UNIT V MEASUREMENT OF POWER, FLOW AND TEMPERATURE

Force, torque, power - mechanical, Pneumatic, Hydraulic and Electrical type.

Flow measurement: Venturi meter, Orifice meter, rotameter, pitot tube – Temperature: bimetallic strip, thermocouples, electrical resistance thermometer – Reliability and Calibration – Readability and Reliability.

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5.1 MEASUREMENT OF FORCE

The methods for measuring force can be classified into two basic categories: direct and indirect. In case of direct methods, a direct comparison is made between an unknown force and the known gravitational force on a standard mass. For this purpose, a beam balance may be employed wherein masses are compared. In this case, the beam neither attenuates nor amplifies. Indirect comparison is made by a calibrated transducer that senses gravitational attraction or weight. Sometimes, the deformation due to a force applied on an elastic member is measured.

5.1.1 Direct Methods

Direct methods involve the comparison of an unknown force with a known gravitational force on the standard mass. A force is exerted on a body of mass m due to the earth's gravitational field, which can be represented by the following equation:

$$W = mg$$

Here m is the standard mass, g is the acceleration due to gravity, and W is the weight of the body.

It is imperative to know the values of mass and acceleration due to gravity accurately in order to determine the force acting on the body. With the help of an analytical balance, a direct comparison can be drawn between an unknown force and the gravitational force.

5.1.1.1 Equal arm balance

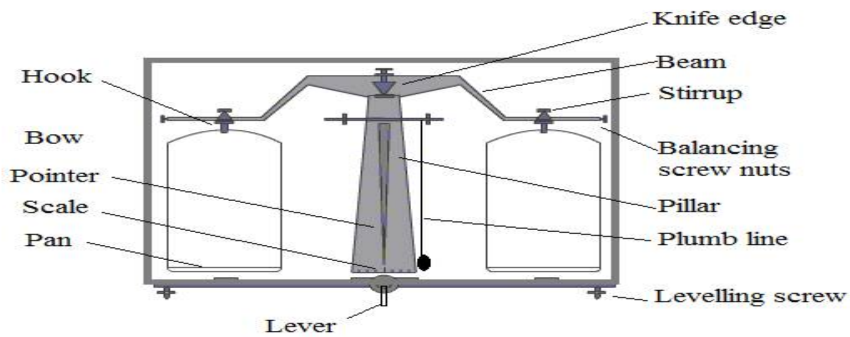

Fig. 5.1 Equal Arm Balance

[source: https://thefactfactor.com/wp-content/uploads/2020/03/Measurement-of-Mass-03.png]

An equal arm balance works on the principle of moment comparison. The beam 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.

The main parts of the arrangement are as follows:

- A beam whose centre is pivoted and rests on the fulcrum of a knife edge. Either side of the beam is equal in length with respect to the fulcrum
- A pointer is attached to the centre of the beam. This pointer will Point vertically downwards when the beam is in equilibrium.
- A Provision to place masses at either end of the beam.

Operation

- A known standard mass (m1) is placed at one end of the beam and an unknown mass (m2) is placed at its other end.
- Equilibrium condition exists when,

  clockwise rotating moment=Anti- clockwise rotating moment

- More over at a given location, the earth's attraction will act equally on both the masses (m_1 and m_2) and hence at equilibrium condition. $W_1=W_2$. That is, the unknown force (weight)will be equal to the known force(weight).

Analytical Balance

An analytical balance, also known as an equal arm balance, is probably the simplest force measuring system. An unknown force is directly compared with a known gravitational force. Comparison of masses is carried out by attaining some kind of beam balance by employing a null balance method. It is sufficient to only find out the magnitude since the unknown force and the gravitational force act in directions parallel to each other.

The rotation of the balance arm is about the knife edge point or fulcrum O. The distance between the fulcrum and the centre of gravity point CG is d_G. Let W_B denote the weight of the balance arms and pointer; W_1 and W_2 are two weights acting on either side of the balance. When the two weights W_1 and W_2 are equal, angle θ will be zero, and hence the weight of the balance arms and pointer will not influence the measurements.

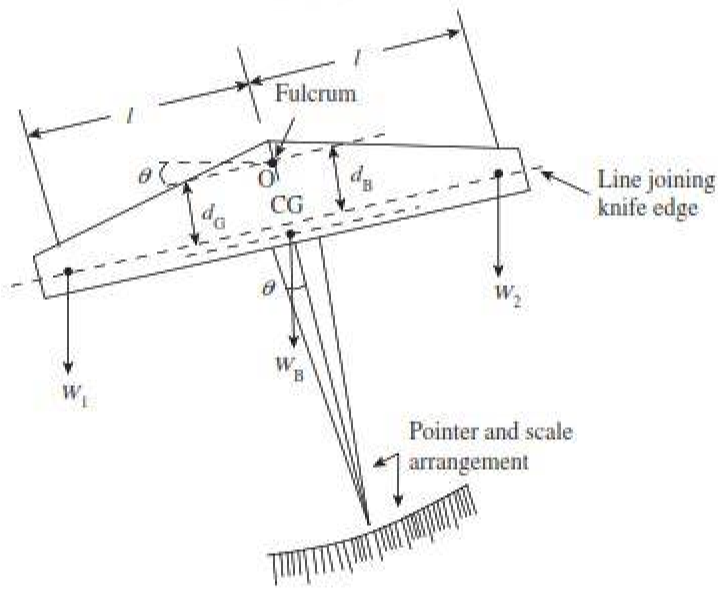

Fig. 5.2 Analytical balance

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 342]

Deflection per unit unbalance gives a measure of the sensitivity of the balance. The difference between the two weights, that is, $W_1 - W_2$, gives the unbalance. Let this difference be ΔW.

Hence, sensitivity $S = \frac{\theta}{(W_1 - W_2)} = \frac{\theta}{\Delta W}$

When the balance is at equilibrium, the following equation is realized:

$$W_1(l \cos\theta - d_B \sin\theta) = W_2(l \cos\theta + d_B \sin\theta) + W_B d_G \sin\theta$$

When the angle of deflection is small, sin q = q and cos q = 1. For such small angles of deflection, can be modified as follows:

$$W_1 (l - d_B \theta) = W_2 (l + d_B \theta) + W_B d_G \theta$$

$$\text{Therefore, } \theta = \frac{l (W_1 - W_2)}{(W_1 + W_2) d_B + W_B d_G}$$

$$\text{Hence, sensitivity } S = \frac{\theta}{(W_1 - W_2)} = \frac{l}{(W_1 + W_2) d_B + W_B d_G}$$

When in equilibrium, $W_1 = W_2 = W$.

$$S = \frac{l}{2W d_B + W_B d_G}$$

If balances are constructed such that d, the distance between the fulcrum and the line joining B the knife edges, is zero, then equation becomes as follows:

$$S = \frac{l}{W_B d_G}$$

5.1.1.2 Unequal Arm Balance

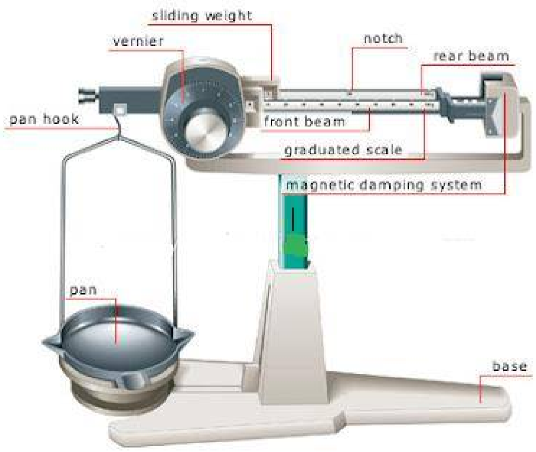

Fig. 5.3 Equal Arm Balance

[source: http://www.visualdictionaryonline.com/science/measuring-devices/measure-weight/unequal-arm-balance.php]

An unequal arm balance works on the principle of moment comparison. The beam of the unequal arm balance is in equilibrium position when,

Clock wise rotating moment = Anti-clockwise rotating moment

$$FxL_2 = F_x x L_1$$

The main parts of the arrangements are as follows:

- A graduated beam pivoted to a knife edge “Y”
- A levelling pointer is attached to the beam
- A known mass “m” is attached to the right side of the beam. This creates an unknown force “F”. This mass “m” can slide on the right side of the beam.
- Provisions are made to apply an unknown force “Fx” on the left side of the beam.

Operation

- An unknown force “Fx” is applied on the left side of the beam through knife edge “Z” as shown
- Now the position of mass “m” on the right side of the beam is adjusted until the levelling pointer reads null balance position. When the levelling pointer is in null balance position, the beam is in equilibrium.

Clock wise rotating moment = Anti-clock wise rotating moment

$$Fx.\ L_1 = F.L_2$$

$$Fx = Mg.L_2/L_1$$

- Thus, the unknown force “Fx” is proportional to the distance “L2” of the mass “m” from the knife edge “Y”
- The right-hand side of the beam which is graduated is calibrated to get a direct Measure of “Fx”

5.1.1.3 Pendulum Scale

It is a moment comparison device. The unknown force is converted to torque which is then balanced by the torque of a fixed standard mass arranged as a pendulum.

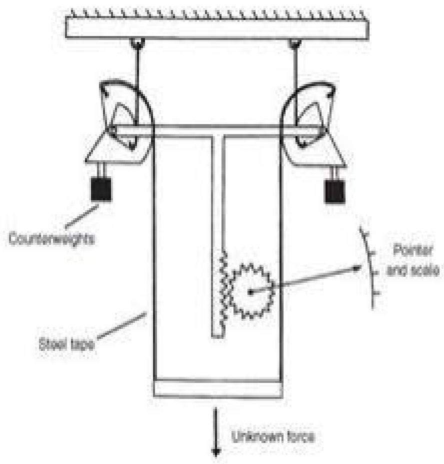

Fig. 5.4 Equal Arm Balance

[source: https://www.brainkart.com/article/Scale-and-balances-on-Measurement-of-Force_5862/]

Description

- The scale's frames carry support ribb These support ribbons are attached to the sectors. The loading ribbons are attached to the sectors and the load rod a shown. The load rod is in turn attached to the weighing platform.
- The two sectors are connected on either side of an equalizer beam. The sectors carry counter weighs. To the center of the equalizer beam is attached a rack and pinion arrangement.
- A pointer is attached to the pinion which sweeps over a weight(force) calibrated scale.

Operation

- The unknown force is applied to the load rod. Due to this force, the loading tapes are pulled downwards. Hence the loading tapes rotate the sectors.
- As the sectors rotate about the pivots, it moves the counter weights outwards, this movements increase the counter weight effective moment until the torque produced by the force applied to the load rod and the moment produced by the counter weight balance each other, thereby establishing an equilibrium.

- During the process of establishing equilibrium, the equalizer beam would be displaced downwards. As the rack is attached to the equalizer beam, the rack also is displaced downwards rotating the pinion.
- As the pointer is attached to the pinion, the rotation of the pinion makes the pointer to assume a new position on the scale. The scale is calibrated to read the weight directly. Thus, the force applied on the load rod is measured.

5.1.1.4 MULTIPLE LEVER SYSTEM

For applications involving measurement of large weights, a platform balance or multiple-lever system is preferred.

In a platform balance, two smaller weights, poise weight W_X and pan weight W_Y, are used for the measurement of a large weight W. The initial zero balance can be set by an adjustable counterpoise. The poise weight W_x is set to zero of the beam scale, and then the counterpoise is adjusted for obtaining the initial balance before applying the unknown weight W on the platform.

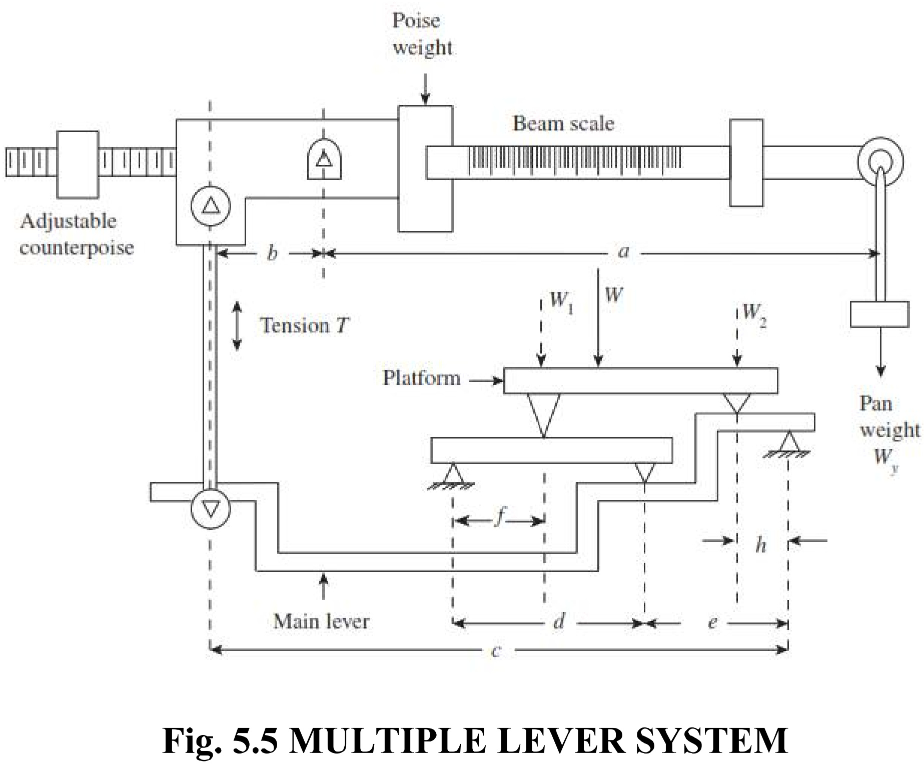

Fig. 5.5 MULTIPLE LEVER SYSTEM

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 344]

For ease of analysis, it can be assumed here that the two weights W_1 and W_2 are substituted by W. Since W_x has already been adjusted to zero, the entire unknown weight W is balanced by the pan weight Wy.

