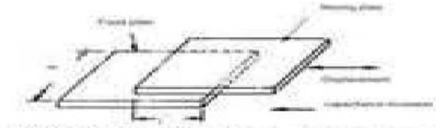
Applications of LVDT

Acting as a secondary transducer it can be used as a device to measure force, weight and pressure etc. The **force measurement** can be done by using a **load cell** as the **primary transducer** while fluid **pressure** can be measured by using **Bourdon tube** which acts as primary transducer. The force or the pressure is converted into a **voltage**. In these applications the **high sensitivity** of LVDTs is a major attraction.

Capacitve Transducer

The capacitive transducer is used extensively for the measurement of displacement, pressure etc. Let us see the principle of working of capacitive transducer or sensor also called as variable capacitance 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.

Capactive Transducer or Capacitive Sensor or Variable Capacitance Transducer



Flat Type of Capacitive Transducer

Concentric Type of Capacitive Transducer

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 this 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

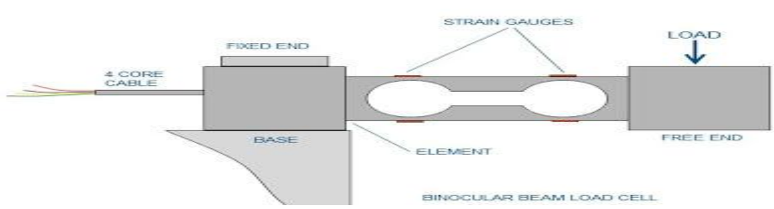
The capacitance of the variable capacitance transducer also changes with the area of the two plates. This principle is used in the torquemeter, used for measurement of the torque on the shaft. This comprises of the sleeve that has teeth cut axially and the matching shaft that has similar teeth at its 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

Load cell

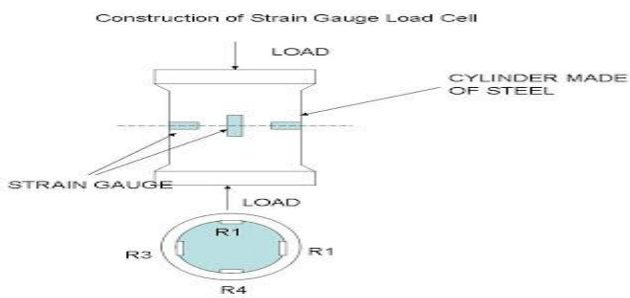
A load cell is a device that is used to convert a force into electrical signal. Strain gauge load cells are the most common types of load cells. There are other types of load cells such as hydraulic (or hydrostatic), Pneumatic Load Cells, Piezoelectric load cells, Capacitive load cells, Piezo resistive load cells etc. Load cells are used for quick and precise measurements. Compared with other sensors, load cells are relatively more affordable and have a longer life span.



Strain Gauge load cell

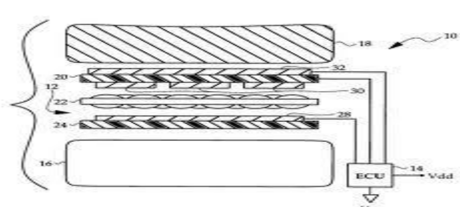
The principle of operation of the Strain Gauge load cell is based on the fact that the resistance of the electrical conductor changes when its length changes due to stress. Cu Ni alloy is commonly used in strain gauge construction as the resistance change of the foil is virtually proportional to the applied strain.

The change in resistance of the strain gauge can be utilized to measure strain accurately when connected to an appropriate measuring circuit. A load cell usually consists of four strain gauges in a Wheatstone bridge configuration. The electrical signal output is typically very small in the order of a few millivolts. It is amplified by an instrumentation amplifier before sending it to the measurement system. The output can be Digital or Analog (0-5V) depending on the application.



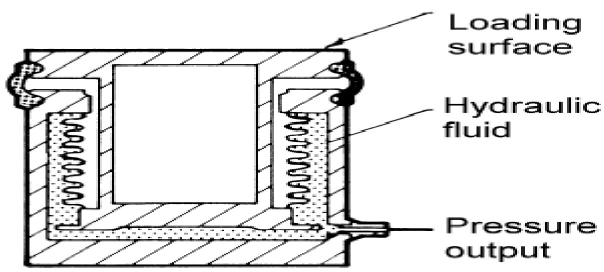
Capacitive Load Cell

Capacitive load cells is based on the principle where the capacitance of a capacitor changes as the load presses the two plates of a capacitor closer together. The construction of a capacitive sensor is simpler than a resistive load cell. Capacitive techniques can be used to measure proximity, humidity, tilt, force, torque, fluid quality, acceleration and many other physical parameters. It is a very versatile parameter that offers tremendous sensitivities in a small package. The capacitive technology is more rugged than strain gauge designs and can therefore be used in a wider variety of engineering applications.



Hydraulic Load Cell

Hydraulic load cells are force-balance devices, measuring weight as a change in pressure of the internal filling fluid. In hydraulic load cell, a load or force acting on a loading head is transferred to a piston that in turn compresses a filling fluid confined within an elastomeric diaphragm chamber. As the force increases, the pressure of the hydraulic fluid increases. This pressure can be locally indicated or transmitted for remote indication or control. This sensor has no electric components and immune to transient voltages so it is ideal for use in hazardous areas. The advantages of Hydraulic load cells are it is expensive and very complex.



Pneumatic load cell

Pneumatic load cells operate on the force-balance principle. These devices use multiple dampener chambers to provide higher accuracy than can a hydraulic device. Pneumatic load cells are often used to measure relatively small weights in industries where cleanliness and safety are of prime concern.

Advantages of Load cell

- Rugged and compact construction
- No moving parts

- Can be used for static and dynamic loading
- Highly Accurate
- Wide range of measurement
-
- Can be used for static and dynamic loading

Disadvantages of Load cell

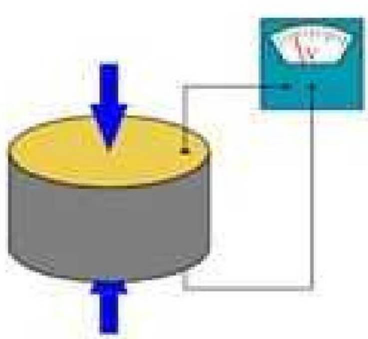
- Mounting is difficult
- Calibration is a tedious procedure

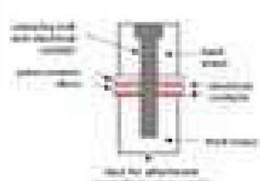
Piezoelectric Transducers

Piezoelectric Effect

There are certain materials that generate electric potential or voltage when mechanical strain is applied to them or conversely when the voltage is applied to them, they tend to change the dimensions along certain plane. This effect is called as the piezoelectric effect. This effect was discovered in the year 1880 by Pierre and Jacques Curie.

Some of the materials that exhibit piezoelectric effect are quartz, Rochelle salt, polarized barium titanate, ammonium dihydrogen, ordinary sugar etc.





The piezoelectric transducers work on the principle of piezoelectric effect. When mechanical stress or forces are applied to some materials along certain planes, they produce electric voltage. This electric voltage can be measured easily by the voltage measuring instruments, which can be used to measure the stress or force.

The physical quantities like stress and force cannot be measured directly. In such cases the material exhibiting piezoelectric transducers can be used. The stress or the force that has to be measured is applied along certain planes to these materials.

The voltage output obtained from these materials due to piezoelectric effect is proportional to the applied stress or force. The output voltage can be calibrated against the applied stress or the force so that the measured value of the output voltage directly gives the value of the applied stress or force. In fact the scale can be marked directly in terms of stress or force to give the values directly.

The voltage output obtained from the materials due to piezoelectric effect is very small and it has high impedance. To measure the output some amplifiers, auxiliary circuit and the connecting cables are required.

Materials used for the Piezoelectric Transducers

There are various materials that exhibit piezoelectric effect as mentioned above. The materials used for the measurement purpose should posses desirable properties like stability, high output, insensitive to the extreme temperature and humidity and ability to be formed or machined into any shape. But none of the materials exhibiting piezoelectric effect possesses all the properties. Quartz, which is a natural crystal, is highly stable but the output obtained from it is very small. It also offers the advantage of measuring very slowly varying parameter as they have very low leakage when they are used with high input impedance amplifiers.

Due to its stability, quartz is used commonly in the piezoelectric transducers. It is usually cut into rectangular or square plate shape and held between two electrodes. The crystal is connected to the appropriate electronic circuit to obtain sufficient output.

Rochelle salt, a synthetic crystal, gives the highest output amongst all the materials exhibiting piezoelectric effect. However, it has to be protected from the moisture and cannot be used at temperature above 115 degree F. Overall the synthetic crystals are more sensitive and give greater output than the natural crystals. The materials used for the measurement purpose should posses desirable properties like stability, high output, insensitive to the extreme temperature and humidity and ability to be formed or machined into any shape. The piezoelectric crystals have high impedance so they have to be connected to the amplifier and the auxiliary circuit, which have the potential to cause errors in measurement. To reduce these errors amplifiers high input impedance and long cables should be used.

