UNIT V MEASUREMENT OF POWER, FLOW AND TEMPERATURE

5.1 MEASUREMENT OF FORCE

The mechanical quantity which changes or tends to change the motion or shape of a body to which it is applied is called force. Force is a basic engineering parameter, the measurement of which can be done in many ways as follows:

- Direct methods

It involves a direct comparison with a known gravitational force on a standard mass, say by a balance.

- Indirect methods

It involves the measurement of effect of force on a body, such as acceleration of a body of known mass subjected to force.

Devices to measure Force

- Scale and balances
  a. Equal arm balance
  b. Unequal arm balance
  c. Pendulum scale

- Elastic force meter (Proving ring)

- Load cells
  a. Strain gauge load cell
  b. Hydraulic load cell
  c. Pneumatic load cell

Scale and balances

a. Equal arm balance

An equal arm balance works on the principle of moment comparison. Thebeam of the equal arm balance is in equilibrium position when,

Clockwise rotating moment = Anti-clockwise rotating moment

$M_2L_2 = M_1L_1$

That is, the unknown force is balanced against the known gravitational force.

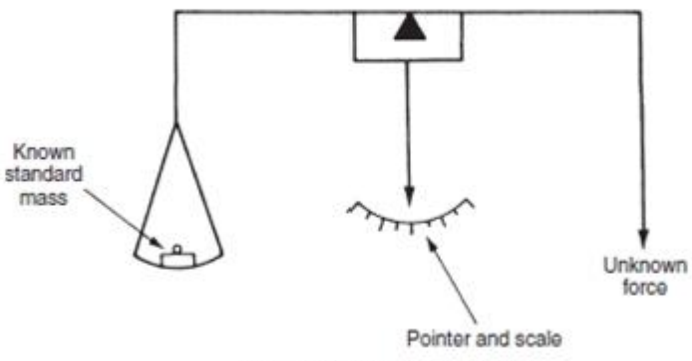


Fig 5.1 Equal Arm Balance

b. Unequal arm balance

An unequal arm balance works on the principle of moment comparison. The beam of the unequal arm balance is in equilibrium position when, Clockwise rotating moment = Anti-clockwise rotating moment

$F \times L_2 = F_x \times L_1$

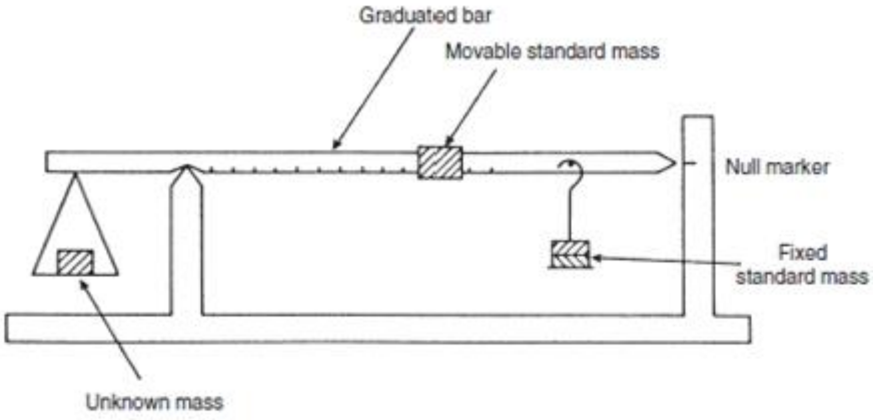


Fig 5.2 Unequal Arm Balance

Elastic force meter (Proving Ring)

When a steel ring is subjected to a force across its diameter, it deflects.This deflection is proportional to the applied force when calibrated.

Operation

The force to be measured is applied to the external bosses of the proving ring. Due to the applied force, the ring changes in diameter. This deflection of the ring is proportional to the applied force.At this stage, the reed is plucked to obtain a vibrating motion. When the reed is vibrating, the micrometer wheel is turned until the micrometer contact moves forward and makes a noticeable damping of the vibrating reed. Now the micrometer reading is noted which is a measure of deflection of the ring. The device is calibrated to get a measure of force in terms of deflection of the proving ring.