It can be seen that $T \times b = W_y \times a$

and $T \times c = W_1(f/d)e + W_2 \times h$

The linkage proportion can be arranged such that $h/e = f/d$.

Hence, we have $T \times c = (W_1 + W_2)h = Wh$

It is clear from these discussions that weight W can be placed anywhere on the platform and its position with respect to the knife edges of the platform is not significant.

From the above Eqs we obtain the following equation:

$$\frac{W_y a}{b} = \frac{Wh}{c}$$

This gives a new equation.

$$W = \frac{a}{b}\frac{c}{h} W_y = S\, W_y$$

where S is known as the scale multiplication ratio, which is given by another equation:

$$S = \frac{a}{b}\frac{c}{h}$$

The multiplication ratio gives an indication of the weight that should be applied to the pan in order to balance the weight on the platform. This means that if the multiplication factor is 100, then a weight of 1 kg applied on the pan can balance a weight of 100 kg placed on the platform. Let us assume that the beam is divided with a scale of m kg per scale division, then a poise movement on the y scale division has to produce the same result as a weight W_x placed on the pan at the end of the beam; hence, $W_x y$ = mya. Therefore, we obtain the following equation:

$$m = W_x/a$$

The required scale divisions on the beam for any poise weight Wx is determined by this relationship. The length of the beam scale a is expressed in terms of scale divisions. The beam is balanced by appropriate combinations of pan weights and an adjustment of the poise weight along the calibrated beam scale.

5.1.2 Indirect Methods

5.1.2.1 Accelerometers

A device for measuring acceleration. The force causing the acceleration of a body is a product of the body mass **m** and the acceleration **a**. This principle allows the use of accelerometers to measure the force caused by vibrating masses under the influence of a dynamic force.

$$F=ma.$$

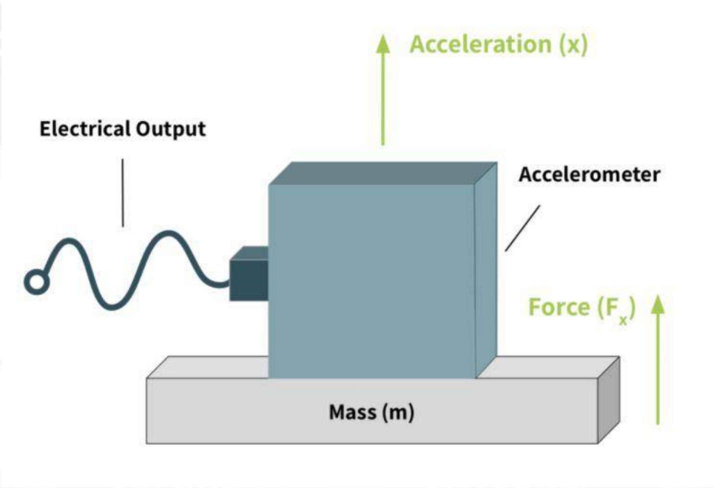

Fig. 5.6 Force Measurement by Accelerometers

[source: https://tacunasystems.com/knowledge-base/force-measurement-glossary/]

5.1.2.2 Electromagnetic Balance

The main parts of the electromagnetic balance are a photoelectric transducer, an amplifer and a coil suspended in a magnetic field. The coil carries a current while produces an electromagnetic torque.

The servo system is used with the coil to balance the difference between unknown force and gravitational force acting on standard mass. The photoelectric transducer is used to check the balance of unknown force and the standard mass produces the electrical voltage in a resistor. It is taken as output and the circuit connected to the resistor is used to measure the unknown force. The output signal can be recorded or used for automatic control applications.

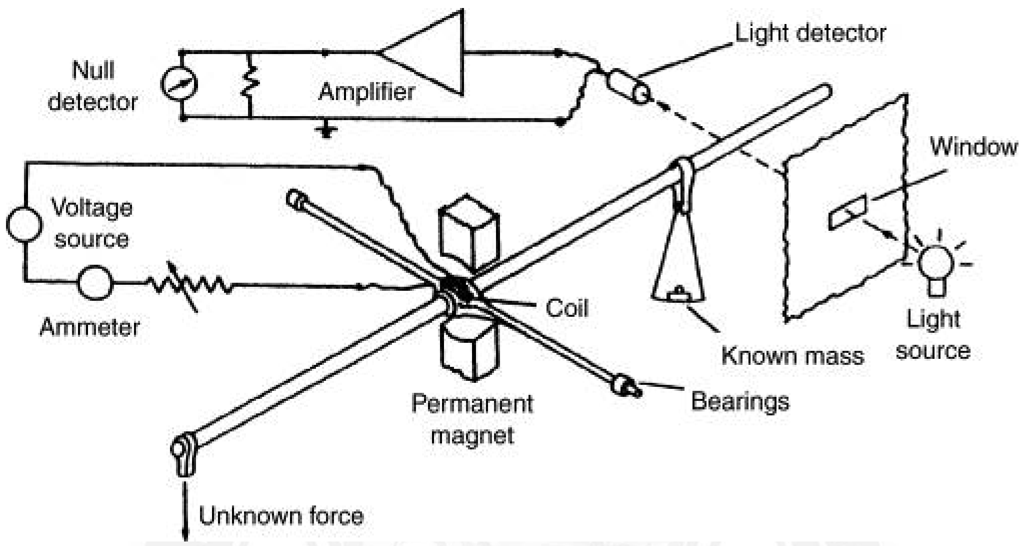

Fig. 5.7 Electromagnetic Balance

[source: https://www.sciencedirect.com/topics/engineering/electromagnetic-balance]

5.1.2.3 Hydraulic and Pneumatic Load Cells

A load cell is a transducer or sensor that converts the kinetic energy of a force (which is impossible to measure without this conversion) into a quantifiable output such as an electrical signal. Each type exploits some physical property of its component materials to create this measurable output. The strength of the output is proportional to the force (compression, tension, pressure, etc.) applied to the load cell. This output data can then be displayed, stored, or used to control complex systems.

Load cells are most commonly used in industrial weighing applications such as scales. Because load cells can convert forces to electrical signals, they are also often used in control systems where the force on a system affects its behavior. For example, a load cell may measure the tension on a machine that winds cabling on a spool to ensure the system uses a consistent tension throughout its process.

Fundamentally, load cells are in systems that test, monitor, and run industrial machinery, medical devices, aircraft loads, and many other applications.

Hydraulic Load Cells

Hydraulic load cells convert a load to hydraulic pressure. The measured load is applied to a load platform attached to a piston. The piston is housed in a closed chamber filled with fluid. When a load is applied, the action of the piston on the diaphragm pressurizes the liquid. The change in liquid pressure is directly proportional to the force applied by the load. The liquid pressure is then read through a bourdon tube pressure gauge.

Hydraulic Load Cell Components

Hydraulic load cells have the following components:

- An elastic diaphragm
- A piston connected to a load platform
- Hydraulic fluid which is usually oil or sometimes water
- Pressure gauge or gauges
- A tube connecting the chamber to the pressure gauge
- Steel housing for the assembly

Features, Benefits and Disadvantages of Hydraulic Load Cells

Because the hydraulic load cell design contains no electrical components, this type of load cell lends itself to environments where explosion safety is a concern, or where an outside power source may be difficult to provide.

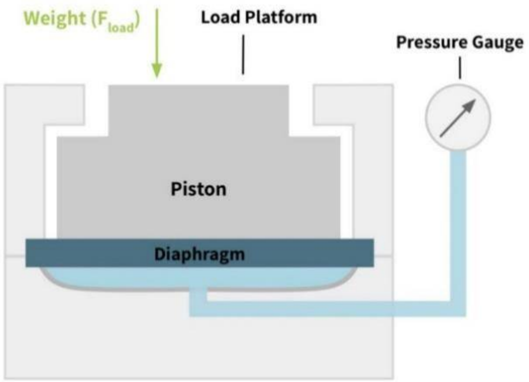

Fig. 5.8 Hydraulic Load Cell

[source: https://tacunasystems.com/knowledge-base/an-overview-of-load-cells/]

On the flip side, hydraulic load cells tend to be more expensive than other types, making them cost-prohibitive for certain applications. Hydraulic load cells can typically measure up to 5MN and have an accuracy of about 0.25 to 1.0 percent of full-scale output. Their resolution is typically about 0.02 percent. Because these load cells are sensitive to ambient pressure, the user must reset the readout to zero before each use.

Pneumatic Load Cells

Pneumatic load cells function similarly to their hydraulic counterparts in that they convert fluid pressure into a load measurement. However, the pressurized fluid in a pneumatic load cell is a type of gas, oftentimes air.

The force to be measured is applied to a loading platform on one side of a diaphragm, and a pressure supply regulator introduces a pressurized gas to a chamber on the opposite side of the diaphragm to balance out the force. A nozzle connected to a pressure gauge allows some of the pressurized gas to escape the chamber. The pressure of the gas flowing through this nozzle is measured. This pressure is proportional to the force applied.

Pneumatic Load Cell Components

Pneumatic load cells have the following components:

- A loading platform to apply the force
- A steel chamber filled with pressurized gas or air

- An elastic diaphragm connected to the loading platform that seals the chamber
- An air supply regulator
- Nozzle (bleed valve)
- Pressure gauge

Features, Benefits and Disadvantages of Pneumatic Load Cells

Like their hydraulic counterparts, pneumatic load cells are explosion resistant and are generally used in applications with intrinsic safety concerns. The pneumatic load cell is also tolerant of temperature changes. Finally, this type of load cell is sensitive to small loads. This makes them practical for systems requiring real-time accuracy with the lightest of loads, such as dispensing IV fluids.

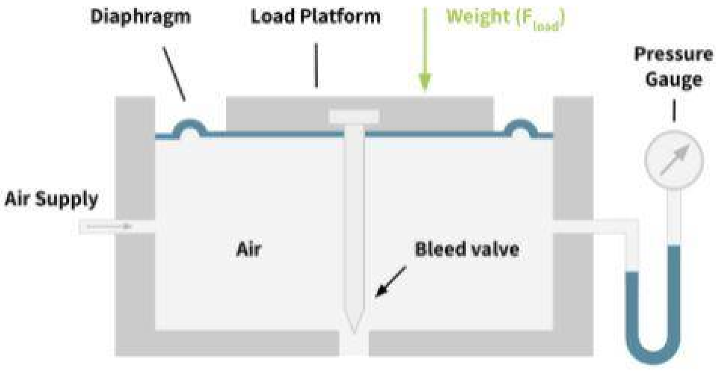

Fig. 5.9 Pneumatic Load Cell

[source: https://tacunasystems.com/knowledge-base/an-overview-of-load-cells/]

5.1.2.4 Coil Springs: Spring Balance

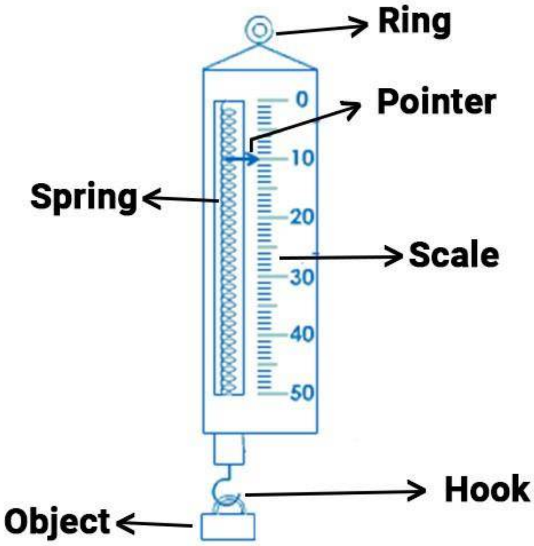

Fig. 5.10 Spring Balance

[source: https://tacunasystems.com/knowledge-base/an-overview-of-load-cells/]

A spring balance is a device used for the direct measurement of force by using coil spring deflection. It consists of a spring fixed at one end and the load is applied at the to end. The displacement at the free end due to the applied force is shown by a pointer moving on a scale.