Advantages of Piezoelectric Transducers

Every devise has certain advantages and limitations. The piezoelectric transducers offer several advantages as mentioned below:

1) High frequency response: They offer very high frequency response that means the parameter changing at very high speeds can be sensed easily.

2) High transient response: The piezoelectric transducers can detect the events of microseconds and also give the linear output.

3) High output: They offer high output that be measured in the electronic circuit.

Digital Transducers

Any Transducer that presents information as discrete samples and that does not introduce a quantization error when reading is represented in the digital form may be classified as a digital transducer. Encoder is an example for digital transducer.

Encoders

- Any transducer that generates a coded reading of a measurement can be termed an *encoder*.

- *Shaft Encoders* are digital transducers that are used for measuring angular displacements and velocities.
- Relative advantages of digital transducers over their analog counterparts:
  - High resolution (depending on the word size of the encoder output and the number of pulses per revolution of the encoder)
  - High accuracy (particularly due to noise immunity of digital signals and superior construction)
  - Relative ease of adaptation in digital control systems (because transducer output is digital) with associated reduction in system cost and improvement of system reliability
- Shaft Encoders can be classified into two categories depending on the nature and method of interpretation of the output:
  - Incremental Encoders
  - Absolute Encoders
- Incremental Encoders
  - Output is a pulse signal that is generated when the transducer disk rotates as a result of the motion that is being measured.

- By counting pulses or by timing the pulse width using a clock signal, both angular displacement and angular velocity can be determined.
- Displacement, however, is obtained with respect to some reference point on the disk, as indicated by a reference pulse (index pulse) generated at that location on the disk. The index pulse count determines the number of full revolutions.

- Absolute Encoders
  - An absolute encoder has many pulse tracks on its transducer disk.
  - When the disk of an absolute encoder rotates, several pulse trains – equal in number to the tracks on the disk

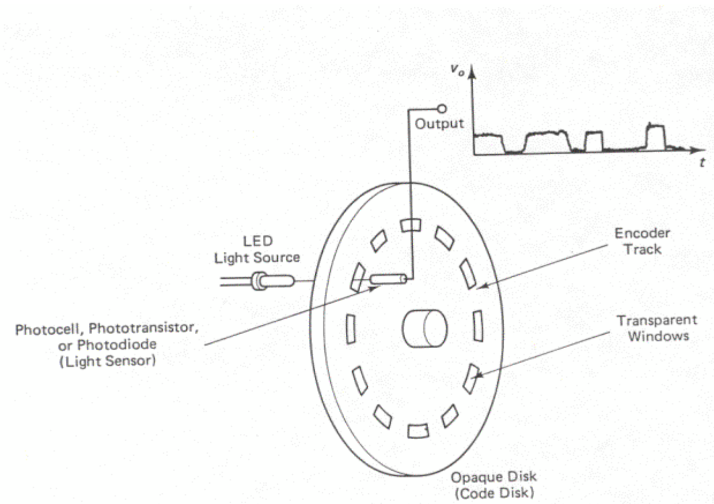
    – are generated simultaneously.
  - At a given instant, the magnitude of each pulse signal will have one of two signal levels (i.e., a binary state) as determined by a level detector. This signal level corresponds to a binary digit (0 or 1). Hence, the set of pulse trains gives an encoded binary number at any instant.
  - The pulse windows on the tracks can be organized into some pattern (code) so that each of these binary numbers corresponds to the angular position of the encoder disk at the time when the particular binary number is detected.
  - Pulse voltage can be made compatible with some form of digital logic (e.g., TTL)
  - Direct digital readout of an angular position is possible.
  - Absolute encoders are commonly used to measure fractions of a revolution. However, complete revolutions can be measured using an additional track that generates an index pulse, as in the case of an incremental encoder.

- Signal Generation can be accomplished using any one of four techniques:
  - Optical (photosensor) method
  - Sliding contact (electrical conducting) method

– Magnetic saturation (reluctance) method

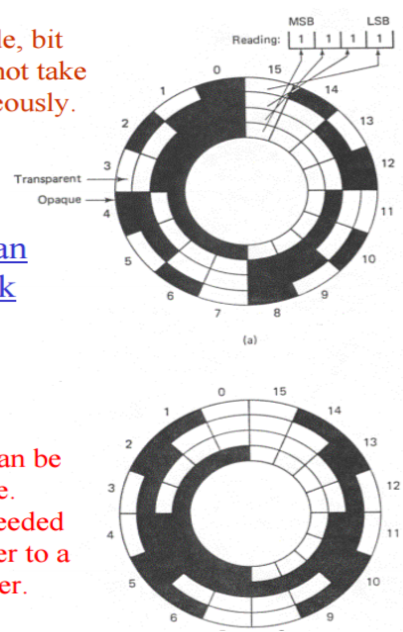
– Proximity sensor method

- Method of signal interpretation and processing is the same for all four types of signal generation.



Schematic Representation of an Optical Encoder

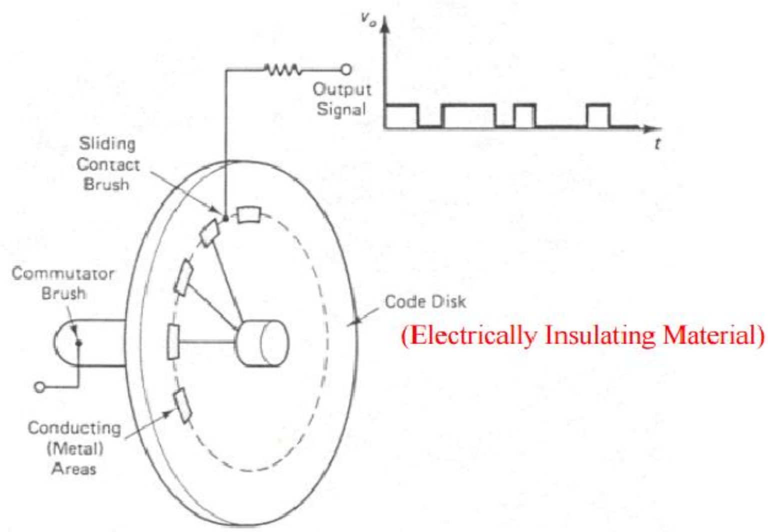
In Binary Code, bit switching may not take place simultaneously.



Schematic Diagram of an Absolute Encoder Disk Pattern
(a) Binary code
(b) Gray code

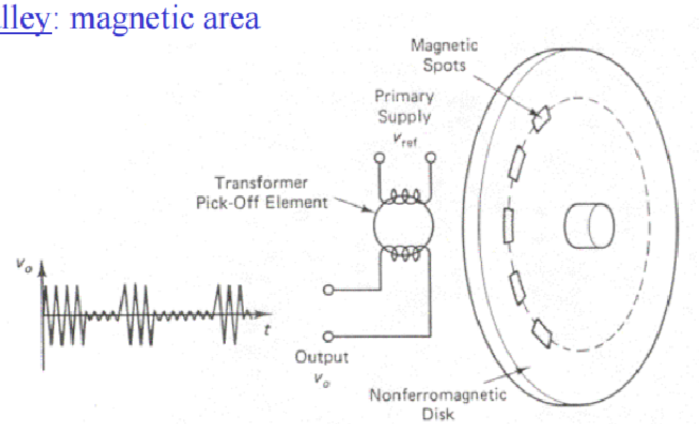
Absolute Encoders must be powered and monitored only when a reading is taken. Also, if a reading is missed, it will not affect the next reading.

Ambiguities in bit switching can be avoided by using gray code. However, additional logic is needed to covert the gray-coded number to a corresponding binary number.