Fig 5.4 Proving Ring

Load cells

a. Strain gauge load cell

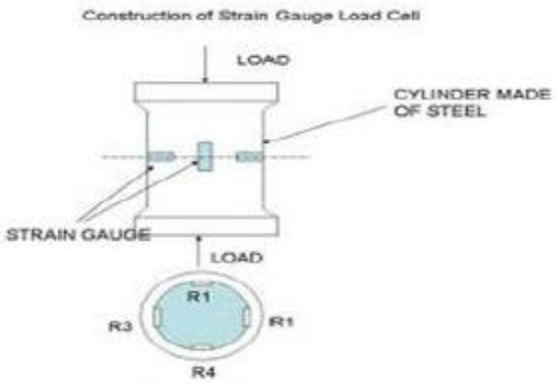


Fig 5.5 Strain Gauge Load Cell

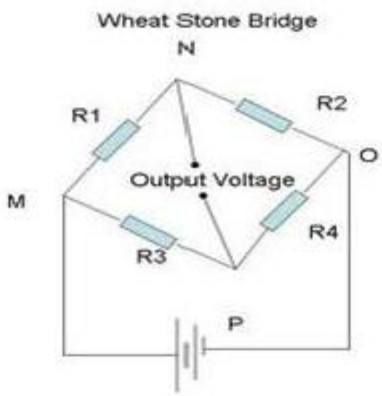


Fig 5.6 Wheat Stone Bridge

When a steel cylinder is subjected to a force, it tends to change in dimension. On this cylinder if strain gauges are bonded, the strain gauge also is stretched or compressed, causing a change in its length and diameter. This change in resistance of the strain gauge becomes a measure of the applied force.

b. Hydraulic Load Cell

When a force is applied on liquid medium contained in a confined space, the pressure of the liquid increases. This increase in pressure of the liquid is proportional to the applied force. Hence a measure of the increase in pressure of the liquid becomes a measure of the applied force when calibrated.The force to be measure is applied to the piston

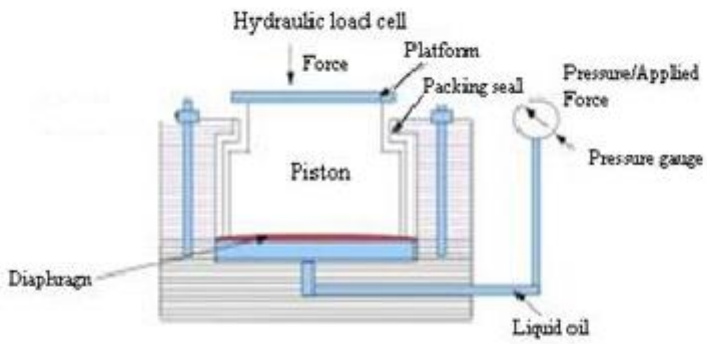


Fig 5.7 Hydraulic Load Cell

This increase in pressure of the liquid medium is proportional to the applied force. This increase in pressure is measured by the pressure gauge which is connected to the liquid medium.

TORQUE MEASUREMENT

Measurement of applied torques is of fundamental importance in all rotating bodies to ensure that the design of the rotating element is adequate to prevent failure under shear stresses. Torque measurement is also a necessary part of measuring the power transmitted by rotating shafts.

The four methods of measuring torque consist of

- Measuring the strain produced in a rotating body due to an appliedTorque
- An optical method
- Measuring the reaction force in cradled shaft bearings
- Using equipment known as the Prony brake.