The deflection of the spring when a force F is applied at the free end is given by the following equation:

$$x=8FD^3n/Gd^4$$

From the above equation, it is clear that the deflection is a linear function of force and it can be directly used as a measure of force.

5.1.2.4 Proving Rings

One of the most popular devices used for force measurement is the proving ring. In order to measure the displacement caused by the applied pressure, a displacement transducer is connected between the top and bottom of the ring. Measurement of the relative displacement gives a measure of the applied force. A proving ring can be employed for measuring the applied load/force, with deflection being measured using a precise micrometer, a linear variable differential transformer (LVDT), or a strain gauge. When compared to other devices, a proving ring develops more strain owing to its construction. A proving ring, which is made up of steel, can be used for measuring static loads, and is hence employed in the calibration of tensile testing machines. It can be employed over a wide range of loads (1.5 kN to 2 MN).

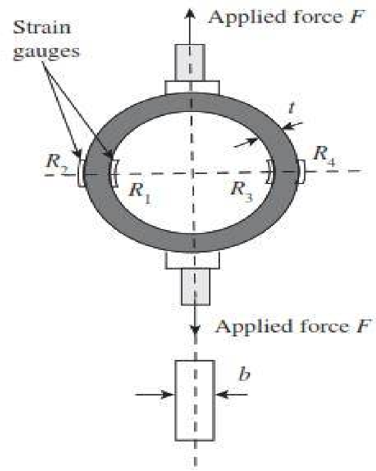

Fig. 5.11 Proving Rings

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 348]

It has a radius R, thickness t, and an axial width b. The proving ring may be subjected to either tensile or compressive forces across its diameters. The two ends between which force is measured are attached with structures. Four strain gauges are mounted on the walls of the proving ring, two on the inner walls, and two other on the outer walls. The applied force induces a strain (compressive) $-\varepsilon$ in gauges 2 and 4, while gauges 1 and 3 undergo tension $+\varepsilon$. The four strain gauges are connected to the bridge circuit, and the unbalanced voltage caused by the applied force can be measured. This voltage is calibrated in terms of force. The magnitude of the strain is given by the following expression:

$$\varepsilon = \frac{1.08FR}{Ebt^2}$$

The relationship between the applied force and the deflection caused by the applied force is given by

$$\delta_y = \left(\frac{\pi}{2} - \frac{4}{\pi}\right)\frac{Fd^3}{16EI}$$

Here, E is the young's modulus, I is the moment of inertia, F is the force, d is the outside diameter of the ring, and is the δ_y deflection.

5.1.2.5 Load Cells

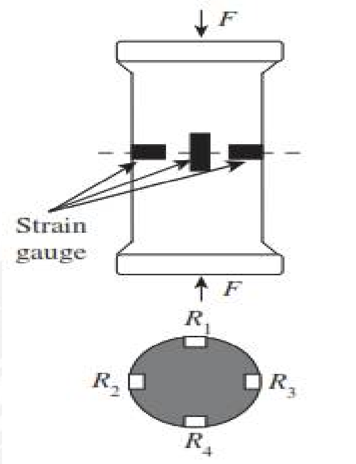

Fig. 5.12 Structure of a Load Cell

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 346]

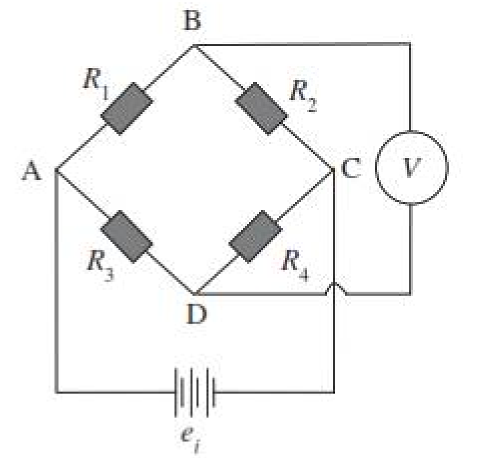

Fig. 5.13 Wheatstone Bridge Circuit

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 346]

A load cell comprises four strain gauges; two of these are used for measuring the longitudinal strain while the other two for measuring the transverse strain. The four strain gauges are mounted at 90° to each other, Two gauges experience tensile stresses while the other two are subjected to compressive stresses.

At the no-load condition, resistance in all the four gauges will be same. The potential across the two terminals B and D are same. The Wheatstone bridge is now balanced and hence output voltage is zero When the specimen is stressed due to the applied force, the strain induced is measured by the gauges.

Gauges R_1 and R_4 measure the longitudinal (compressive) strain, while gauges R_2 and R_3 measure the transverse (tensile) strain. In this case, voltages across the terminals B and D will be different, causing the output voltage to vary, which becomes a measure of the applied force upon calibration.

The longitudinal strain developed in the load cell is compressive in nature and given by the following relation:

$$\varepsilon_1 = -\frac{F}{AE}$$

Here, F is the force applied, A is the cross-sectional area, and E is the young's modulus of elasticity.

Gauges 1 and 4 experience this strain. Strain gauges 2 and 3 would experience a strain given by the following relation:

$$\varepsilon_2 = -\frac{\gamma F}{AE}$$

Here, Ɣ is the Poisson's ratio.

This arrangement of mounting of gauges compensates the influence of bending and temperature. In fact, a complete compensation is obtained if the gauges are mounted symmetrically.

5.1.2.6 Bourdon tube Pressure Guage

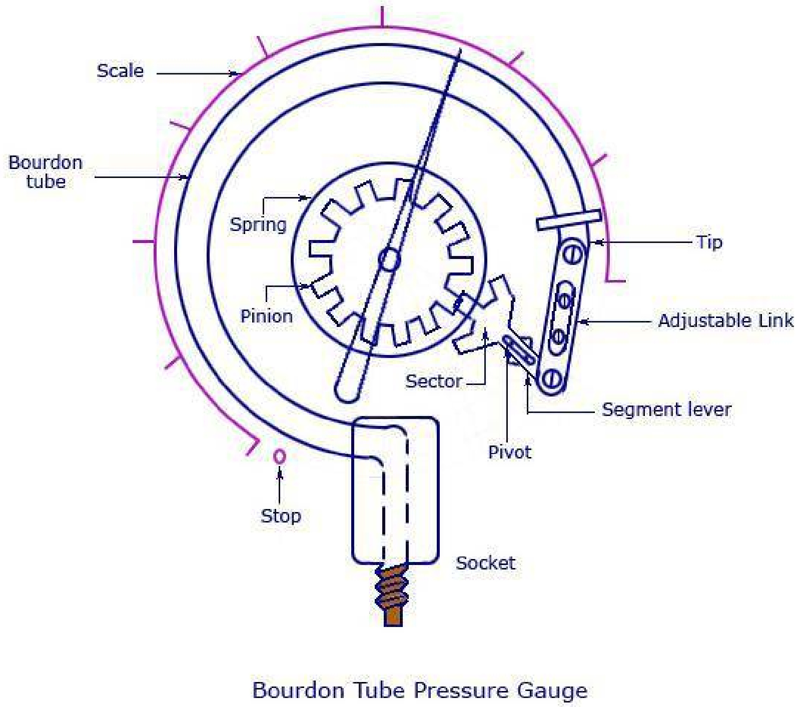

Fig. 5.14 Bourdon tube Pressure Guage

[source:https://mgdic.files.wordpress.com/2016/12/elastic_type_pressure_transducers.pdf]

Principle:

When an elastic transducer (bourdon tube in this case) is subjected to a pressure, it deflects. This deflection is proportional to the applied pressure when calibrated.

Construction:

A C-type Bourdon tube consists of a long thin-walled cylinder of non-circular cross-section, sealed at one end, made from materials such as phosphor bronze, steel and beryllium copper, and attached by a light line work to the mechanism which operates the pointer. The other end of the tube is fixed and is open for the application of the pressure which is to be measured. The tube is soldered or welded to a socket at the base, through which pressure connection is made.

Working:

As the fluid under pressure enters the Bourdon tube, it tries to change the section of the tube from oval to circular, and this tends to straighten out the tube. The resulting movement of the free end of the tube causes the pointer to move over the scale. The tip of the

Bourdon tube is connected to a segmental lever through an adjustable length link. The segmental lever end on the segment side is provided with a rack which meshes to a suitable pinion mounted on a spindle. The segmental lever is suitably pivoted and the spindle holds the pointer.

Bourdon tubes are made of a number of materials, depending upon the fluid and the pressure for which they are used, such as phosphor bronze, alloy steel, stainless steel, "Monel" metal, and beryllium copper. Bourdon tubes are generally made in three shapes: C-type, Helical type and Spiral type

Adjustments need to perform on bourdon tube

Multiplication adjustment:

Because of the compound stresses developed in the Bordon tube, actual travel is nonlinear in nature. However, for a small travel of the tip, this can be considered to be linear and parallel to the axis of link. Small linear tip movement is matched with a rotational pointer movement. This is known as multiplication and can be adjusted by adjusting the length of the lever. Shorter lever gives larger rotation for same amount of the tip travel.

Angularity:

When the approximately linear motion of the tip is converted to a circular motion with the link lever and pinion attachment, a one-to-one correspondence between them may not occur and a distortion results. This is known as angularity. This can be minimized by adjusting the length of the link.

Advantages:

1. These Bourdon tube pressure gauges give accurate results.

2. Bourdon tube cost low.

3. Bourdon tube are simple in construction.

4. They can be modified to give electrical outputs.

5. They are safe even for high pressure measurement.

6. Accuracy is high especially at high pressures.

Disadvantages:

1. They respond slowly to changes in pressure

2. They are subjected to hysteresis.

3. They are sensitive to shocks and vibrations.

4. Amplification is a must as the displacement of the free end of the bourdon tube is low.

5. It cannot be used for precision measurement.

5.1.2.7 Diaphragm pressure Gauge

A diaphragm pressure transducer is used for low pressure measurement. They are commercially available in two types – metallic and non-metallic. Metallic diaphragms are known to have good spring characteristics and non-metallic types have no elastic characteristics. Thus, non-metallic types are used rarely, and are usually opposed by a

calibrated coil spring or any other elastic type gauge. The non-metallic types are also called slack diaphragm.

Construction:

It is made up of rubber or other flexible material. Making a diaphragm slack rather than tight allows it to move large distance in response to a small pressure. A pointer is attached with the diaphragm via linkage. Pressure is applied at the input and is indicated on the scale.

Working

The diagram of a diaphragm pressure gauge is shown below. Unknown pressure is applied to the input (P1) of the gauge which will exerts force on the slack diaphragm. When a force acts against a thin stretched diaphragm, it causes a deflection of the diaphragm with its center deflecting the most. This movement is transferred to the pointer mechanism via leaf spring as shown in figure.

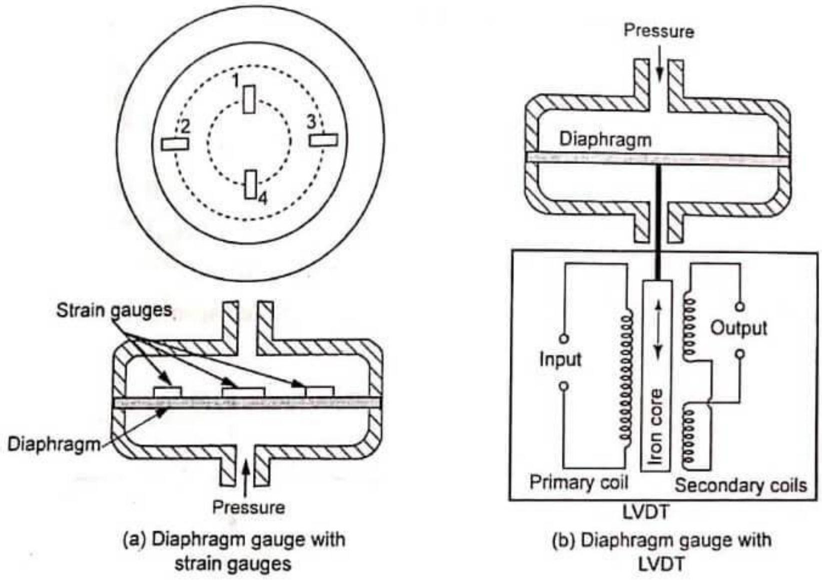

Fig. 5.15 Diaphragm pressure Gauge

[source: Metrology and Measurements, Dr. Vijayaragavan, Pg. No 5.15]

diaphragms are used for measuring very small pressures. The commonly used materials for making the diaphragm are polythene, neoprene, animal membrane, silk, and synthetic materials. Due to their non-elastic characteristics, the device will have to be opposed with external springs for calibration and precise operation. The common range for pressure measurement varies between 50 Pa to 0.1 MPa.