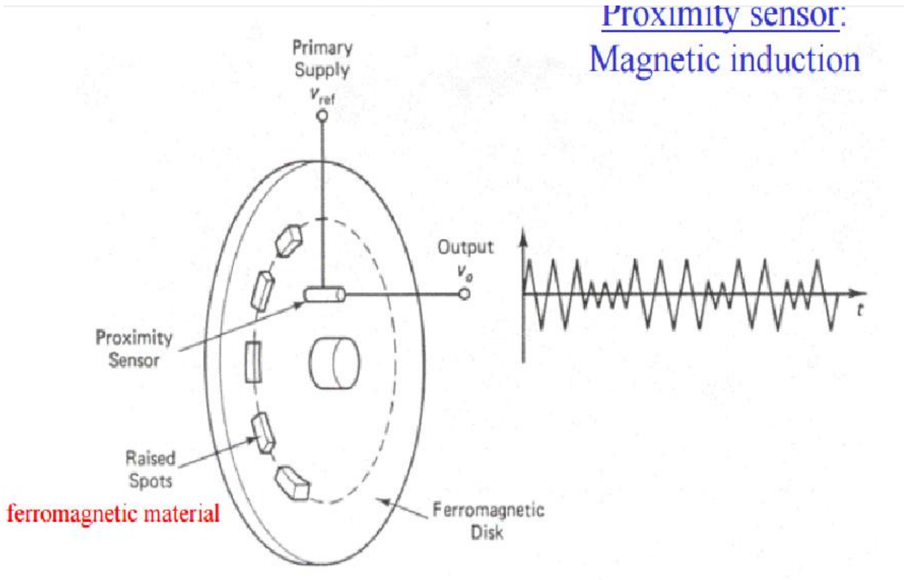


Schematic Representation of a Sliding Contact Encoder

Pulse peak: nonmagnetic are
Pulse valley: magnetic area



Schematic Representation of a Magnetic Encoder



Schematic Representation of a Proximity Probe Encoder

Elements of the Optical Encoder

- The optical encoder uses an opaque disk (code disk) that has one or more circular tracks, with some arrangement of identical transparent windows (slits) in each track.
- A parallel beam of light (e.g., from a set of light- emitting diodes) is projected to all tracks from one side of the disk.
- The transmitted light is picked off using a bank of photosensors on the other side of the disk that typically has one sensor for each track.
- The light sensor could be a silicon photodiode, a phototransistor, or a photovoltaic cell.
- Since the light from the source is interrupted by the opaque areas of the track, the output signal from the probe is a series of voltage pulses. This signal can be interpreted to obtain the angular position and angular velocity of the disk.
- Note that an incremental encoder disk requires only one primary track that has equally spaced and identical window (pick-off) areas. The window area is equal

to the area of the inter-window gap. Usually, a reference track that has just one window is also present in order to generate a pulse (known as the index pulse) to initiate pulse counting for angular position measurement and to detect complete revolutions.

– In contrast, absolute encoder disks have several rows of tracks, equal in number to the bit size of the output data word. Furthermore, the track windows are not equally spaced but are arranged in a specific pattern on each track so as to obtain a binary code (or gray code) for the output data from the transducer.

– It follows that absolute encoders need as least as many signal pick-off sensors as there are tracks, whereas incremental encoders need one pick-off sensor to detect the magnitude of rotation and an additional sensor at a quarter-pitch separation (pitch = center-to-center distance between adjacent windows) to identify the direction of rotation, i.e., the *offset sensor configuration.*

– Some designs of incremental encoders have two identical tracks, one a quarter-pitch offset from the other and the two pick-off sensors are placed radially without any circumferential offset, i.e., the *offset track configuration*.

– A pick-off sensor for a reference pulse is also used.

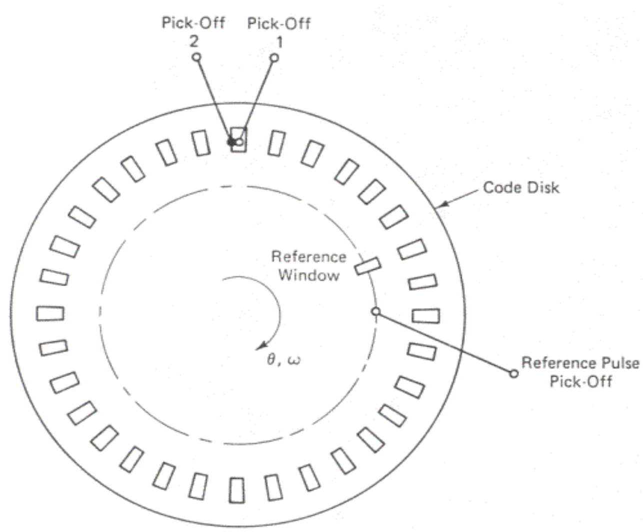
- Signal interpretation depends on whether the particular optical encoder is an incremental device or an absolute device.

  – We will focus on the incremental optical encoder.

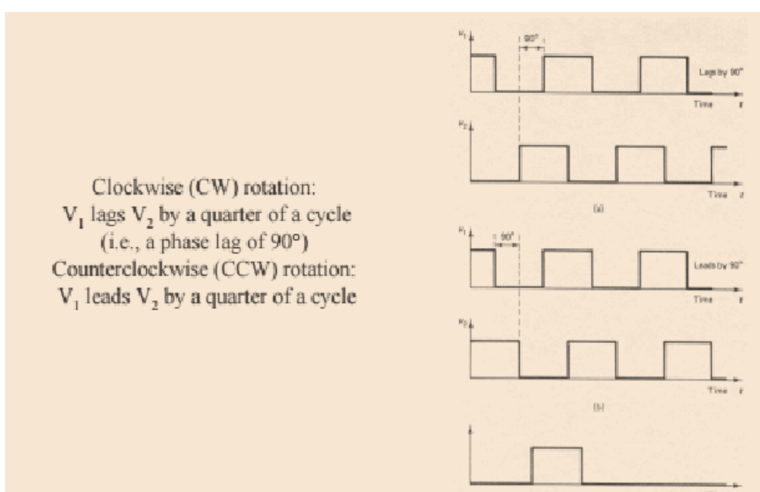
  – The output signals from either the offset sensor configuration or the offset track configuration are the same.

  – Note that the pulse width and pulse-to-pulse period (encoder cycle) are constant in each sensor output when the disk rotates at constant angular velocity. When the disk accelerates, the pulse width decreases continuously; when the disk decelerates, the pulse width increases continuously.

- The quarter-pitch offset in sensor location or track position is used to determine the direction of rotation of the disk. It is obtained by determining the phase difference of the two output signals, using phase- detection circuitry. One method for determining the phase difference is to time the pulses using a high- frequency clock signal.



Incremental Optical Encoder Disk



Incremental Encoder Pulse Signals
(a) CW rotation (b) CCW rotation (c) reference

Displacement Computation

– Maximum count possible: M pulses

$$\theta = \frac{n \text{ pulses}}{M} \theta_{max}$$

– Range of the encoder: $\pm \theta_{max}$

– If the data size is r bits, allowing for a sign bit, $M = 2^{r-1}$,

where zero count is also included.

– If zero count is not included, $M = 2^{r-1} - 1$

– If θ_{max} is 2π and θ_{min} is zero, then θ_{max} and θ_{min} will correspond to the same position of the code disk.

To avoid this ambiguity, we use

$$\theta_{min} = \frac{\theta_{max}}{2^{r-1}}$$

– The conventional definition for digital resolution is:

$$\frac{(\theta_{max} - \theta_{min})}{(2^{r-1} - 1)}$$

• T w o methods are available for determining

Velocities using an incremental encoder:

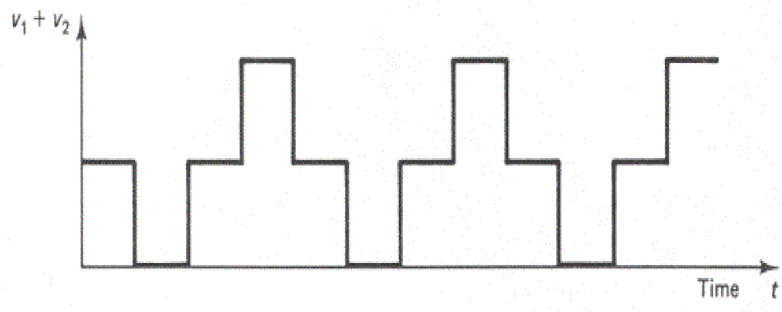
– *Pulse-counting method*

– *Pulse-timing method*

- Pulse-Counting Method
  - The pulse count over the sampling period of the digital processor is measured and is used to calculate the angular velocity. For a given sampling period, there is a lower speed limit below which this method is not very accurate.
  - To compute the angular velocity $\boldsymbol{\omega}$, suppose that the count during a sample period T is n pulses. Hence, the average time for one pulse is T/n. If there are N windows on the disk, the average time for one revolution is NT/n. Hence $\boldsymbol{\omega}$ $(rad/s) = 2\pi n/NT$.

- P u l s e -Timing Method
  - The time for one encoder cycle is measured using a high-frequency clock signal. This method is particularly suitable for measuring low speeds accurately.
  - Suppose that the clock frequency is f Hz. If m cycles of the clock signal are counted during an encoder period (interval between two adjacent windows), the time for that encoder cycle (i.e., the time to rotate through one encoder pitch) is given by m/f.
    - With a total of N windows on the track, the average time for one revolution of the disk is Nm/f. Hence $\boldsymbol{\omega} = 2\pi f/Nm$.