Measurement of Induced Strain

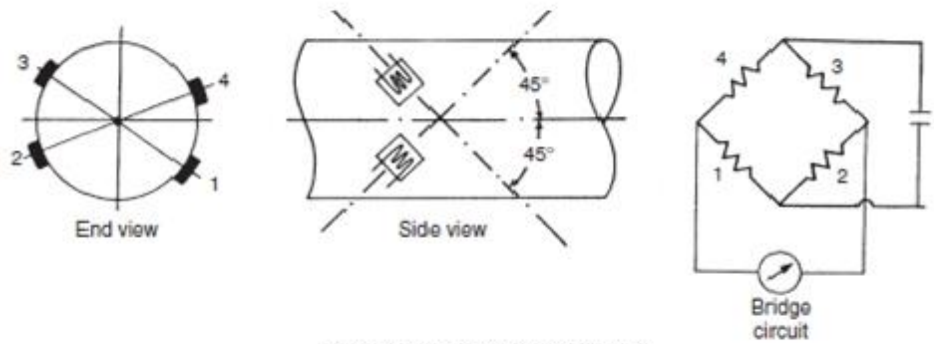


Fig 5.9 Induced Strain Gauge

Measuring the strain induced in a shaft due to an applied torque has been the most common method used for torque measurement in recent years. The method involves bonding four strain gauges onto a shaft as shown in Figure, where the strain gauges are arranged in a d.c. bridge circuit. The output from the bridge circuit is a function of the strain in the shaft and hence of the torque applied. It is very important that positioning of the strain gauges on the shaft is precise, and the difficulty in achieving this makes the instrument relatively expensive. This technique is ideal for measuring the stalled torque in a shaft before rotation commences. However, a problem is encountered in the case ofrotating shafts because a suitable method then has to be found for making the electricalconnections to the strain gauges. One solution to this problem found in many commercial instruments is to use a system of slip rings and brushes for this, although this increase the cost of the instrument still further.

Optical Torque Measurement

Once techniques for torque measurement have become available recently with the development of laser diodes and fiber-optic light transmission systems. One such system is shown in fig. Two black and white stipedwheels are mounted at either end of therotating shaft and are in alignment whenno torque is applied to the shaft. Light from a laser diode light source is directed by a pair of fiber-optic cables onto the wheels. The rotation of the wheels causes pulses of reflected light, which are transmitted back to a receiver by a second pair of fiber-optic cables. Under zero torque conditions, the two pulse trains of reflected light are in phase with each other. If torque is now applied to the shaft, the reflected light is modulated. Measurement by the receiver of the phase difference between the reflected pulse trains therefore allows the magnitude of torque in the shaft to be calculated. The cost of such instruments is relatively low, and anadditional advantage in many applications is their small physical size.

Reaction Forces in Shaft Bearings

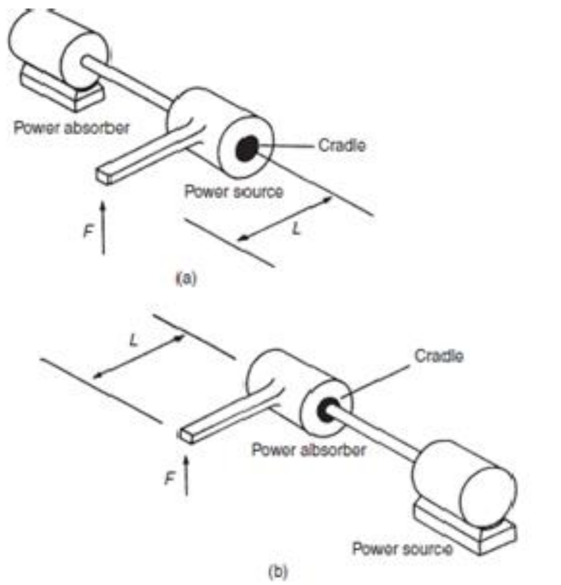


Fig 5.11 Measuring Reaction forces in cradled shaft bearing

Any system involving torque transmission through a shaft contains both a power source and a power absorber where the power is dissipated. The magnitude of the transmitted torque can be measured by cradling either the power source or the power absorber end of the shaft in bearings, and then measuring the reaction force, F, and the arm length, L, as shown in Figure. The torque is then calculated as the simple product, FL. Pendulum scales are used very commonly for measuring the reaction force. Inherent errors in the method are bearing friction and windage torques. This technique is no longer in common use.

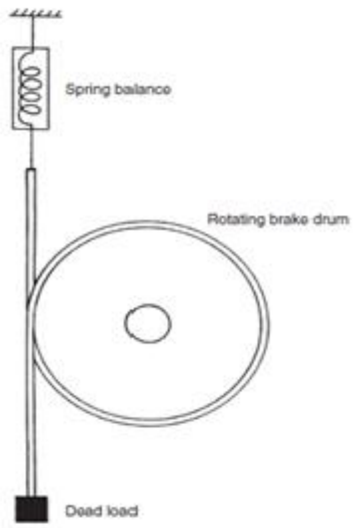


Fig 5.12 Prony Brake

Prony Brake

The Prony brake is another torque- measuring system that is now uncommon. It is used to measure the torque in a rotating shaft and consists of a rope wound round the shaft, as illustrated in Figure. One end of the rope is attached to a spring balance and the other end carries a load in the form of a standard mass, m. If the measured force in the spring balance is Fs, then the effective force, Fe, exerted by the rope on the shaft is given by