Advantages of diaphragm gauges:

1. Best advantage is they cost less

2. They have a linear scale for a wide range

3. They can withstand over pressure and hence they are safe to be used.

4. No permanent zero shift.

5. They can measure both absolute and gauge pressure, that is, differential pressure.

Disadvantages of diaphragm gauges:

1. Shocks and vibrations affects their performance and hence they are to be protected.

2. When used for high pressure measurement, the diaphragm gets damaged.

3. These gauges are difficult to be repaired.

5.1.2.8 Bellows type pressure gauge

Like a diaphragm, bellows are also used for pressure measurement, and can be made of cascaded capsules. The basic way of manufacturing bellows is by fastening together many individual diaphragms. The bellows element, basically, is a one-piece expansible, collapsible and axially flexible member. It has many convolutions or fold. It can be manufactured form a single piece of thin metal.

Construction:

A bellows gauge contains an elastic element that is a convoluted unit that expands and contracts axially with changes in pressure. Most bellows gauges are spring-loaded; that is, a spring opposes the bellows, thus preventing full expansion of the bellows. Limiting the expansion of the bellows in this way protects the bellows and prolongs its life. In a spring-loaded bellows element, the deflection is the result of the force acting on the bellows and the opposing force of the spring. The movement of bellows is transferred to a pointer though a linkage. Bellows can also be used to measure differential pressure as shown in figure. Here two different pressure are applied to the two different pressure connection. Scale and Pointer is attached with gauge movement linkage at the center of the force bar. The bellows are connected between the input pressure connection and force bar.

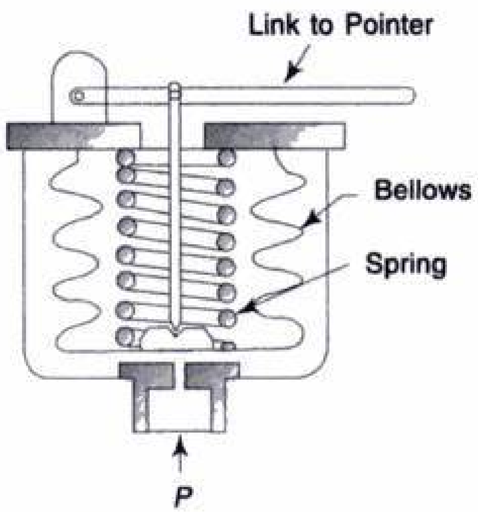

Fig. 5.16 Bellows type pressure gauge

[source:https://mgdic.files.wordpress.com/2016/12/elastic_type_pressure_transducers.pdf]

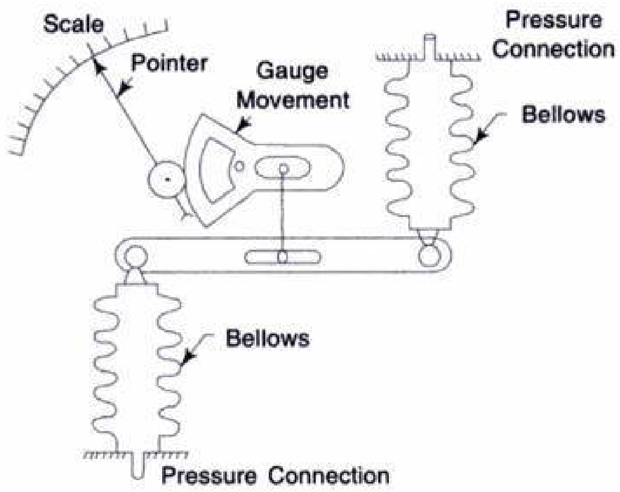

Fig. 5.17 Differential Bellows type pressure gauge

[source:https://mgdic.files.wordpress.com/2016/12/elastic_type_pressure_transducers.pdf]

Working:

The pressure to be measured is applied to the outside or inside of the bellows. However, in practice, most bellows measuring devices have the pressure applied to the outside of the bellows. As the inlet pressure varies, the bellows will expand or contract. This will move the linkage assembly and pointer will shows the applied pressure on the scale. For differential pressure measurement using bellows, applied differential pressure will try to imbalance the force bar and accordingly this movement is transferred to scale via gauge movement and pointer.

Like Bourdon-tube elements, the elastic elements in bellows gauges are made of brass, phosphor bronze, stainless steel, beryllium-copper, or other metal that is suitable for the intended purpose of the gauge.

Although some bellows instruments can be designed for measuring pressures up to 800 psig, their primary application is in the measurement of low pressures or small pressure differentials.

Advantages

• Bellow joints do not require access; i.e. They can be direct buried, however a telltale is recommended

- No maintenance is required.
- Low cost
- Can be used to measured differential pressure

Disadvantages

- Bellows joints can fail catastrophically.
- No in place maintenance or repair can be performed - they must be replaced if damaged
- Require that the system to be shut down when a failure occurs.
- Smaller pressure range of application.
- Temperature compensation needed

5.1.2.9 Pressductor

This type utilizes the magneto-elastic effect or the change in permeability in a magnetic core occurring when a force is applied to the core. When exposed to mechanical force, ferromagnetic elements change the magnetic moments of its "Weiss" domains when pressure is applied, resulting in changes in the magnetic characteristics in the directions in which the mechanical forces act.

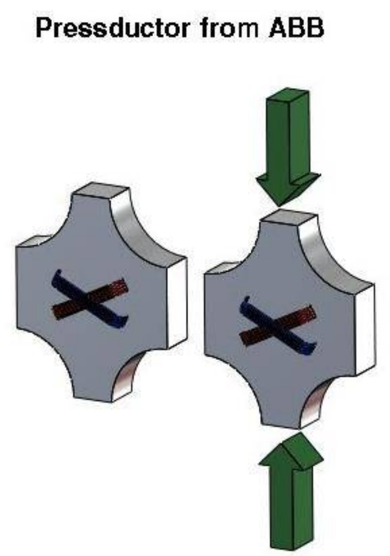

Fig. 5.18 Pressductor

[source: https://www.iqsdirectory.com/articles/load-cell.html]

5.1.2.10 Electronic Weighing System

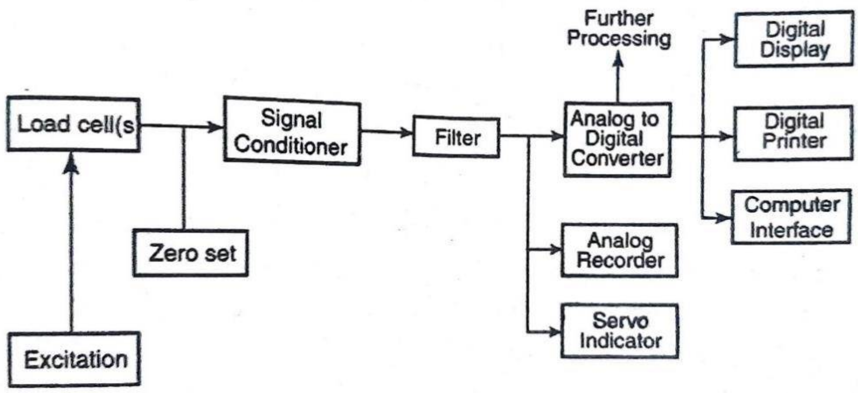

Fig. 5.19 Block Diagram of Electronic Weighing System

[source: Metrology and Measurements, Dr. Vijayaragavan, Pg. No 5.21]

The above figure shows the Block Diagram of Electronic Weighing System. The system comprises the load cell, suitable signal conditioners and output recorders/ indicators giving both analog and digital output for further processing. The signal from the load cells are added and amplified to give an output 0V to 5V or 4 to 20mAfor process instrumentation. It is further converted into a digital format with an analog to digital converter so that the output can be indicated or printed out in a digital format or used for processing. The electronic weighing system can be designed to integrate with computer system with a suitable software to include all functions such as totalizing, averaging, counting and processing or any other such control operation.

Applications:

- Platform weighing
- Truck weighing
- Crane weighing
- Weighing of vehicle in motion,
- weigh feeders
- Tank and hooper weighing
- Bulk load sensing as encountered in steel plants

- Chemical plants
- Petro chemical plants
- Fertilizers
- Pharmaceuticals and
- Textile industries etc.

5.2 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 applied torque
  - An optical method
  - Measuring the reaction force in cradled shaft bearings
  - Using equipment known as the Prony brake.

5.2.1 PRONY BRAKE SYSTEM

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. 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 $F_e = mg - F_s$.

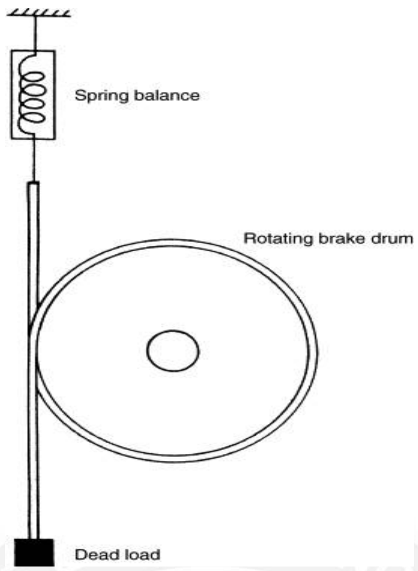

Fig. 5.20 Prony Brake

[source: https://www.sciencedirect.com/topics/engineering/prony-brake]

If the radius of the flywheel is R, the torque is given by

Torque, $T = (mg-F_s) R_e$

Where $R_e = R+r$

R = Radius of the Brake drum

R = Radius of the rope or thickness of the belt.

5.2.2 Torque Measurement Using strain gauges

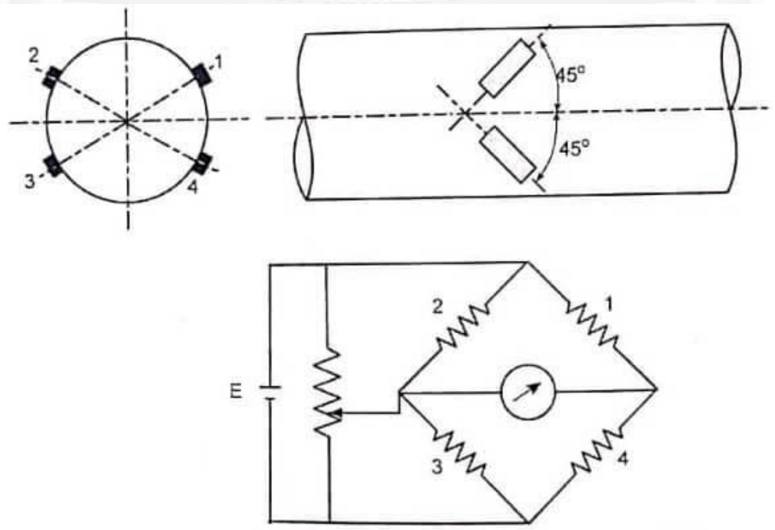

Fig. 5.21 Strain gauges for shaft torque measurement

[source: https://theteche.com/torque-measurement-using-strain-gauges/]

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. Torque transducers based on strain measurement are normally made by applying strain gauges to a shaft to measure the shear strain caused by torsion. The shear stress causes strains to appear at 45° to the longitudinal axis of the shaft. So, the strain gauges must be placed precisely at 45° to the shaft axis as shown in fig.

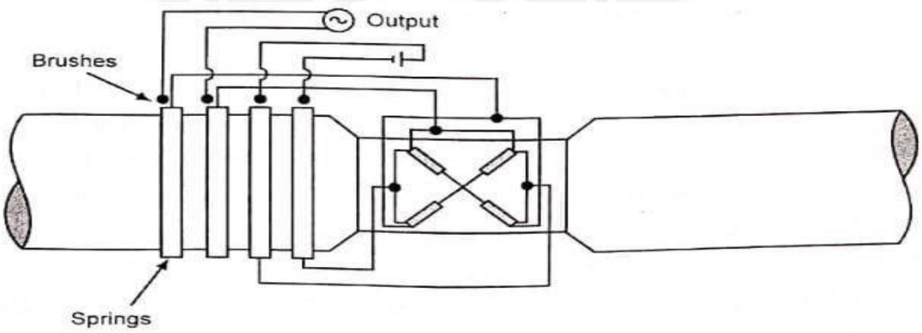

Fig. 5.22 Slip Ring arrangement in torque transducer

[source: https://theteche.com/torque-measurement-using-strain-gauges/]

Otherwise, the arrangement is sensitive to bending and axial stresses in addition to those caused by torsion. The output is increased by using four gauges so that the adjacent arms have strains of opposite nature. Also this arrangement provides complete thermal compensation. For taking signals in and out of the rotating shaft, slip rings and brushes are used. The arrangement of slip rings and brushes are shown on fig.

It is easier to measure bending strains rather than strains due to torque at 45° and so an arrangement using beams may be employed, in which the transmitted torque results in bending the beams. This arrangement is shown in fig.

A slip ring arrangement results in noise due to change in contact resistance also slip rings and brushes wear out and hence it needs to be renewed. A non-contacting type of arrangement as shown in fig is preferred.