- Resolution of an Encoder
  - The resolution of an encoder represents the smallest change in measurement that can be measured realistically. Since an encoder can be used to measure both displacement and velocity, a resolution can be identified for each case.
  - The *displacement resolution* of the incremental encoder depends on the following factors:
    - Number of windows on the code track
    - Gear ratio
    - Word size of the measurement buffer



– *Velocity Resolution*

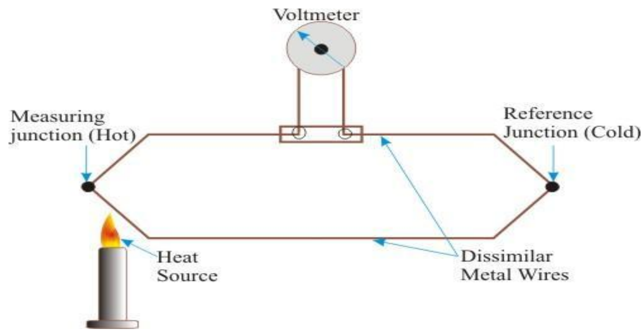
– the *speed resolution* of an incremental encoder depends on the following factors:

  - number of windows N
  - sampling period T
  - clock frequency f
  - speed
  - gear ratio

- Errors in shaft encoder readings can come from several factors:
  - Quantization error (due to digital word size limitations)
  - Assembly error (eccentricity, etc.)
  - Coupling error (gear backlash, belt slippage, loose fit, etc.)
  - Structural limitations (disk deformation and shaft deformation due to loading)
  - Manufacturing tolerances (errors from inaccurately imprinted code patterns, inexact positioning of the pick- off sensors, limitations and irregularities in signal generation and sensing components, etc.)
  - Ambient effects (vibration, temperature, light noise, humidity, dirt, smoke, etc.)
- These factors can result in erroneous displacement and velocity readings and inexact direction detection.
- One form of error in an encoder reading is the hysteresis.

Thermoelectric Transducers

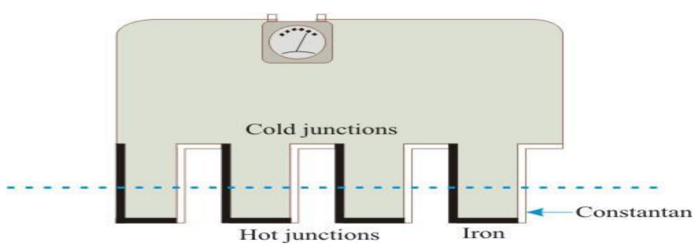
Thermocouples



Principle of measurement of temperature by a thermocouple

In 1821 Thomas Seebeck' discovered that when two dissimilar metals were in contact, a voltage was generated where the voltage was a function of temperature. The device, consisting of two dissimilar metals joined together, is called a Thermocouple and the voltage is called the Seebeck voltage. As an example, joining copper and Constantan produces a voltage on the order of a few tens of milli-volts with the positive potential at the copper side. An increase in temperature causes an increase in voltage. When two dissimilar metals such a iron and copper are gained to form a closed circuit, current flow when one junction is at higher temperature and the other one is at lower temperature as shown in the figure.

The emf driving the current is called a thermoelectric emf and the phenomenon is known as thermoelectric effect or Seeback effect. Usually a thermoelectric emf is very small. A pair of dissimilar metals welded together at their junction forms what is called a thermocouple. When several thermocouples are arranged in series, the emf is added together to give an appreciable output, this arrangement is called thermopile as shown in the figure.



Arrangement of thermocouple to form a thermopile

When two dissimilar metals are joined together, the free electrons move randomly across the junction. Because of the different atomic structure of each metal, electrons pass more readily across the boundary in one direction than in other. This results in displacement of charges, making one metal positive and other negative.

Materials for thermocouple:

1. Melting point of thermocouple materials must be higher than the measuring temperature.
2. The dissimilar materials on joining should be able to produce large emf for accuracy of measurements.
3. Temperature is determined indirectly i.e. through calibrations of emf with temperature. As for as possible, the linear variation of emf with temperature is desired.
4. Thermocouple materials should be resistant to atmospheres in furnaces. Available thermocouples.

Type	Positive wire (+ve)		Negative wire (-ve)		Maximum temperature ( )	Suitable under
T		C	Ni	Cu	370 °C °C	Oxidizing & reducing
S	Pt	Rh	Pt		1700 °C	Oxidizing & inert
N	Ni	Cr Si .	Ni	. Si . Mn .	°C 1260	Oxidizing & inert
K	Ni	Cr	Ni	Mn At Si	1260	Oxidizing &inert
J	Fe		Ni	Cu	760	Oxidizing and reducing
B	Pr	Rh	Pt	Rh	1750	Oxidizing, inert & vacuum

°C

°C

Cold junction compensation

Application of see back effect to thermocouple requires that one end of the junction (cold) must be at constant temperature. The standard calibration data for all thermocouples are based on 0°C cold junction temperature. In Practice it may not be possible to keep cold junction at zero degree temperature. Hence standard data need to be corrected. One way is to add the environmental temperature to the value of temperature determined by thermocouple measurement. In another method, thermistor may be put in the thermo-couple circuit. The voltage drop across thermistor depends on environmental temperature which then compensates for the error.

Compensating wires

Compensating wires are those wires which are connected from the thermocouple to the temperature indicator. Compensating wires should have same emf as that of thermocouples. Compensating wires are color coded.

Positive wire	Color	Thermocouple
Fe	White	Fe-constantan
Ni Cr	Yellow	Chromel - alumel
Cu	Blue	Cu-NI base
Ni Cr	Purple	Chromel constantan
Ni - Cr - Si	Orange	Nicrosil / Nisil

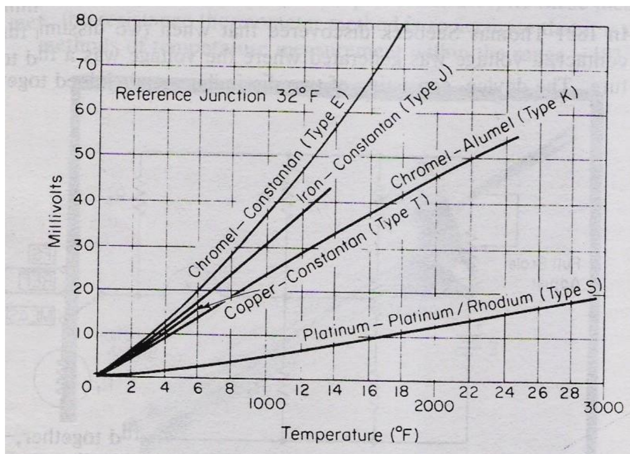
The negative wires in all thermocouples are red.

Selection of thermocouples

1) Type of furnace; whether batch or continuous and the frequency of measurement.

2) Furnace atmosphere: The furnace atmosphere may be oxidizing or reducing, inert or vacuum. Accordingly thermocouples are selected. For example Pt, Pt-Rh can be used in oxidizing and inert atmospheres up to 1480. Chromel -alumel thermocouples may be used in reducing atmosphere but at low temperatures.

3) Response of thermocouple to temperature difference is important. Normally thermocouples are inserted in a ceramic sheath. During temperature measurement, The hot junction of the thermocouple is heated by the transfer of heat from sheath. Also large diameter of wire requires sufficient time for heating.

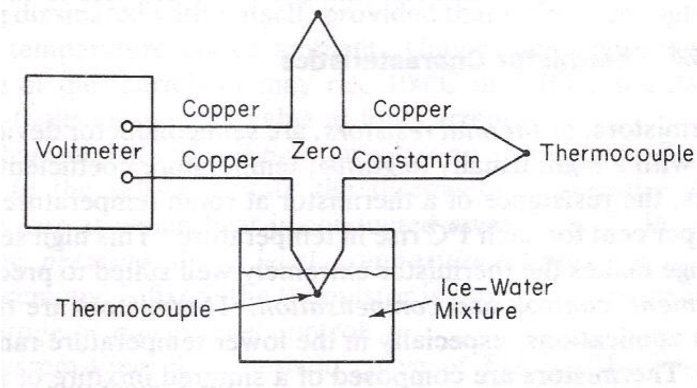


Thermocouple output voltage as a function of temperature for various thermocouple materials.

There are several methods of joining the two dissimilar metals. One is to weld the wires together. This produces a brittle joint, and if not protected from stresses, this type of thermocouple can fracture and break apart. During the welding process gases from the welding can diffuse into the metal and cause a change in the characteristic of the thermocouple.

Another method of joining the two dissimilar metals is to **solder the wires** together. This has the disadvantage of introducing a third dissimilar metal. But if both sides of the thermocouple are at the same temperature, the Seebeck voltage due to thermocouple action between the two metals of the thermocouple and the solder will have **equal and opposite voltages** and the **effect will cancel**.