$Fe = mg - Fs$

If the radius of the shaft is Rs and that of the rope is Rr, then the effective radius, Re, of the rope and drum with respect to the axis of rotation of the shaft is given by

$Re = R_s + R_r$

The torque in the shaft, T, can then be calculated as

$T = F_e R_e$

While this is a well-known method of measuring shaft torque, a lot of heat is generated because of friction between the rope and shaft, and water cooling is usually necessary.

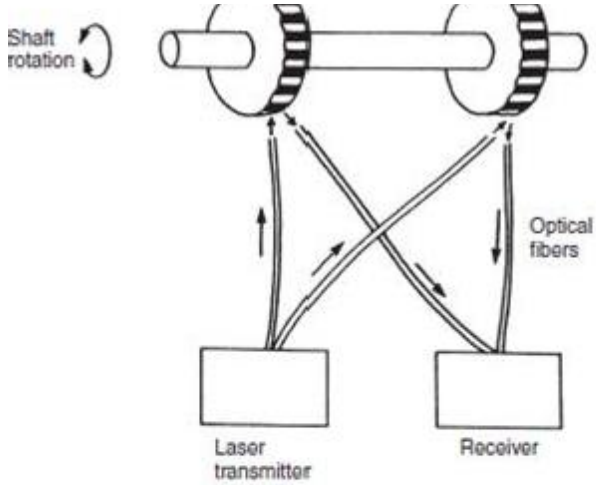


Fig 5.10 Optical Torqu Measurement

MEASUREMENT OF POWER

Torque is exerted along a rotating shaft. By measuring this torque which is exerted along a rotating shaft, the shaft power can be determined. For torque measurement dynamometers are used.

$$T = F.r$$

$$P = 2\pi NT$$

Where, T – Torque, F – Force at a known radius r, P – Power

FLOW MEASUREMENTS

The flow rate of a fluid flowing in a pipe under pressure is measured for a variety of applications, such as monitoring of pipe flow rate and control of industrial processes. Differential pressure flow meters, consisting of orifice, flow nozzle, and venturi meters, are widely used for pipe flow measurement and are the topic of this course. All three of these meters use a constriction in the path of the pipe flow and measure the difference in pressure between the undisturbed flow and the flow through the constriction. That pressure difference can then be used to calculate the flow rate. Flow meter is a device thatmeasures the rate of flow or quantity of a moving fluid in an open or closed conduit.Flow measuring devices are generally classified into four groups. They are

1. Mechanical type flow meters

Fixed restriction variable head type flow meters using different sensorslike orifice plate, venturi tube, flow nozzle, pitot tube, dall tube, quantitymeters like positive displacement meters, mass flow meters etc. fall undermechanical type flow meters.

2. Inferential type flow meters

Variable area flow meters (Rotameters), turbine flow meter, target flowmeters etc.

3. Electrical type flow meters

Electromagnetic flow meter, Ultrasonic flow meter, Laser Doppler Anemometers etc. Fall underelectrical type flow meter.

4. Other flow meters

Purge flow regulators, Flow meters for Solids flow measurement, Cross-correlation flow meter, Vortex shedding flow meters, flow switches etc

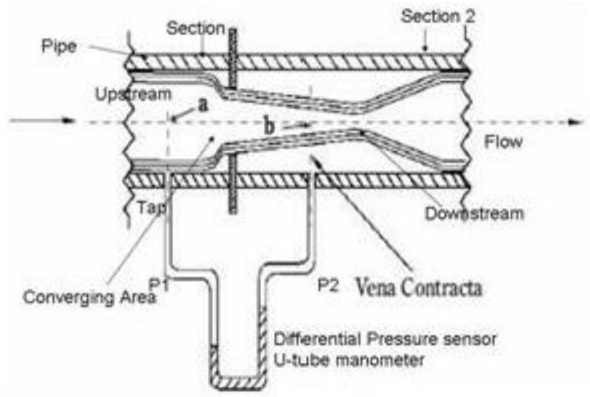


Fig 5.16 Orifice Meter

Orifice Flow Meter

An Orifice flow meter is the most common head type flow measuring device. An orifice plate is inserted in the pipeline and the differential pressure across it is measured.