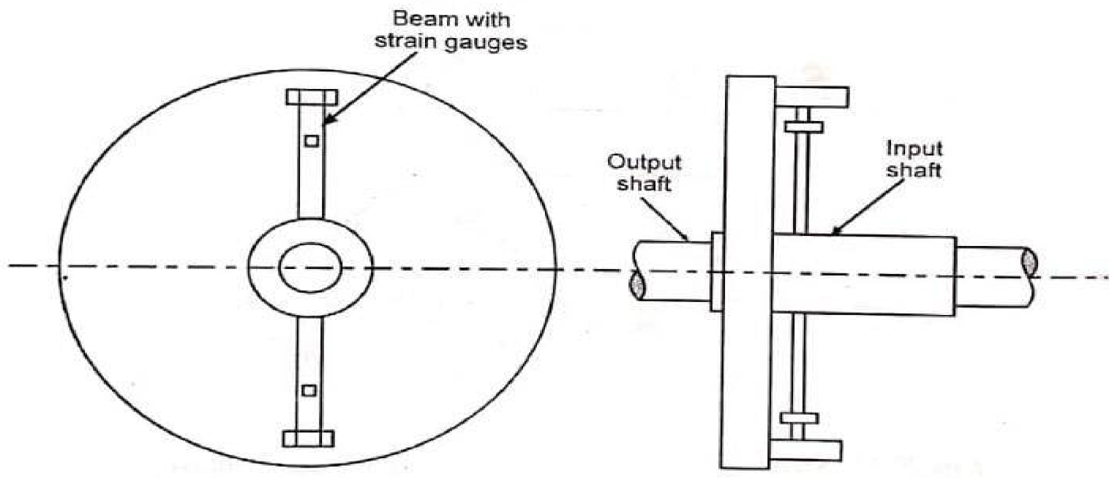

Fig. 5.23 Strain gauge transducer using beams in bending

[source: https://theteche.com/torque-measurement-using-strain-gauges/]

This bridge supply and output signals are transmitted between the rotating and stationary member through transformers. Through AC supply of the bridge, an amplitude modulated AC voltage proportional to the torque is obtained as the output of the bridge. The AC voltage necessary for supply, the strain gauge bridge and the measurement signal can be transmitted via rotating transformer.

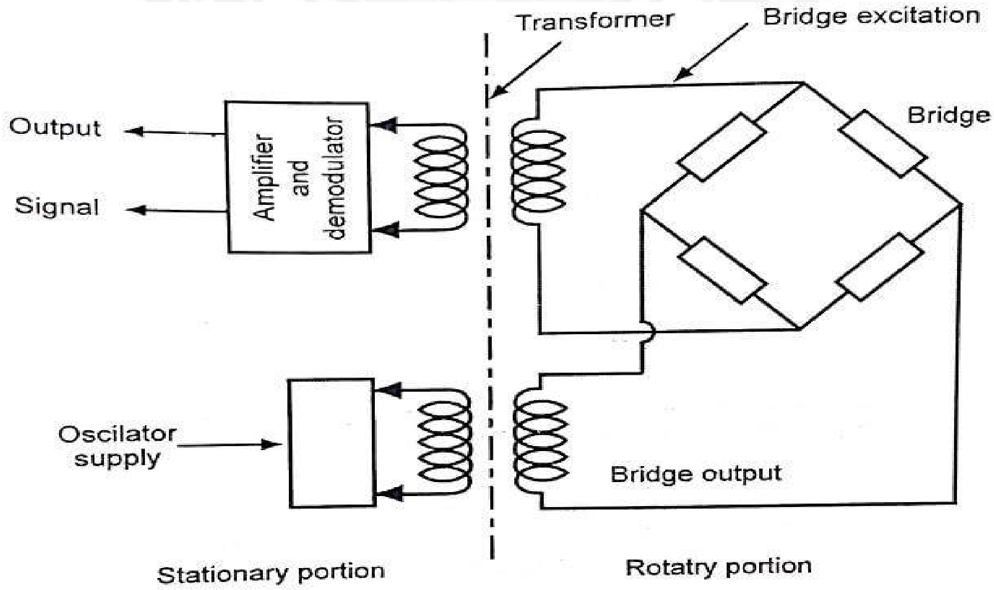

Fig. 5.24 Block circuit diagram for rotating sensors with AC supply

[source: https://theteche.com/torque-measurement-using-strain-gauges/]

5.2.3 Torque Measurement Using Torsion Bars

5.2.3.1 Optical Method

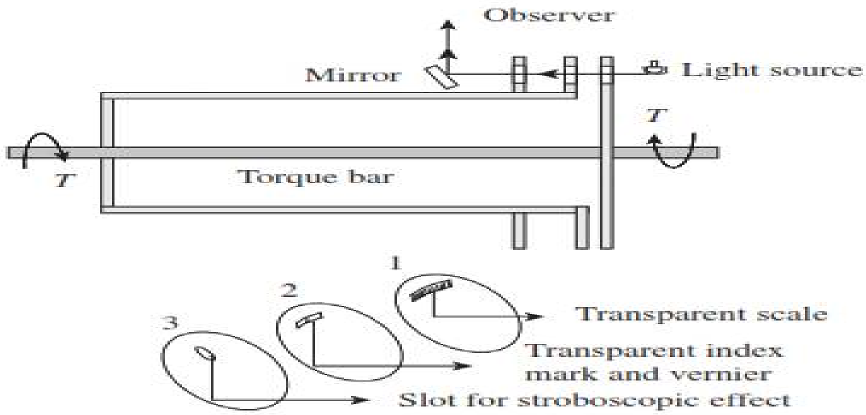

Fig. 5.25 Torsion Bar Torque Transducer

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 349]

Elastic deflection of the transmitting element may be used for the measurement of torque, which can be achieved by measuring either a gross motion or a unit strain. The main problem associated with either case is the difficulty in reading the deflection of the rotating shaft. A torsion-bar dynamometer is also known as a torsion-bar torque meter, which employs optical methods for deflection measurement, as shown in Fig.

Calibrated scales are used to read the relative angular displacement of the two sections of the torsion bar. This is possible because of the stroboscopic effect of intermittent viewing and persistence of vision. Transmission dynamometers, which employ this principle, are available in ranges up to 60,000 m kgf and 50,000 r/min, having an error of ±0.25%.

Replacing the scales on disks 1 and 2 with sectored disks, which are alternately transparent and opaque sectors, and the human eye with an electro-optical transducer, a version having an electrical output is obtained. When there is no torque, the sectored disks are positioned to give a 50% light transmission area. The area of proportionality increases with positive torque and decreases with negative torque, thus giving a linear and direction-sensitive electric output.

5.2.3.2 Capacitive Method

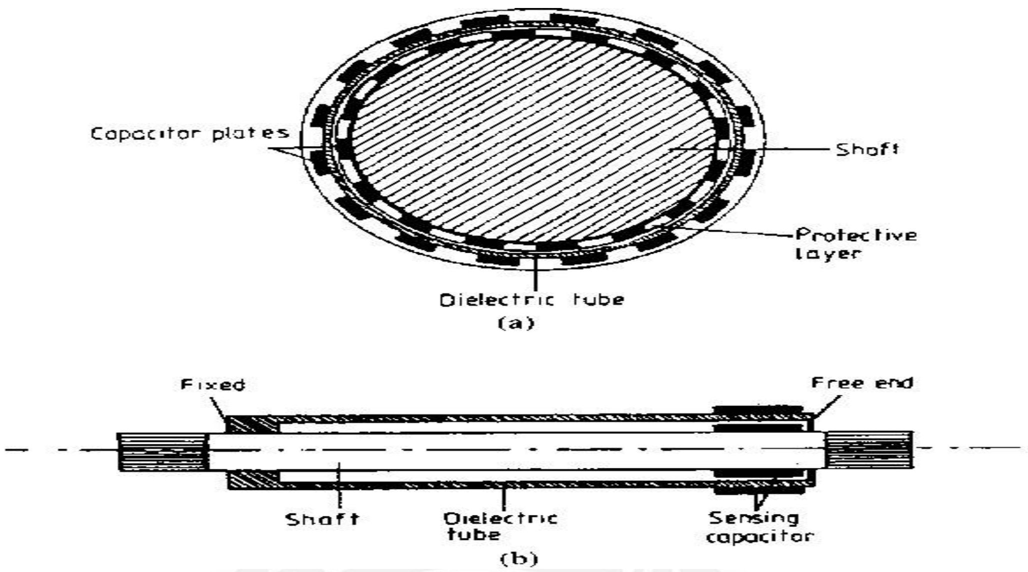

Fig. 5.25 Torsion Bar Torque Transducer

[source: https://www.semanticscholar.org/paper/Noncontact-capacitive-torque-sensor-for-use-on-a-Wolffenbuttel-Foerster/2cc240329d42e4a64b59bcff6bdd4532e38fe227]

A Torsion bar system using capacitive torque sensing method. A shaft is fitted with a concentric sleeve of die electric material. The sleeve is fixed to the shaft at one end and its rests on a rubbing bearing at other end. When the torque is applied to the shaft, it causes a relative motion between surface of a shaft and free end of a concentric tube. The motion is used to vary the capacitance applied to two opposing patterns of conducting strips. One of them is applied to vary the capacitance applied to two opposing patterns of conducting strips. One of them is applied to the shaft and the other one is applied to the tube.

The capacitive sensor is connected to an inductor coil wound around the shaft. The resulting passive circuit thus has a resonance frequency which depends on the applied torque. The passive resonance circuit rotates with the drive shaft. Torque measurement can be done by measuring the resonance frequency.

When the oscillator frequency is the same at which the resonance occurs in the passive circuit, an increased current is drawn. If the frequency at which it occurs is measured, it can be used to indicate torque. The advantage of this arrangement is that no physical connection between rotating shaft and frame.

5.2.4 Laser Optic Method

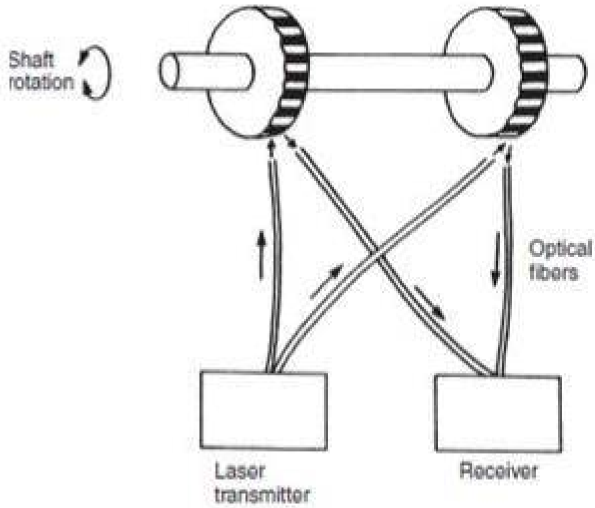

Fig. 5.26 Laser Optic Method

[source: https://www.brainkart.com/article/Torque-Measurement_5863/]

Laser Optical 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 Figure. Two black-and-white striped wheels are mounted at either end of the rotating shaft and are in alignment when no 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 an additional advantage in many applications is their small physical size.

5.2.5 Proximity Sensor Method

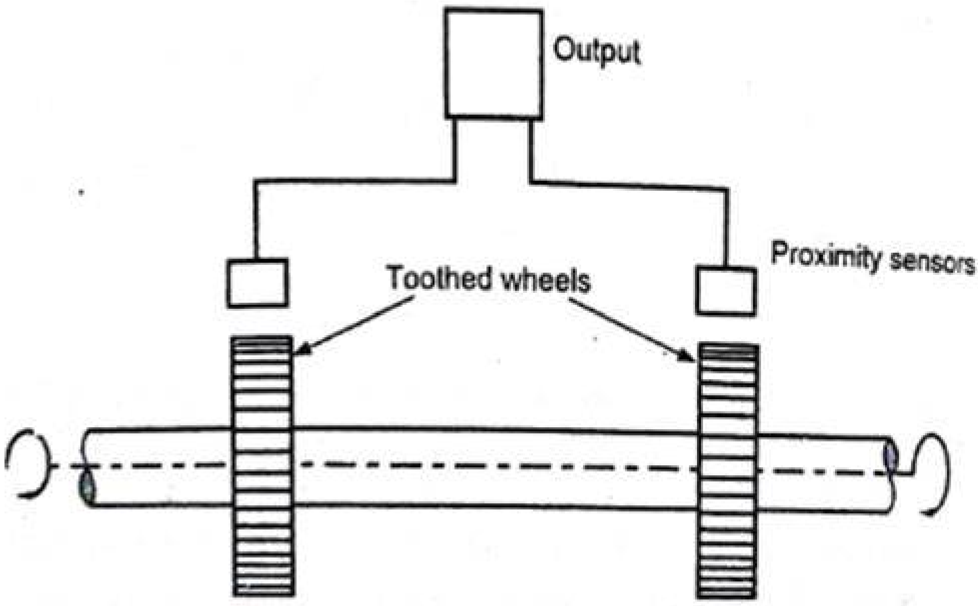

Fig. 5.27 Proximity Sensors for Torque Measurement

[source: Metrology and Measurements, Dr. Vijayaragavan, Pg. No 5.29]

An arrangement using toothed wheels and proximity sensors is shown in figures. Two identical toothed wheels are fixed on the shaft at a certain distance. The two proximity sensors produce the output voltage with phase difference proportional to torque. Alternatively, an arrangement using photocells and a light source maybe employed.