A more significant disadvantage is that the thermocouple is a desirable transducer for measuring high temperatures. In many cases the temperatures to be measured are **higher than the melting point of the solder** and the thermocouple will come apart. There will be at least two thermocouple junctions in the system. To contend with this, it is necessary that the temperature of one of the junctions be known and constant. Therefore, there is a fixed offset voltage in the measuring system. It was customary a long time ago to place this junction in a mixture of ice and water, thus stabilizing the temperature to $O^{O}C$ as shown in fig. More modern techniques use electronic reference junctions that are not necessarily at $0^{O}C$. This junction is called the **reference or cold junction** due to the fact that this junction was in the ice bath.



Application of a reference junction.

Thermistors

Principle

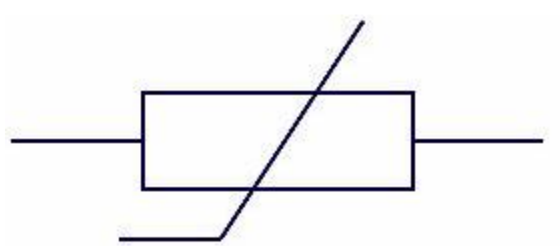
A resistor is an electrical component that limits the amount of current flows through a circuit. Thermistor is special type of resistor, whose resistance varies more significantly with temperature than in standard resistors. Generally, the resistance increases with the temperature for most of the metals but the thermistors respond negatively i.e. the resistance of the thermistors decrease with the increase in temperature. This is the main principle behind thermistor. As the resistance of thermistors depends on the temperature, they can be connected in the electrical circuit to measure the temperature of the body.

Thermistors are mainly used as temperature sensors, in rush current limiters, self-resetting over-current protectors and self-regulating heating elements. A thermistor is made from a semiconductor material. It is shaped into a disc, a rod or a bead. Bead thermistors may be only a few millimetres in diameter. Some bead thermistors have the bead enclosed in a glass capsule.

Thermistors work on the principle that resistance of some materials changes with the change in their temperature. When the temperature of the material changes, its resistance changes and it can be measured easily and calibrated against the input quantity. The commonly used thermistors are made up of the ceramic like semiconducting materials such as oxides of manganese, nickel and cobalt. Thermistors can be used for the measurement of temperature, as electric power sensing devices and also as the controls for various processes.

Thermistors are temperature sensitive resistors. All resistors vary with temperature, but thermistors are constructed of semiconductor material with a resistivity that is especially sensitive to temperature. However, unlike most other resistive devices, the resistance of a thermistor decreases with increasing temperature. That's due to the properties of the semiconductor material that the thermistor is made from. For some, that may be counterintuitive, but it is correct. Here is a graph of resistance as a function of temperature for a typical thermistor. Notice how the resistance drops from 100 k , to a very small value in a range around room temperature. Not only is the resistance change in the opposite direction from what you expect, but the magnitude of the percentage resistance change is substantial.

The symbol of Thermistors can be represented as follows



Thermistor Symbol

Types of Thermistors:

There are mainly 2 types of thermistors namely Positive-temperature coefficient (PTC) and Negative-temperature coefficient (NTC).

Positive Temperature Coefficient (PTC):

PTC thermistors increase their resistance as the temperature rises. The relationship between resistance and temperature is linear, as expressed in the following equation: deltaR = k(deltaT) where deltaR is the change in resistence, deltaT is the change in temperature and k is the temperature coefficient. When k is positive, it causes a linear increase in resistance as the temperature rises.

PTC Uses: PTC thermistors can be used in place of fuses for circuit protection. As the circuit heats up, resistance increases to prevent overload. They are also used as timing devices in televisions. When the unit is switched on, the degaussing coil is activated to eliminate the magnetic field; the thermistor automatically switches it off when the temperature reaches a certain point.

Negative Temperature Coefficient (NTC):

Many NTC thermistors are made from a pressed disc or cast chip of a semiconductor such as a sintered metal oxide. They work because raising the temperature of a semiconductor increases the number of electrons able to move about and carry charge – it promotes them into the conduction band. The more charge carriers that are available, the more current a material can conduct. This is described in the formula:

I = n.A.v.e

Where

I = electric current (amperes)

n = density of charge carriers (count/m^3)

A = cross-sectional area of the material (m^2)

v = velocity of charge carriers (m/s)

e = charge of an electron (e=1.602 \times 10^{-19} coulomb)

The current is measured using an ammeter. Over large changes in temperature, calibration is necessary. Over small changes in temperature, if the right semiconductor is used, the resistance of the material is linearly proportional to the temperature. There are many different semiconducting thermistors with a range from about 0.01 kelvin to 2,000 kelvins (-273.14 °C to 1,700 °C)

NTC Uses: NTC thermistors, on the other hand, are used as current-limiters and temperature monitors in digital thermostats and automobiles.

Testing of a Thermistor:

This is just a sample and rough test for basic understand about how to test a thermistor. The analog multimeter has to be kept in resistance mode. The multimeter terminals are to be connected to the thermistor leads. No need not concentrate on polarity here. Now, heat the thermistor by moving the heated soldering iron tip to it. Now observe that the multimeter reading increases or decreases smoothly depending o whether the thermistor under test is PTC or NTC.

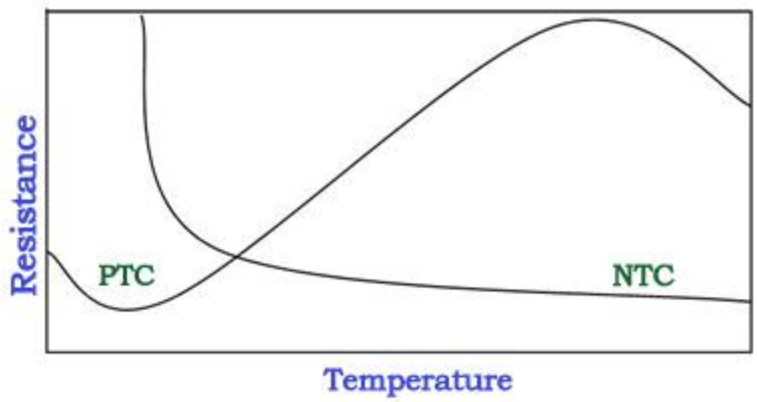
For faulty thermistors, we may observe the following things.

- The change in reading will never be smooth or there will not be any change at all.
- For a short thermistor, the meter reading will be always zero where as for an open thermistor the meter reading will be always infinity.

For perfect confirmation, we need to follow some process of measuring the temperature and corresponding resistance reading and that has to be compared with the thermistor's temperature-resistance characteristics provided by the manufacturer.

Thermistor characteristics:

As just mentioned above, resistance increase with increase in temperature for PTC and resistance decrease with increase in temperature for NTC. The thermistor exhibits a highly non-linear characteristic of resistance vs temperature.



PTC thermistors can be used as heating elements in small temperature controlled ovens. NTC thermistors can be used as inrush current limiting devices in power supply circuits. Inrush current refers to maximum, instantaneous input current drawn by an electrical device when first turned on. Thermistors are available in variety of sizes and shapes; smallest in size are the beads with a diameter of 0.15mm to 1.25mm.

There are two fundamental ways to change the temperature of thermistor internally or externally. The temperature of thermistor can be changed externally by changing the temperature of surrounding media and internally by self-heating resulting from a current flowing through the device.

The dependence of the resistance on temperature can be approximated by following equation,

$$R = R_0 e^{\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)} \quad \text{---------------------------------} \ (1)$$

Where,

R is the resistance of thermistor at the temperature T (in K)
R0 is the resistance at given temperature T0 (in K)
β is the material specific-constant

The material specific-constant of a NTC thermistor is a measure of its resistance at one temperature compared to its resistance at a different temperature. Its value may be calculated by the formula shown below and is expressed in degrees Kelvin (°K).

Differentiating (1) with respect to T, we get

$$\frac{dR}{dT} = -\frac{R\beta}{T^2}$$

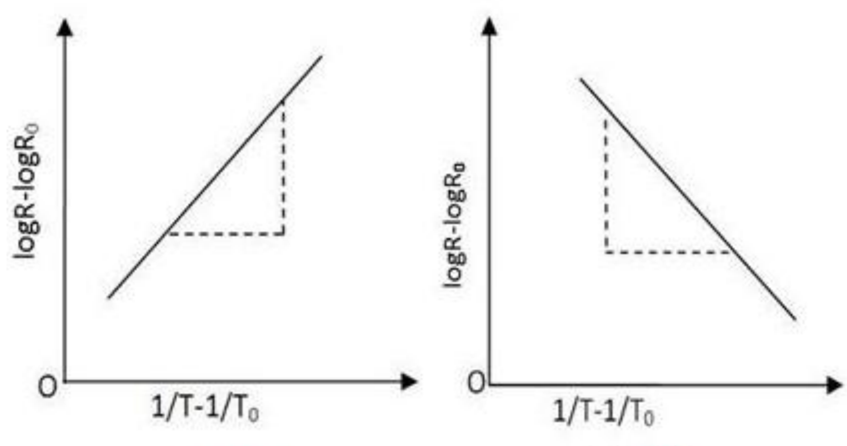
$$\alpha = -\frac{dR}{RdT}$$ is the temp coefficient of resistance.