Principle of Operation

The orifice plate inserted in the pipeline causes an increase in flow velocity and a corresponding decrease in pressure. The flow pattern shows an effective decrease in cross section beyond the orifice plate, with a maximum velocity and minimum pressure at the venacontracta.

The flow pattern and the sharp leading edge of the orifice plate which produces it are of major importance. The sharp edge results in an almost pure line contact between the plate and the effective flow, with the negligible fluid-to-metal friction drag at the boundary.

Venturi Meter

Venturi tubes are differential pressure producers, based on Bernoulli's Theorem. General performance and calculations are similar to those for orifice plates. In these devices, there is a continuous contact between the fluid flow and the surface of the primary device.

It consists of a cylindrical inlet section equal to the pipe diameter, a converging conical section in which the cross sectional area decreases causing the velocity to increase with a corresponding increase in the velocity head and a decrease in the pressure head; a cylindrical throat section where the velocity is constant so that the decreased pressure head can be measured and a diverging recovery cone where the velocity decreases and almost all of the original pressure head is recovered. The unrecovered pressure head is commonly called as head loss.

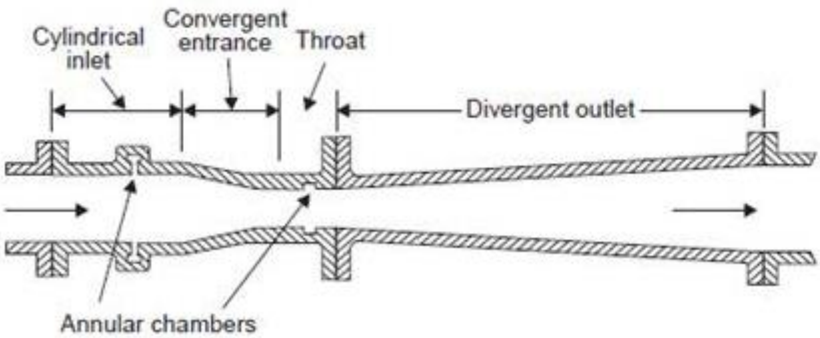


Fig 5.18 Long form Venturi

$$\frac{p_1}{\rho} + \frac{v_1^2}{2} = \frac{p_2}{\rho} + \frac{v_2^2}{2}$$

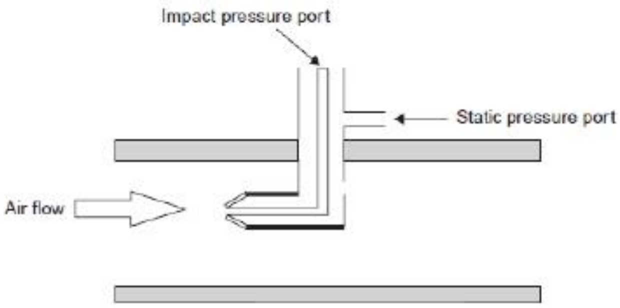
where

p is pressure (N/m^2)
v is velocity (m/s)
ρ is the density of the liquid (kg/m^3).

$$\therefore \dot{Q} = \frac{a_1 a_2}{\sqrt{(a_1^2 - a_2^2)}} \sqrt{\frac{2}{\rho}(p_1 - p_2)} \text{ m}^3/\text{s}$$

$$\dot{Q} = a_2 \sqrt{\frac{2(p_1 - p_2)}{\rho(1-\beta^4)}}$$

β is the ratio : $\frac{\text{thr}}{\text{pi}}$



Pitot tube

An obstruction type primary element used mainly for fluid velocity measurement
is the Pitot tube.

Principle

Consider Figure which shows flow around a solid body. When a solid body is held centrally and stationary in a pipeline with a fluid streaming down, due to the presence of the body, the fluid while approaching the object starts losing its velocity till directly in front of the body, where the velocity is zero. This point is known as the stagnation point. As the kinetic head is lost by the fluid, it gains a static head. By measuring the difference of pressure between that at normal flow line and that at the stagnation point, the velocity is found out. The principal is used in pilot tube sensors.