5.2.6 Stroboscope Method

Principle of Stroboscope Method

When a shaft is connected between a driving engine and driven load, a twist (angular displacement) occurs on the shaft between its ends. This angle of twist is measured and calibrated in terms of torque.

Construction of Stroboscope Method

The main parts of the mechanical torsion meter are as follows:

A shaft which has two drums and two flanges mounted on its ends as shown in the diagram. One drum carries a pointer and other drum has a torque calibrated scale. A stroboscope is used to take readings on a rotating shaft.

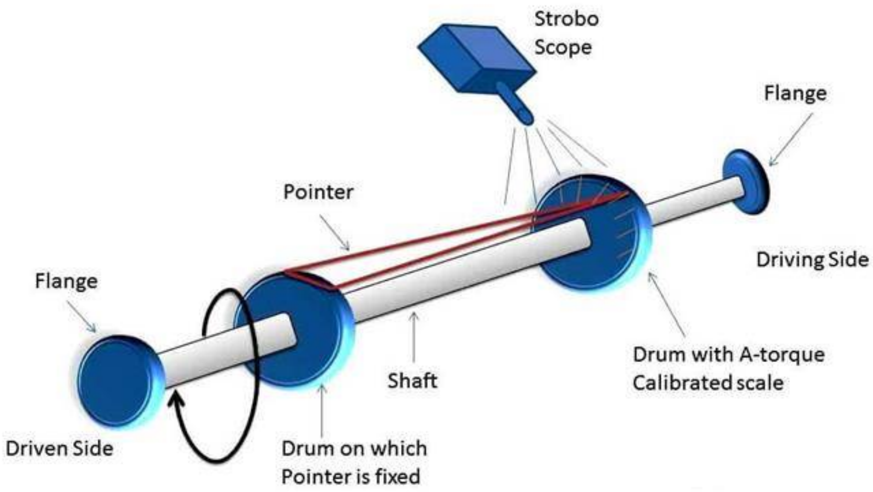

Fig. 5.28 Stroboscope Method

[source: https://instrumentationtools.com/mechanical-torsion-meter-principle/]

Operation of Stroboscope Method:

One end of the shaft of the torsion meter is connected to the driving engine and its other end to the driven load.

An angle of twist is experienced by the shaft along its length between the two flanges which is proportional to the torque applied to the shaft.

A measure of this angle of twist becomes a measure of torque when calibrated.

The angular twist caused is observed on the torque calibrated scale corresponding to the position of the pointer. As the scale on the drum is rotating, reading cannot be taken directly. Hence a stroboscope is used. The stroboscope's flashing light is made to fall on the scale and the flashing frequency is adjusted till a stationary image is obtained. Then the scale reading is noted.

Application of Stroboscope Method

- Simple and inexpensive method
- Power of shaft can be calculated (flashing frequency gives information about speed).

Limitation of Stroboscope Method

- Poor accuracy due to small displacement of the pointer.
- Sensitivity is reduced even due to small variation in speed.
- It can be used only on shafts rotating at a constant speed.

5.2.7 Magnetostrictive method

Magnetostriction is the process in which a ferromagnetic material can change its size or shape when it is placed in a magnetic field. This device can be used to do the position control. The Magnetostrictive position sensor uses a ferromagnetic element in order to determine the location of a position magnet which is displaced along its length. This sensor has good accuracy and it is also resistant to vibration and shock. These sensors can be considered as a rugged device that can deliver 30 to 400mv signals at their output terminals and it would only need less or no additional signal conditioning. The important requirement in this sensor is that the waveguide must be as long as the measured stroke.

This sensor is composed of a magnetic core, a small amount of the current is applied to the core by using a drive coil that is around it. The senor has a steel housing and the drive coil and the core is situated inside it. The housing, piston, and core would act as a closed magnetic flux path. The materials that are used in this position sensors are transition metals and they are iron, nickel, and cobalt.

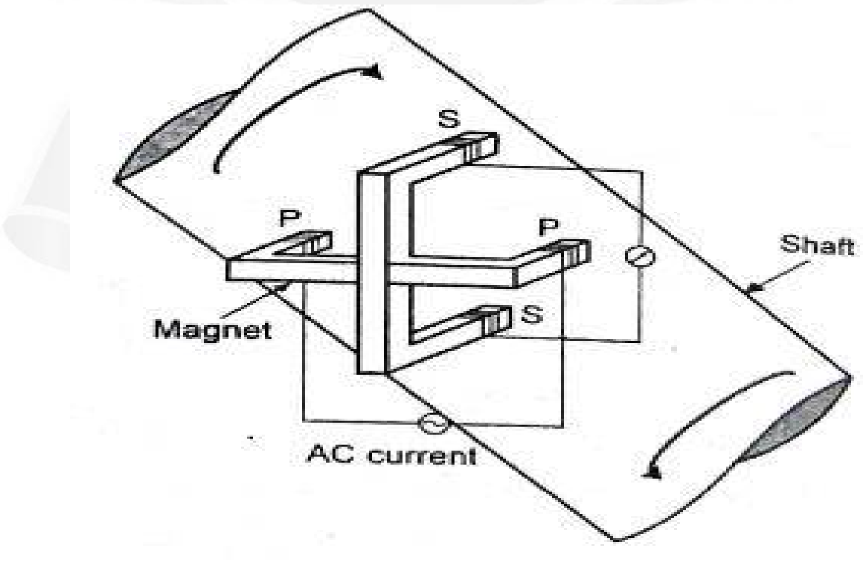

Fig. 5.29 Magnetostrictive Transducer

[source: Metrology and Measurements, Dr. Vijayaragavan, Pg. No 5.30]

The magneto-resistors can be used similar to a hall element, it is simpler because there is no need to create a control current. The Magnetostrictive material will be exposed to a magnetic field to be sensed. The sensitivity of this device is higher than the hall device, the bidirectional effect between the magnetic and the mechanical states of Magnetostrictive material is a transduction capability that is used for actuation and sensing.

APPLICATIONS

- It can be used for position sensing
- It is used in the torque measurement system
- It can be used for water level sensing
- Accelerometer sensor
- Load sensor
- It is used in sonars
- Acoustic devices use this sensor
- Medical and industrial field

5.3 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

Types of dynamometers

- Absorption dynamometers
- Driving dynamometers
- Transmission dynamometers

5.3.1 Mechanical Dynamometers

They come under the absorption type. There are two types of mechanical dynamometers as follows

a) Prony brake

b) Rope brake

5.3.1.1 Prony Brake Dynamometer

Pony Brake is one of the simplest dynamometers for measuring power output (brake power). It is to attempt to stop the engine using a brake on the flywheel and measure the weight which an arm attached to the brake will support, as it tries to rotate with the flywheel.

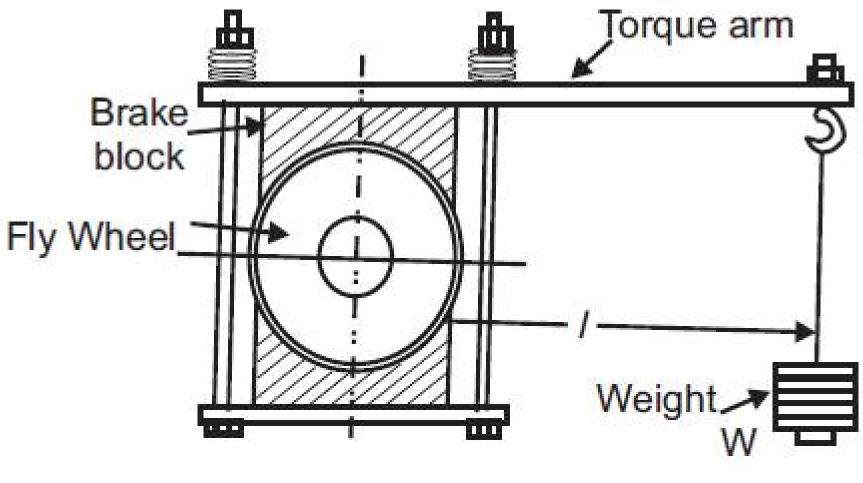

Fig. 5.30 Prony Brake Dynamometer

[source: https://www.mechbix.com/p/mechanical-dynamometers.html]

The Prony brake shown in the above consists of a wooden block, frame, rope, brake shoes and flywheel. It works on the principle of converting power into heat by dry friction. Spring-loaded bolts are provided to increase the friction by tightening the wooden block.

The whole of the power absorbed is converted into heat and hence this type of dynamometer must the cooled.

The brake power is given by the formula

Brake Power (Pb) = $2\pi NT$

Where T = Weight applied (W) × distance (l)

5.3.1.2 Rope Brake Dynamometer

The rope brake as shown in below figure is another device for measuring brake power of an engine. It consists of some turns of rope wound around the rotating drum attached to the output shaft. One side of the rope is connected to a spring balance and the other side to a loading device. The power is absorbed in friction between the rope and the drum. Therefore drum in rope brake requires cooling.

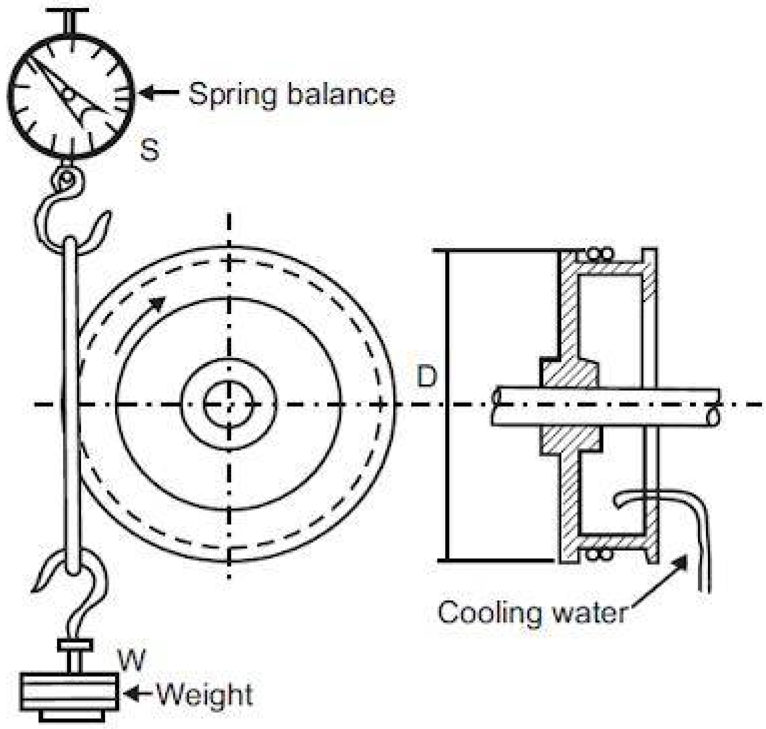

Fig. 5.31 Rope Brake Dynamometer

[source: https://www.mechbix.com/p/mechanical-dynamometers.html]

Rope brake dynamometers are cheap and can be constructed quickly but brake power can't be measured accurately because of change in the friction coefficient of the rope with a change in temperature.

The brake power is given by the formula

Brake Power (Pb) = πDN (W − S)

Where,

D is the brake drum diameter,

W is the weight of the load and

S is the spring balance reading.

5.3.2 Eddy Current Dynamometer:

The working principle of **eddy current dynamometer** is shown in the figure below. It consists of a stator on which are fitted some electromagnets and a rotor disc made of copper or steel and coupled to the output shaft of the engine. When the rotor rotates, eddy currents are produced in the stator due to magnetic flux set up by the passage of field current in the electromagnets. These eddy currents are dissipated in producing heat so that this type of dynamometer requires some cooling arrangement. The torque is measured exactly as in other types of absorption dynamometers, i.e., with the help of a moment arm. The load in internal combustion engine testing is controlled by regulating the current in the electromagnets.

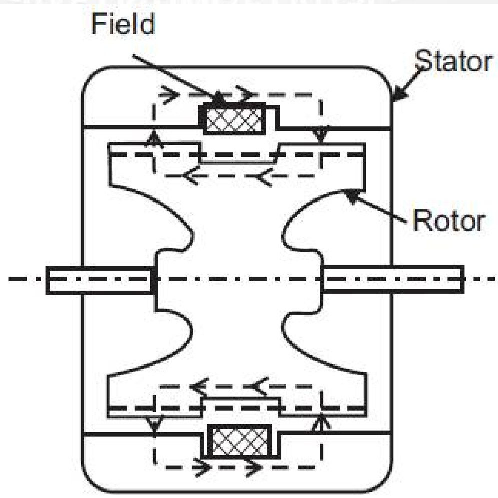

Fig. 5.32 Eddy Current Dynamometer

[source: https://mechanicalengineering.blog/dynamometer-introduction-types/]

The following are the main advantages of eddy current dynamometers:

- High brake power per unit weight of dynamometer.
- They offer the highest ratio of constant power speed range (up to 5 : 1).
- Level of field excitation is below 1% of total power being handled by the dynamometer. Thus, they are easy to control and operate.
- Development of eddy current is smooth hence the torque is also smooth and continuous under all conditions.
- Relatively higher torque under low-speed conditions.
- It has no intricate rotating parts except shaft bearing.
- No natural limit to size, either small or large.