Taking log of (1) and simplifying we get,

$$\beta = \frac{\log R - \log R_0}{\frac{1}{T} - \frac{1}{T_0}} \quad \text{-------------------------------- (2)}$$

so $$\alpha = -\frac{\beta}{T^2} \quad \text{------------------------------------ (3)}$$

A graph plotted with $\log R - \log R_0$ in Y axis and $\frac{1}{T} - \frac{1}{T_0}$ in X axis for NTC and PTC is shown below. The slope of graph gives value of β.

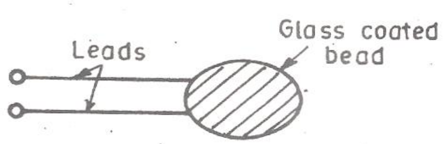


1. NTC 2. PTC

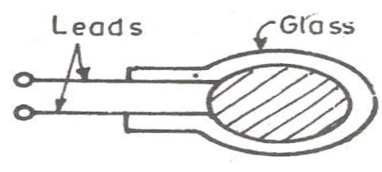
Thermistor Applications:

- PTC thermistors were used as timers in the degaussing coil circuit of most CRT displays. A degaussing circuit using a PTC thermistor is simple, reliable (for its simplicity), and inexpensive.
- We can also use PTC thermistors as heater in automotive industry to provide additional heat inside cabin with diesel engine or to heat diesel in cold climatic conditions before engine injection.
- We can use PTC thermistors as current-limiting devices for circuit protection, as replacements for fuses.
- We can also use NTC thermistors to monitor the temperature of an incubator.
- Thermistors are also commonly used in modern digital thermostats and to monitor the temperature of battery packs while charging.
- We regularly use NTC thermistors in automotive applications.
- NTC thermistors are used in the Food Handling and Processing industry, especially for food storage systems and food preparation. Maintaining the correct temperature is critical to prevent food borne illness.
- NTC thermistors are used throughout the Consumer Appliance industry for measuring temperature. Toasters, coffee makers, refrigerators, freezers, hair dryers, etc. all rely on thermistors for proper temperature control.
- We can regularly use the Thermistors in the hot ends of 3D printers; they monitor the heat produced and allow the printer's control circuitry to keep a constant temperature for melting the plastic filament.
- NTC thermistors are used as resistance thermometers in low-temperature measurements of the order of 10 K.
- NTC thermistors can be used as inrush-current limiting devices in power supply circuits.

Some materials, such as carbon and germanium, have a negative temperature coefficient of resistance that implies that the resistance decreases with an increase in temperature. Thermistors or *thermal resistors,* are semiconductor devices that behave as resistors with a high, usually ***negative*** **temperature coefficient of resistance.** In some cases, the resistance of a thermistor at room temperature may decrease as much as 6 per cent for each 1^{O}C rise in temperature. This high sensitivity to temperature change makes the thermistor extremely well suited to precision temperature *measurement, control.* and *compensation.* Thermistors are widely used in **applications,** especially in the lower temperature range of -100'C to **300 ^{o}C.** Thermistors are composed of a sintered mixture of metallic oxides, such as manganese, nickel, cobalt, copper, iron, and uranium. Their resistances range from 0.5 Ω to 75 MΩ and they are available in a wide variety of shapes and sizes. Smallest in size are the beads with a diameter of 0.15 mm to 1.25 mm.

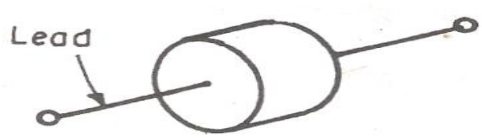


(*a*) Bead

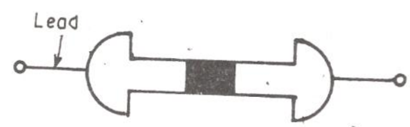


(*b*)Probe

Beads may be sealed in the tips of solid glass rods to form probes that are somewhat easier to mount than beads. Disks and washers are made by pressing thermistor material under high pressure into flat cylindrical shapes with diameters from 2.5 mm to 25 mm. Washers can be stacked and placed in series or in parallel for increased power dissipation.

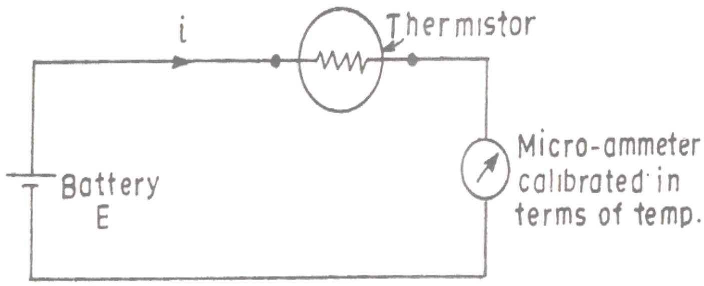


(*c*) Disc

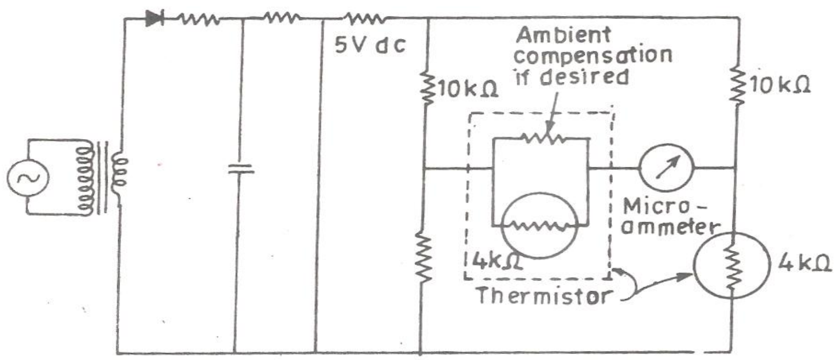


(*d*) Rod

A thermistor produces a large change of resistance with a small change in the temperature being measured. This large sensitivity of thermistor provides **good accuracy and resolution.** A typical industrial-type thermistor with a 2000 Ω resistance at 25^{O}C and a resistance temperature co-efficient of 3.9% per ^{O}C exhibits a change of **78 Ω per degree ^{o}C** change in temperature.



Simple series circuit for measurement of temperature using a thermistor



Measurement of temperature using a thermistor & a bridge circuit for getting higher sensitivities.

Three important characteristics of thermistors make them extremely useful in measurement and control applications: the *resistance-temperature* characteristic, the *voltage-current* characteristic, and the *current-time* characteristic.

Radiation Pyrometer

Black body radiation

A body at higher temperatures emits electromagnetic radiation. The rate at which energy is emitted depends on surface temperature and surface conditions. The thermal radiation from a body is composed of wavelengths forming an energy distribution. The total emissive power of a black body at a particular temperature is

$$e_b = \int_0^\lambda e_{b\lambda}\, d\lambda$$

In which λ is wavelength and e_{by} is monochromatic emissive power. Planck's distribution law relates to the wavelength and temperature:

$$e_{b\lambda} = \frac{2\,\pi\,h\,a^2\,\lambda^{-5}}{\exp\left[\frac{ch}{K_B\,\lambda T}\right]-1}$$

In which h is Planck's constant, a is velocity of light, λ is wavelength. T is absolute temperature and K_B is Boltzmann constant. Total emissive power of a black body is

$$e_b = \sigma\,T^4.$$

In which σ is Stefan's Boltzmann constant and its value is 5.67 10 Wm.

Radiation from real surfaces

Black body is an idealized concept in radiation. A black body absorbs all incoming radiation and transmits none. Black body is also a perfect emitter, since it emits radiation of all wavelengths. Its total emissive power is theoretically the highest that can be achieved at any given temperature. Thus, all real surfaces emit thermal radiations lower than black surface at any temperature such that

$$e = \epsilon\,e_b$$

In which e is emissivity and ε is total radiation from a real surface. Obviously, one for a black body and other for a real surface. Thus, monochromatic emissive power of a real surface is

$$e_\lambda = \frac{2\,\epsilon\,\pi\,ha^2\,\lambda^{-5}}{\exp\left[\frac{ch}{K_B\,\lambda T}\right]-1}$$

In view of the Stefan-Boltzmann equation, the total emissive power of a real surface is

$$e = \epsilon\sigma T^4$$

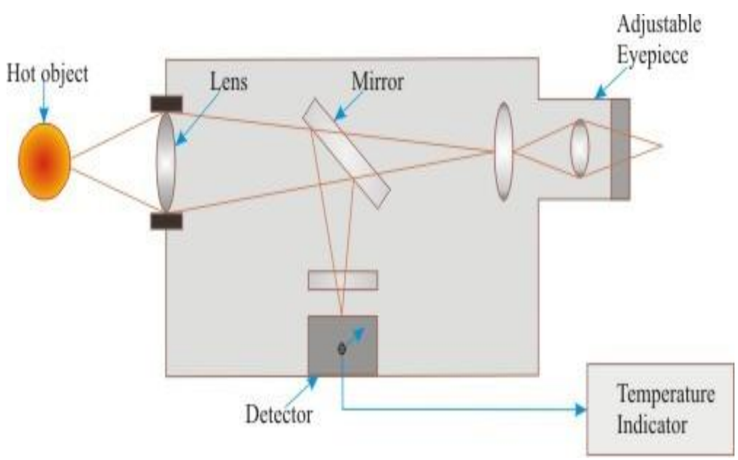
Qualitatively the spectral emissivity of metals decreases with increasing wavelength. For the bare metal surface, the emissivity decreases with increasing wavelength. Roughness increases emissivity.