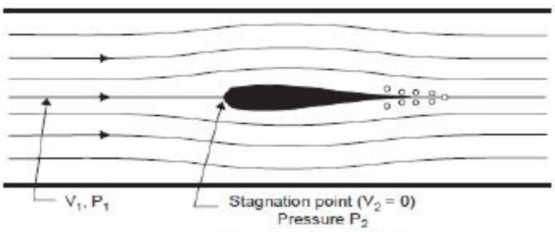
A common industrial type of piltot tube consists of a cylindrical probe inserted into the air stream, as shown in Figure. Fluid flow velocity at the upstream face of the probe is reduced substantially to zero. Velocity head is converted to impact pressure, which is sensed through a small hole in the upstream face of the probe. A corresponding small hole in the side of the probe senses static pressure. A pressure instrument measures the differential pressure, which is proportional to the square of the stream velocity in the vicinity of the impact pressure sensing hole.
The velocity equation for the pitot tube is given by,

$$v = \mathrm{C}p\sqrt{2gh}$$

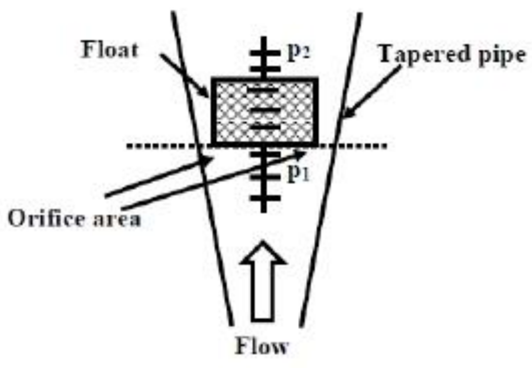
Rotameter

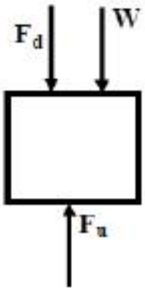
The orificemeter, Venturimeter and flow nozzle work on the principle of constant area variable pressure drop. Here the area of obstruction is constant, and the pressure drop changes with flow rate. On the other hand Rotameter works as a constant pressure drop variable area meter. It can be only be used in a vertical pipeline. Its accuracy is also less (2%) compared to other types of flow meters. But the major advantages of rotameter are, it is simple in construction, ready to install and the flow rate can be directly seen on a calibrated scale, without the help of any other device, e.g. differential pressure sensor etc.

Moreover, it is useful for a wide range of variation of flow rates (10:1). The basic construction of a rotameter is shown in figure. It consists of a vertical pipe, tapered downward. The flow passes from the bottom to the top. There is cylindrical type metallic float inside the tube. The fluid flows upward through the gap between the tube and the float. As the float moves up or down there is a change in the gap, as a resultchanging the area of the orifice. In fact, the float settles down at a position, where the pressure drop across the orifice will create an upward thrust that will balance the downward force due to the gravity. The position of the float is calibrated with the flow rate.



Flow around a solid body





$$Q = \frac{C_d A_2}{\sqrt{1-(\frac{A_2}{A_1})^2}}\sqrt{\frac{2g}{\gamma_2}(p_1 - p_2)}$$

γ_1= Specific weight of the float

γ_2= specific weight of the fluid

ν= volume of the float

A_f= Area of the float.

A_t= Area of the tube at equilibrium (corresponding to the dotted line)

F_d = Downward thrust on the float

F_u = Upward thrust on the float

The major source of error in rotameter is due to the variation of density of the fluid. Besides, the presence of viscous force may also provide an additional force to the float.

TEMPERATURE MEASUREMENT

Temperature is one of the most measured physical parameters in science and technology; typically for process thermal monitoring and control. There are many ways to measure temperature, using various principles.

Bimetallic strip thermometer

Two dissimilar metals are bonded together into what is called a bimetallic strip, as sketched to the right. Suppose metal A has a smaller coefficient of thermal expansion than does metal B. As temperature increases, metal B expands more than does metal A, causing the bimetallic strip to curl upwards as sketched. One common application of bimetallic strips is in home thermostats, where a bimetallic strip is used as the arm of a switch between electrical contacts. As the room temperature changes, the bimetallic strip bends as discussed above. When the bimetallic strip bends far enough, it makes contact with electrical leads that turn the heat or air conditioning on or off. Another application is in circuit breakers High temperature indicates over-current, which shuts off the circuit.