5.3.3 Hydraulic Dynamometer:

A hydraulic dynamometer as shown in the figure below works on the principle of dissipating the power in fluid friction rather than in dry friction.

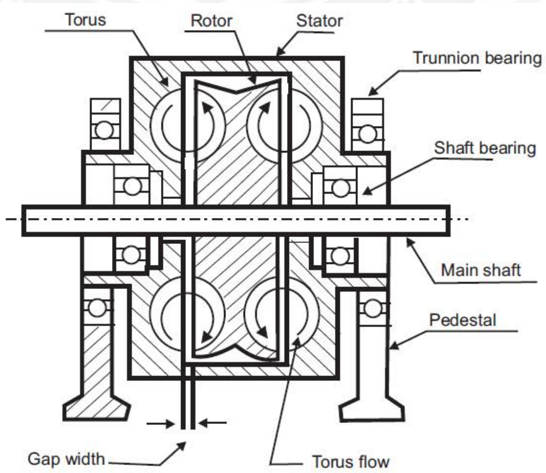

Fig. 5.33 Hydraulic Dynamometer

[source: https://mechanicalengineering.blog/dynamometer-introduction-types/]

- In principle, hydraulic dynamometer construction is similar to that of a fluid flywheel.

- Hydraulic dynamometer consists of an impeller or inner rotating member coupled to the output shaft of the engine.
- The impeller in this dynamometer rotates in a casing filled with a fluid.
- Due to the centrifugal force developed in the outer casing, tends to revolve with the impeller, but is resisted by a torque arm supporting the balance weight.
- The frictional forces generated between the impeller and the fluid are measured by the spring balance fitted on the casing.
- The heat developed due to the dissipation of power in Hydraulic dynamometer is carried away by a continuous supply of the working fluid.
- The output power can be controlled by regulating the sluice gates which can be moved in and out to partially or wholly obstruct the flow of water between the casing and the impeller.

5.4 FLOW MEASUREMENT

The flowrate 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 flowmeters, consisting of orifice, flow nozzle, and venturimeters, 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 flowrate. Flow meter is a device that measures 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 flowmeters

Fixed restriction variable head type flowmeters using different sensors like orifice plate, venturi tube, flow nozzle, pitot tube, dall tube, quantity meters like positive displacement meters, mass flowmeters etc. fall under mechanical type flow meters.

2. Inferential type flowmeters

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

3. Electrical type flow meters

Electromagnetic flow meter, Ultrasonic flowmeter, Laser doppler Anemometers etc. fall under electrical type flowmeter.

4. Other flowmeters

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

5.4.1 Orifice Meter

Orifice Meter is an instrument which is used to measure average velocity of a flowing fluid or flow rate of a flowing fluid.

It measures the average velocity and the flow rate of the flowing fluid by introducing a restriction in the direction of the flowing fluid. The effect of the restriction is to lower the pressure drop of the flowing fluid. This decrease in pressure can be related to average velocity or the flow rate of the flowing fluid mathematically.

The orifice plates are placed in between the flanges of the two sections of pipe and they are tightened by a nut.

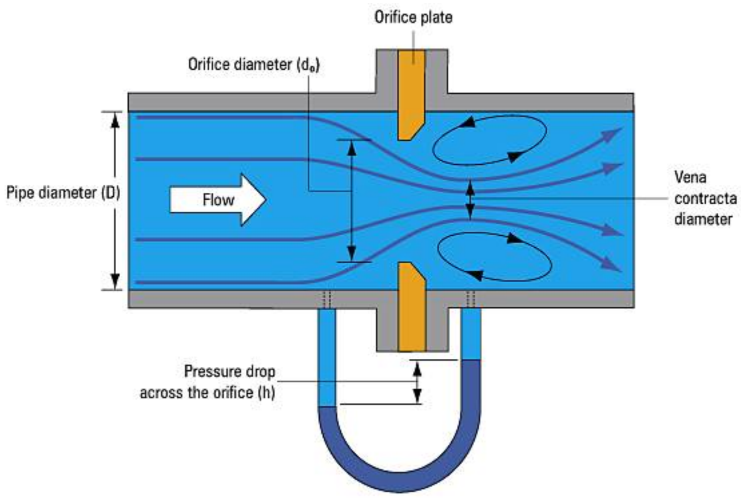

Fig. 5.34 Orifice Meter

[source: https://instrumentationtools.com/what-is-an-orifice-meter/]

The main purpose of an orifice plate is to act as a restriction in the direction of flow of fluid in order to decrease the pressure of the flowing fluid but it must be properly designed so that it doesn't lower pressure too much and also it most not create much turbulence on the downstream side of the plate.

$$\text{Flow rate, } Q = C_d . a_1 . a_0 \sqrt{2gh} \;/\; \sqrt{a_1^2 - a_0^2}$$

Working of Orifice Meter

The fluid flowing in the pipe converges when it starts nearing the plate. The degree of convergence depends on the size and location of bore. After the fluid reaches the bore and passes through the bore, its convergence does not stop immediately. As the fluid is converged more and more, its pressure decreases more and more.

Due to the inertia of flowing fluid, the liquid converges until some distance downstream the plate and it reaches a point known as vena contracta. The state of the fluid at the point of vena contracta is such that it is the point of maximum velocity and minimum pressure.

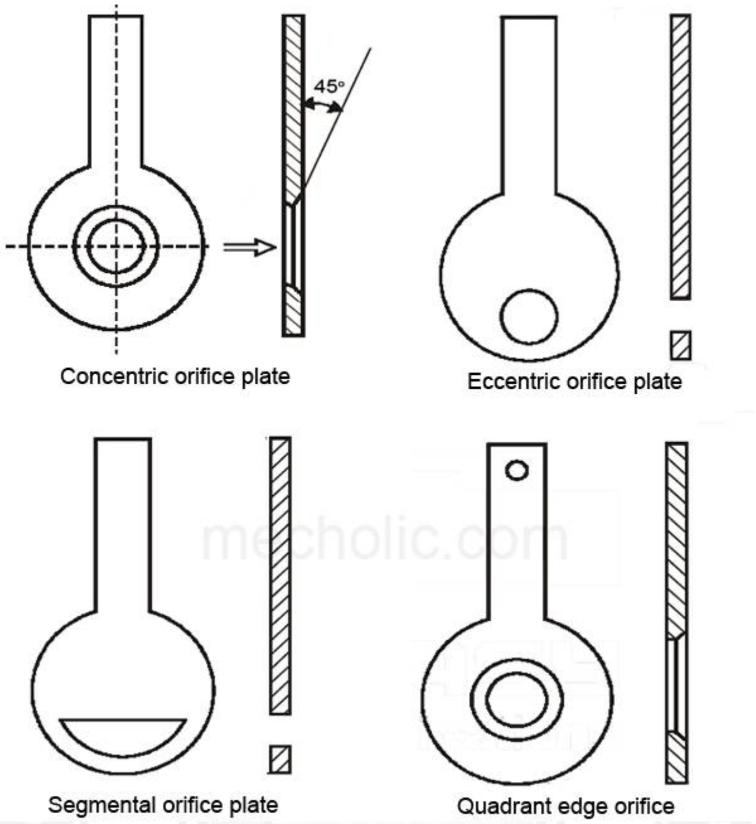

Fig. 5.35 Orifice Plate Configurations

[source: https://instrumentationtools.com/what-is-an-orifice-meter/]

The orifice plates have to be properly designed so that the pressure of the liquid does not fall below its vapour pressure at the fluid temperature because if it falls below the vapour pressure then the liquid will vaporize in the vena contracta region and it may happen that the vapours will collapse in some region downstream to vena contracta, this is the phenomenon of cavitation and it damages the pipe.

The decrease in pressure is sensed by a manometer or a pressure gauge.

5.4.2 Venturimeter

Working

The venturimeter works on the principle of Bernoulli's equation, i.e., the pressure decreases as the velocity increases.

The cross-section of the throat is less than the cross-section of the inlet pipe.

As the cross-section from the inlet pipe to the throat decreases, the velocity of the fluid increases, and hence the pressure decreases.

Due to the decrease in pressure, a pressure difference is created between the inlet pipe and the venturimeter throat.

This pressure difference can be measured by applying a differential manometer between the inlet section and throat section or using two gauges on the inlet section and throat.

The pressure difference through the pipe is calculated after obtaining the flow rate.

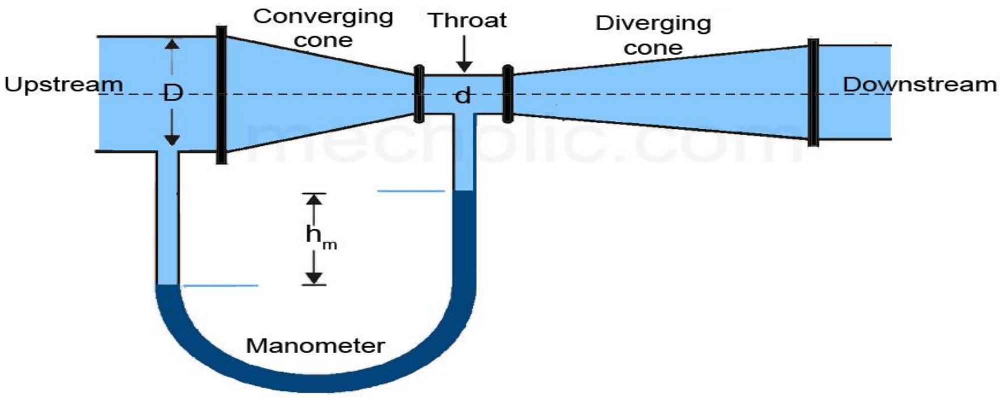

Fig. 5.36 Venturimeter

[source: https://www.mecholic.com/2016/11/venturi-meter-construction-working-equation-application-advantages.html]

Construction

It consists of three parts, the part of the larynx and the deviation. These three parts are arranged in a systematic order. The first is an inlet section or converging section.

This is the area where the cross-section emerges in a conical shape for contact with the throat region. In this section, the cross-section area decreases from beginning to end.

This section is connected by an inlet pipe at one end and a cylindrical throat at the other end. The angle of convergence is typically 20–22 °. the other is a cylindrical larynx.

This is the central part of the venturimeter. It is a cylindrical pipe in the ventimeter through which the fluid passes after converting to the convergence section.

The throat usually has a diameter of the throat that is half the diameter of the pipe. The throat diameter remains the same through its length. The last one is turning the section.

This is the end of the venturimeter. On one side, it is connected to the throat of the venturimeter, and on the other side is attached to the pipe.

$$\text{Flow rate, } Q = C_d .\ a_1 .\ a_2 \sqrt{2gx} \ / \sqrt{a_1^2 - a_0^2}$$

The divergent section has an angle of 5 to 15 degrees. The deviation angle is less than the convergence angle because the length of the deviation cone is larger than the convergence cone. The main reason for the small deviation angle is to avoid isolation of the flow from the walls.

5.4.3 Flow nozzle

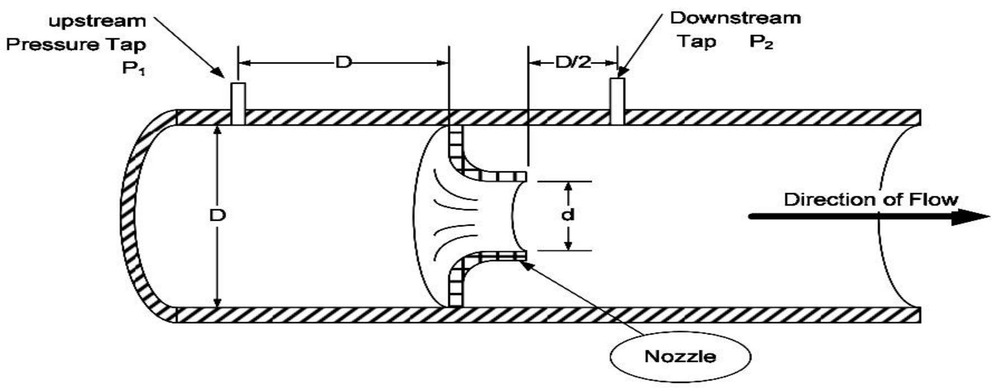

Fig. 5.37 Flow nozzle

[source: https://instrumentationforum.com/t/nozzle-flow-meter-equations/6167]

Flow nozzle is similar to the venturi meter. Its shape provides lesser resistance to flow, and it has a higher coefficient of discharge. Moreover, it has no divergent cone for pressure recovery. Figure shows a standard flow nozzle.