Principles of radiation pyrometer

Temperature measurement is based on the measurement of radiation either directly by a sensor or by comparing with the radiation of a body of known temperature. The radiation pyrometer is a non contact type of temperature measurement. The wavelength region having high intensity is between 0.1 to about 10µm. In this region, 0.1 to 0.4µm is the ultraviolet region, 0.4 to 0.7 is the visible region and 0.7 onwards is the infrared region. With the increase in temperature, radiation intensity is stronger toward shorter wavelengths. The temperature measurement by radiation pyrometer is limited within 0.5 to 8µm wave length region.

Total radiation pyrometer

A radiation pyrometer consists of optical component to collect the radiation energy emitted by the object, a radiation detector that converts radiant energy into an electrical signal, and an indicator to read the measurements.



Total Radiation Pyrometer

The optical pyrometer is designed to respond narrow band of wavelengths that fall within the visible range of the electro-magnetic spectrum. Thermal detectors are used as sensors. Their hot junction is the radiation sensing surface. Thermopiles can detect radiation of all wavelengths. A number of semiconductors are developed to sense the radiation. These are materials of Si, PbS, indium antimonides etc. Their response is though instantaneous but it is selective to wavelength. Silicon is suitable only around 0.8-0.9 µm and lead sulphide around 1 to 2µm.

It is important that gases like CO_2, H_2O and dust should not obstruct the path of radiation. The dust particles scatter the radiation, whereas CO_2 and water vapor selectivity absorbs radiation. Any instrument built to sense the radiation has to be in an enclosure to avoid dirt, dust and gases present in industrial environment. Normally a window is provided with some optical materials to see the radiating body. The materials should have good transmissivity. All optical materials allow only particular wavelength to pass through it with sufficient intensity. For other wavelengths they are opaque.

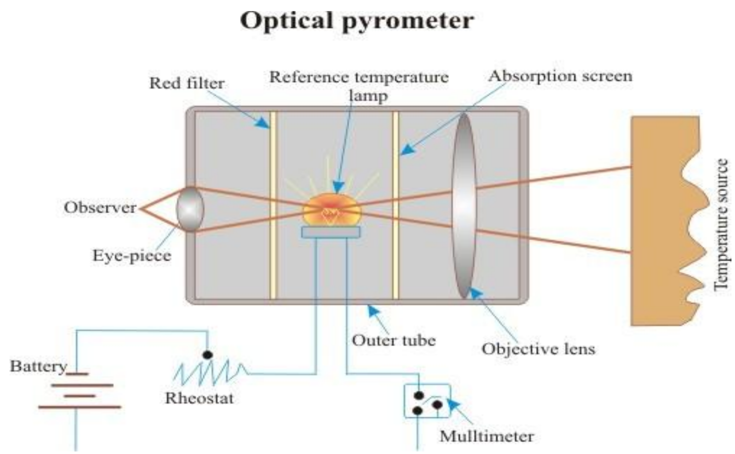
Material for windows	Transmissivity
Glasses like quartz, Pyrex, ruby etc.	Good in ultraviolet and visible region of wavelength but are opaque to infrared. Glass windows are useful for wavelengths lower than 2.5µm. Beyond wavelength of 2.5 µm , transmissivity decreases drastically.
Barium fluoride and zinc sulphide	They have 60 – 80% transmissivity in the infrared and visible region.
Calcium fluoride	It has a very good transmissivity in visible and infrared region.

Limitations of Radiation Pyrometer

1. Availability of optical materials limit on the wavelengths that can be measured.
2. The surface of the hot object should be clean. It should not be oxidized. Scale formation does not allow to measure radiation accurately.
3. Emissivity correction is required. Change in emissivity with temperature need to be considered.

Disappearing Filament Pyrometer

In this type of pyrometer, the tungsten filament of an electric bulb is used as a radiator. The intensity of radiation of filament is compared with the intensity of the radiation of the hot surface. When both the intensity matches, the filament disappears against the back ground. The intensity of the filament can be controlled by the current flowing through it. The maximum temperature of the filament is 2800°C-3000°C at the rated voltage. The minimum visible radiation is at 600°C. Hence we can measure the temperature in between 600°C-28OO°C. The ampere meter in the lamp circuit is calibrated is degree centigrade



Disappearing Filament Pyrometer

Figure shows an optical pyrometer. The radiations from the source are focused onto the filament of the reference temperature using an objective lens. Now the eye piece is adjusted to focus the images the hot source and the filament. Now the lamp current is controlled such that filament appears dark if it is cooler than the source, the filament will appear bright if it is hotter than source and filament will not be seen if the filament and the temperature source are at same temperature.

Interfacing Transducers to Measurement Systems

IEEE – 488

Introduction

IEEE-488 refers to the Institute of Electrical and Electronics Engineers (IEEE) Standard number 488. This standard was first established in 1978, 13 years after Hewlett-Packard (HP) of Palo Alto, CA, began work to enable its broad range of instruments to communicate with one another and with "host" computers.

At the time of its development, IEEE-488 was particularly well-suited for instrument applications when compared with the alternatives. In essence, IEEE-488 comprises a "bus on a cable," providing both a parallel data transfer path on eight lines and eight dedicated control lines. Given the demands of the times, its nominal 1 Mbyte/sec maximum data transfer rate seemed quite adequate; even today; IEEE-488 is sufficiently powerful for many highly sophisticated and demanding applications.

However, IEEE-488, as originally defined, left some ambiguities in the specifics of controller-instrument interaction and communication. While these open issues were likely intended to give instrument and controller designers some latitude, the result was confusion and compatibility problems among instruments from different manufacturers.

During the 1980's, a new layer was added to the IEEE- 488 standard, IEEE-488.2. The original standard was re-designated IEEE-488.1. IEEE-488.2 provides for a minimum set of capabilities among "controllers" and "devices," as well as for more specific content and structure of messages and communications protocols.

IEEE-488.2 is fully backward compatible with IEEE- 488.1; the use of a "488.2"-compliant controller affords the ability to use the new protocols available with "488.2" instruments while retaining the ability to communicate with and control "488.1"-compliant instruments and associated vendor idiosyncrasies.

Today, IEEE-488 is the most widely recognized and used method for communication among scientific and engineering instruments. Major stand-alone general purpose instrument vendors include IEEE-488 interfaces in their products. Many vertical market instrument makers also rely on IEEE-488 for data communications and control.

IEEE-488 controllers support a variety of personal computers, from the IBM PC/XT/AT and PS/2 and compatibles to the multifaceted Macintosh family. Some of these controllers are plug-in cards; others are protocol converters (e.g., SCSI-to-IEEE-488). All provide at least IEEE-488.1 in compliance, and a growing number adhere to “488.2.”

General Information

The IEEE-488 interface, sometimes called the General Purpose Interface Bus (GPIB), is a general purpose digital interface system that can be used to transfer data between two or more devices. It is particularly well suited for interconnecting computers and instruments. Some of its key features are

- Up to 15 devices may be connected to one bus
- Total bus length may be up to 20 m and the distance between devices may be up to 2 m
- Communication is digital (as opposed to analog) and messages are sent one byte (8 bits) at a time
- Message transactions are hardware handshaked
- Data rates may be up to 1 Mbyte/sec

Mechanical Specifications

Connector

The IEEE-488 connector is a 24-pin connector. Devices on the IEEE-488 bus have female receptacles; interconnecting cables have the mating male connectors. Connecting cables will typically have male and female receptacles wired in parallel at each connecting head to allow parallel connection of cables at a device and/or to allow daisy chaining between devices.

Interconnection Cabling

Any individual IEEE-488 bus is limited to 15 devices including the controller. However, the IEEE-488 specification limits the total length of all cabling used to interconnect devices on a common bus to 20 m, or 2 m times the number of interconnected devices (up to 20 m). Cable lengths between devices may vary, as long as total cable length does not exceed these restrictions. Devices may be interconnected in a star or linear topology, or in a combination of the two, as long as the distance limits are observed. For maximum data transfer rates, the total cable length should be reduced to 15 m, with the average inter-device cable 1 m or less.