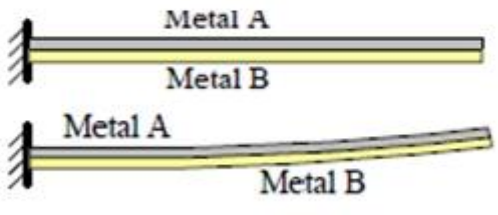


Fig 5.25 Bimetallic Strip

THERMOCOUPLES (Thermo-junctive temperature measuring devices)

Thomas Johan Seeback discovered in 1821 that thermal energy can produce electric current. When two conductors made from dissimilar metals are connected forming two common junctions and the two junctions are exposed to two different temperatures, a net thermal emf is produced, the actual value being dependent on the materials used and the temperature difference between hot and cold junctions. The thermoelectric emf generated, in fact is due to the combination of two effects: Peltier effect and Thomson effect. A typical thermocouple junction is shown in fig. 5. The emf generated can be approximately expressed by the relationship:

Thermocouples are extensively used for measurement of temperature in industrial situations. The major reasons behind their popularity are:

- They are rugged and readings are consistent

$$e_0 = C_1(T_1 - T_2) + C_2(T_1^2 - T_2^2)\ \mu v$$

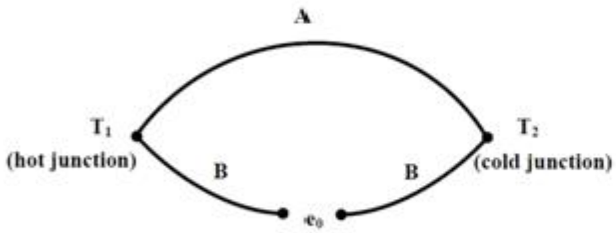


Fig 5.27 Thermocouple

- They can measure over a wide range of temperature
- Their characteristics are almost linear with an accuracy of about 0.05%.
- However, the major shortcoming of thermocouples is low sensitivity
- compared to other temperature measuring devices (e.g. RTD, Thermistor).

THERMORESISTIVE TEMPERATURE MEASURING DEVICES

A resistance temperature detector (abbreviated RTD) is basically either a long, small diameter metal wire (usually platinum) wound in a coil or an etched grid on a substrate, much like a strain gauge.

The resistance of an RTD increases with increasing temperature, just as the resistance of a strain gage increases with increasing strain. The resistance of the most common RTD is 100 Ω at 0ºC.

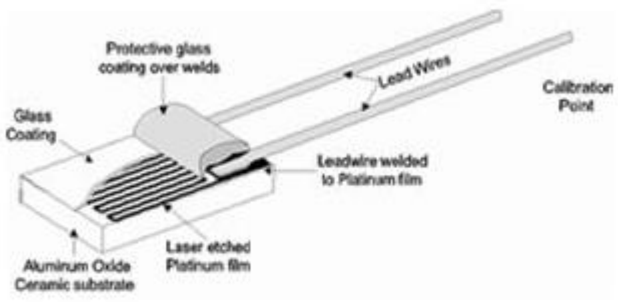


Fig 5.28 RTD

If the temperature changes are large, or if precision is not critical, the RTD resistance can be measured directly to obtain the temperature. If the temperature changes are small, and/or high precision is needed, an electrical circuit is built to measure a change in resistance of the RTD, which is then used to calculate a change in temperature. One simple circuit is the quarter bridge Wheatstone bridge circuit, here called a two-wire RTD bridge circuit R_{lead} represents the resistance of one of the wires (called lead wires) that run from the bridge to the RTD itself. Lead resistance is of little concern in strain gage circuits because R_{lead} remains constant at all times, and we can simply adjust one of the other resistors to zero the bridge.

For RTD circuits, however, some portions of the lead wires are exposed to changing temperatures. Since the resistance of metal wire changes with temperature, R_{lead} changes with T and this can cause errors in the measurement. This error can be non- trivial changes in lead resistance may be misinterpreted as changes in RTD resistance, and therefore give a false temperature measurement.