Electrical Specifications

Bus Lines

The IEEE-488 bus is a multidrop interface in which all connected devices have access to the bus lines. The 24 bus lines group into four categories:

Data Lines - Eight lines (DIO1 through DIO8) used to transfer information (data and commands) between devices on the bus, one byte at a time.

Handshake Lines - Three lines used to handshake the transfer of information across the data lines:

DAV: Data Valid

NDAC: Not Data Accepted

NRFD: Not Ready for Data

Bus Management Lines - Five lines used for general control and coordination of bus activities:

ATN: Attention

I FC: Interface Clear

REN: Remote Enable

SRQ: Service Request

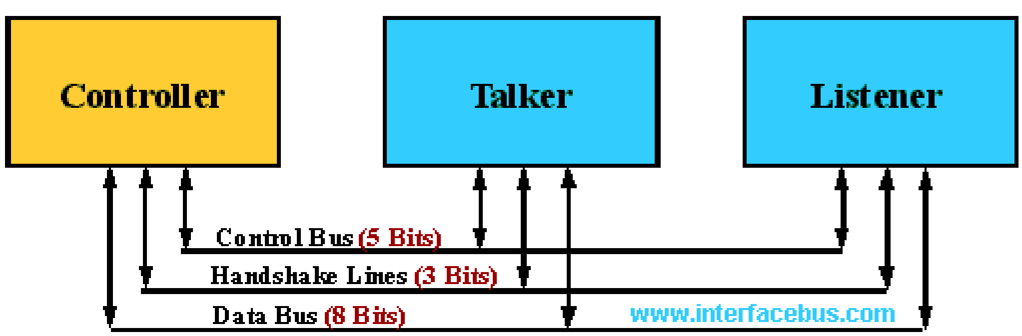
EOI: End or Identify

Ground Lines - Eight lines used for shielding and signal returns: One Shield

One General Signal Ground Six logic ground lines paired off with ATN, SRQ, IFC, NDAC, NRFD and DAV

Handshaking

The IEEE-488 bus uses three handshake lines in a “We're ready - Here's the data - We've got it” sequence to transfer information across the data bus. The handshake protocol assures reliable data transfer at the rate determined by the slowest Listener. The handshake lines, like all other IEEE-488 lines, are active low. DAV is controlled by the Active Talker. Before sending any data, the Talker verifies that NDAC is asserted (low) which indicates that all Listeners have accepted the previous data byte. The Talker then places a byte onto the data lines and waits until NRFD is unasserted (high), indicating that all Addressed Listeners are ready to accept the information. When NRFD and NDAC are in the proper state, the Talker asserts DAV (active low) to indicate that the data on the bus is valid. NRFD is used by the Listeners to inform the Talker that they are ready to accept the new data. The Talker must wait for each Listener to unasserted this line (high), which they do at their own rates when they are ready for more data. This assures that all devices accepting the information are ready to receive it. NDAC, also controlled by the Listeners, indicates to the Talker that each device addressed to listen has accepted the information. Each device releases NDAC (high) at its own rate, but NDAC does not go high until the slowest Listener has accepted the data byte. This type of handshaking permits multiple devices to receive data from a single data transmitter on the bus. All active receiving devices participate in the data handshaking on a byte-by-byte basis and operate the NDAC and NRFD lines in a “wired-or” scheme so that the slowest active device determines the rate at which the data transfers take place.



Within IEEE 488, the equipment on the bus falls into three categories, although items can fulfil more than one function:

Controller: As the name suggests, the controller is the entity that controls the operation of the bus. It is usually a computer and it signals that instruments are to perform the various functions. The GPIB controller also ensures that no conflicts occur on the bus. If two talkers tried to talk at the same time then data would become corrupted and the operation of the whole system would be seriously impaired. It is possible for multiple controllers to share the same bus; but only one can act as a controller at any particular time.

Listener: A listener is an entity connected to the bus that accepts instructions from the bus. An example of a listener is an item such as a printer that only accepts data from the bus

Talker: This is an entity on the bus that issues instructions / data onto the bus.

IEEE 488 / GPIB FEATURES SUMMARY	
PARAMETER	DETAILS
Max length of bus	20 metres
Max individual distance between instruments	2 metres average 4 metres maximum in any instance.
Maximum number of instruments	14 plus controller, i.e. 15 instruments total with at least two-thirds of the devices powered on.
Data bus width	8 lines.
Handshake lines	3
Bus management lines	5
Connector	24-pin Amphenol (typical) D-type occasionally used.

IEEE 488 / GPIB FEATURES SUMMARY	
PARAMETER	DETAILS
Max data rate	~ 1 Mbyte / sec (HS-488 allows up to ~8Mbyte / sec).

IEEE-488 Functions

When information is placed on the data lines, it can represent either a data byte or a command. If the Attention bus management line (ATN) is asserted while the data is transferred, then the data lines are carrying a multiline command to be received by every bus device. If ATN is not asserted, then a data byte is being transferred, and only the Active Listeners receive that byte. The IEEE-488 bus also has a number of uniline commands that are carried on a single bus management line. For example, the Interface Clear (IFC) line, when asserted, sends the Interface Clear command to every bus device, causing each to reset its IEEE-488 bus interface.

Addressing

The IEEE-488 standard normally permits up to 15 devices to be configured within one system. Each of these devices has a unique bus address, a number from 0 to 30. Address limits can be circumvented directly by the use of bus expanders or indirectly through the use of an isolator or an extender. A device becomes Addressed to Talk when it receives a Talk Address Group (TAG) multiline command (a byte transferred with ATN asserted) specifying its own address from the Active Controller. Similarly, it becomes addressed to listen when it receives a Listen Address Group (LAG) multiline command. Other address commands include My Talk Address (MTA) and My Listen Address (MLA), which are the TAG and LAG commands of the Active Controller. The secondary Command Group (SCG) is used to refer to sub-addresses or sub-functions within a particular device. This permits direct access and control of the sub-devices or sub-instruments embedded within complex devices or instruments.

The System Controller

The System Controller, usually a computer with an IEEE- 488 board installed, always retains ultimate control of the bus. When the system is first powered up, the System Controller is the Active Controller and controls all bus transactions. The System Controller may Pass Control to a device, making it the New Active Controller, which may then Pass Control to yet another device. Even if it is not the Active Controller, the System Controller maintains exclusive control of the Interface Clear (IFC) and Remote Enable (REN) bus management lines and can take control of the bus whenever it desires.

IEEE-488.2

The IEEE-488.2 standard was developed to simplify the basic process of communicating with instruments. IEEE488.2 extends the 488 standard with code, format and protocol standardization and serves to resolve issues left open in 488.1. IEEE-488.2 details preferred implementation of many of the issues that were either optional or unspecified on the first standard. IEEE-488.1 covers the key physical issues (connector type, bus length, maximum number of instruments, etc.), electrical issues (open collector TTL, tristate) and low-level protocols (device addressing, control passing and data handshaking/timing). Four basic device functions (Talker, Listener, Controller and System Controller) are specified, as are capability subsets for each type of device. A number of items not covered by 488.1 can cause problems for the test engineer, particularly regarding equipment compatibility and data corruption. For example, 488.1standard does not cover these specifications.

Minimum Device Capability Requirements

No minimum set of requirements is mandated in IEEE- 488.1 for Talkers, Listeners, Controllers or System Controllers. Hence, a device may implement all, or only some, of the capability sets set forth in 488.1, giving rise to systems containing devices with varying levels of abilities. The Controller, in such a situation, has no guarantee of a basic communication subset among system devices. This can lead to confusion for the system operator and miscommunication between devices.

Data Coding, Formats and Message Protocol

Under 488.1, the messages transferred between the Controller and a device is entirely at the discretion of the device manufacturer. The use of ASCII, binary or some other form of data code and the choice of terminators such as carriage-return or EOI is arbitrary. Also, the sequence of the sending of commands and the reading of their responses is unspecified and varies from instrument to instrument.

Definition of the Status Byte

488.1 define a status byte and one bit within, but the meaning of the other seven bits is at the discretion of the device designer. This forces the user to provide a unique interpretation of each bit of the status byte. Also, the relationship between the status byte and the device's other internal status registers is unspecified.

Driver Software for IBM PC

Great variety is found in the software required to complete the interface between the user's program and the IEEE instruments. Two fundamental techniques are used: the DOS device driver and the subroutine library. These are not mutually exclusive, as subroutine libraries can be implemented via a DOS device driver.

Controlling Instruments from Any Language

Just as DOS and spreadsheets can access IEEE instruments directly using the file I/O services provided by DOS for device drivers, most programming languages also can use file I/O to quickly and easily access the IEEE-488 bus.