Nozzle meter is bolted between flanges of pipe carrying the fluid. The pressures on upstream and downstream (P1and P2) are noted by using a differential pressure sensor for the calculation of flow rate.

$$\text{Flow rate, } Q = C_d.\ a_1.\ a_2 \sqrt{2gx} \ / \sqrt{a_1^2 - a_0^2}$$

Applications of the Flow Nozzle

- They can use for measurement of flow rate of fluid that has suspended solid particle.
- It can be used in high temperature and pressure fluid flow conditions. In high-velocity fluid flow, where turbulence is high and erosion may cause on other primary devices.
- Flow Nozzle is used when fluid is discharged to the open atmosphere.

Advantages

- Compact - Low dimension as compared to venturi meter.
- Cheaper and easy to install as compared to venturi meter.
- High coefficient of discharge than the orifice meter.
- Less susceptible to wear.

Disadvantages

- It has no divergent outlet and hence low-pressure recovery.
- It cannot be used in a low-pressure head.
- It cannot use as a flow meter if the fluid has a high percentage of the solid particle.

5.4.4 Rotameter

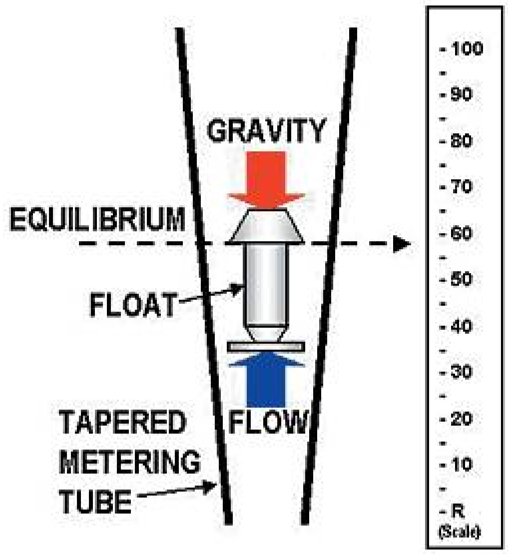

Fig. 5.38 Rotameter

[source: https://instrumentationforum.com/t/nozzle-flow-meter-equations/6167]

Rotameter is a device which is used in chemical and related industries in order to measure the flow rate or average velocity of the flowing fluid.

Rotameter is a simple equipment which consists of a tapered tube and a float. The float is placed inside the tube and usually nets are placed at both the ends of the tube. This arrangement can be connected with a pipe line with flanged connections. Rotameters are always installed vertically in the pipelines. A scale is marked on the tube to read the values of flow rate directly.

Working

When the fluid is not flowing then the float rests at the bottom of the rotameter. The fluid is made to pass through the rotameter such that the direction of flow of the fluid is parallel to the axis of the rotameter.

The flow of fluid through the rotameter causes the float to move along with the fluid. There are two primary forces involved, an upward drag force due to the motion of the fluid in upward direction and a downward force due to gravity which is due to the weight of the float itself. When these forces are balanced then the float moves to a particular location in the tube and it stays right there because it has achieved dynamic equilibrium.

In case it happens that the flow rate of fluid flowing through the rotameter is very high then it may happen that the float may get swept along with the fluid. The nets attached to either side of the rotameter ensure that the float does not get carried away in the pipe line. If it happens then it may get stuck near a valve in pipeline and cause blockage or enter equipment down the line and cause it to malfunction. A down side of net is that if the flow rate of flowing fluid is very high then the float will get stuck near the net and act as a blockage for the fluid flow, this may cause the flanges to get weakened and the liquid may start showering at the site of rupture.

Advantages

- It is simple to install and is easy and cheap to maintain.
- It has a linear scale over large range of flow rates.
- The pressure drop across the float is constant. Hence the pressure loss due to the float itself is quite small.
- Rotameters are very versatile; they can be easily sized or their use can be changed for different systems.

Disadvantages

- It requires a certain minimum magnitude of flow rate of fluid below which the float would fall and just stick to the rotameter.
- If opaque fluid is used then the scale is not properly visible, it may cause misreading the meter.
- It cannot be installed in a horizontal position.
- If flow rate of fluid is very high, then glass tubes may be subject to breakage.

5.4.5 Electromagnetic flow meter

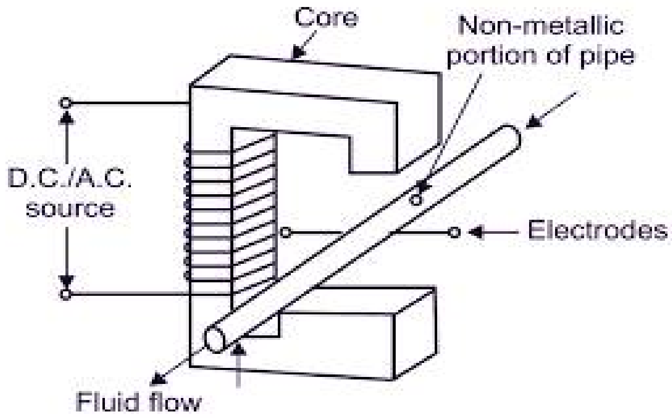

Fig. 5.39 Electromagnetic flow meter

[source: https://electricalworkbook.com/electromagnetic-flow-meter/]

Principle

Magnetic flow meters works based on Faraday's Law of Electromagnetic Induction. According to this principle, when a conductive medium passes through a magnetic field B, a voltage E is generated which is proportional to the velocity v of the medium, the density of the magnetic field and the length of the conductor.

In a magnetic flow meter, a current is applied to wire coils mounted within or outside the meter body to generate a magnetic field. The liquid flowing through the pipe acts as the conductor and this induces a voltage which is proportional to the average flow velocity.

This voltage is detected by sensing electrodes mounted in the flow meter body and sent to a transmitter which calculates the volumetric flow rate based on the pipe dimensions.

we can state Faraday's law as

E is proportional to V x B x L

[E is the voltage generated in a conductor, V is the velocity of the conductor, B is the magnetic field strength and L is the length of the conductor].

It is very important that the liquid flow that is to be measured using the magnetic flow meter must be electrically conductive. The Faraday's Law indicates that the signal voltage (E) is dependent on the average liquid velocity (V), the length of the conductor (D) and the magnetic field strength (B). The magnetic field will thus be established in the cross-section of the tube.

Electromagnetic flow meters use Faraday's law of electromagnetic induction for making a flow measurement. Faraday's law states that, whenever a conductor of length 'l' moves with a velocity 'v' perpendicular to a magnetic field 'B', an emf 'e' is induced in a mutually perpendicular direction which is given by

$e = Blv$

where

B = Magnetic flux density (Wb/m2)

l = length of conductor (m)

v = Velocity of the conductor (m/s)

Advantages of Electromagnetic Flow Meter

(i) The obstruction to the flow is almost nil and therefore this type of meters can be used for measuring heavy suspensions, including mud, sewage and wood pulp.

ii) There is no pressure head loss in this type of flow meter other than that of the length of straight pipe which the meter occupies.

(iii) They are not very much affected by upstream flow disturbances.

(iv) They are practically unaffected by variation in density, viscosity, pressure and temperature.

(v) Electric power requirements can be low (15 or 20 W), particularly with pulsed DC types.

(vi) These meters can be used as bidirectional meters.

(vii) The meters are suitable for most acids, bases, water and aqueous solutions because the lining materials selected are not only good electrical insulators but also are corrosion resistant.

(viii) The meters are widely used for slurry services not only because they are obstruction less but also because some of the liners such as polyurethane, neoprene and rubber have good abrasion or erosion resistance.

(ix) They are capable of handling extremely low flows.

Disadvantages of Magnetic Flow Meter

(i) These meters can be used only for fluids which have reasonable electrical conductivity.

(ii) Accuracy is only in the range of ± 1% over a flow rate range of 5%.

(iii) The size and cost of the field coils and circuitry do not increase in proportion to their size of pipe bore. Consequently, small size meters are bulky and expensive.

Applications of Magnetic Flow Meters

This electromagnetic flow meter being non-intrusive type, can be used in general for any fluid which is having a reasonable electrical conductivity above 10 microsiemens/cm.

Fluids like sand water slurry, coal powder, slurry, sewage, wood pulp, chemicals, water other than distilled water in large pipe lines, hot fluids, high viscous fluids specially in food processing industries, cryogenic fluids can be metered by the electromagnetic flow meter.

5.4.6 Hot Wire Anemometer

Principle

Hot Wire Anemometer works When an electrically heated wire is placed in a flowing gas stream, heat is transferred from the wire to the gas and hence the temperature of the wire reduces, and due to this, the resistance of the wire also changes. This change in resistance of the wire becomes a measure of flow rate.

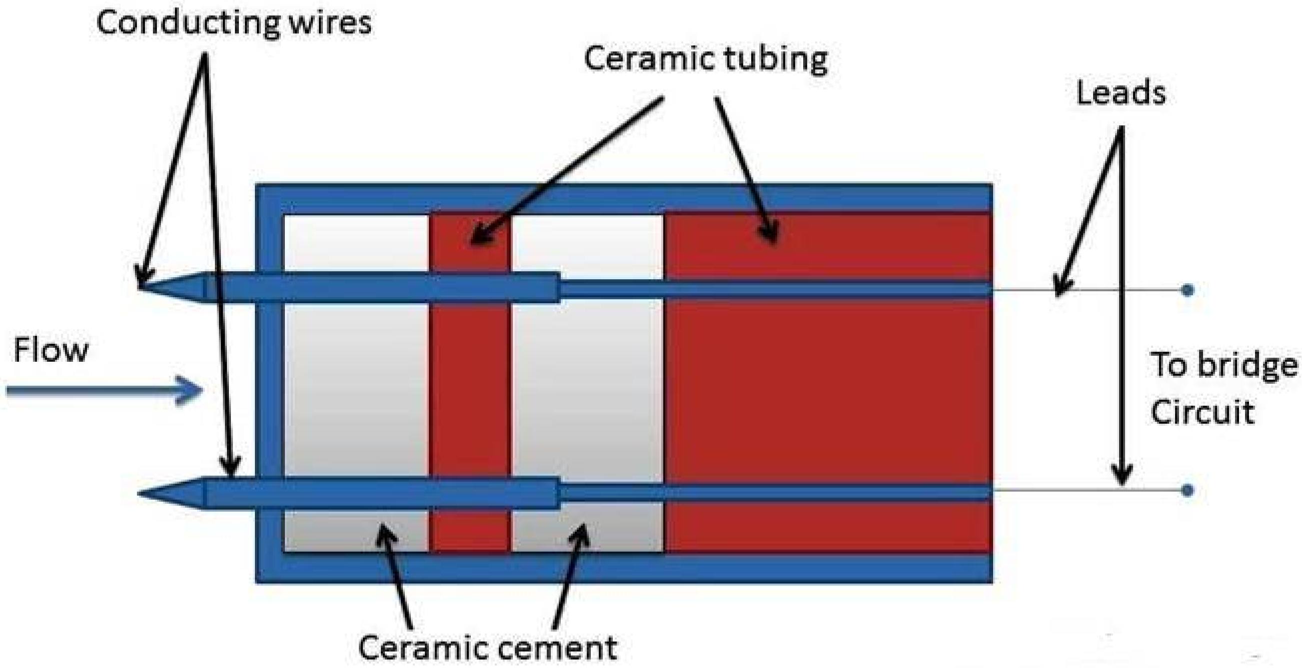

Fig. 5.40 Hot Wire Anemometer

[source: https://instrumentationtools.com/hot-wire-anemometer-principle/]

The main parts of the arrangement are as follows:

- Conducting wires placed in a ceramic body.
- Leads are taken from the conducting wires and they are connected to one of the limbs of the wheat stone bridge to enable the measurement of change in resistance of the wire.

Types of Hot wire Anemometer

There are two methods of measuring flow rate using a anemometer bridge combination namely:

- Constant current method
- Constant temperature method

5.4.6.1 Constant current method Hot wire Anemometer

The bridge arrangement along with the anemometer has been shown in diagram. The anemometer is kept in the flowing gas stream to measure flow rate.

A constant current is passed through the sensing wire. That is, the voltage across the bridge circuit is kept constant, that is, not varied.

Due to the gas flow, heat transfer takes place from the sensing wire to the flowing gas and hence the temperature of the sensing wire reduces causing a change in the resistance of the sensing wire. (this change in resistance becomes a measure of flow rate).

Due to this, the galvanometer which was initially at zero position deflects and this deflection of the galvanometer becomes a measure of flow rate of the gas when calibrated.

5.4.6.2 Constant temperature method

The bridge arrangement along with the anemometer has been shown in diagram. The anemometer is kept in the flowing gas stream to measure flow rate.

A current is initially passed through the wire.

Due to the gas flow, heat transfer takes place from the sensing wire to the flowing gas and this tends to change the temperature and hence the resistance of the wire.

The principle in this method is to maintain the temperature and resistance of the sensing wire at a constant level. Therefore, the current through the sensing wire is increased to bring the sensing wire to have its initial resistance and temperature.

The electrical current required in bringing back the resistance and hence the temperature of the wire to its initial condition becomes a measure of flow rate of the gas when calibrated.

5.4.7 Pitot Tube

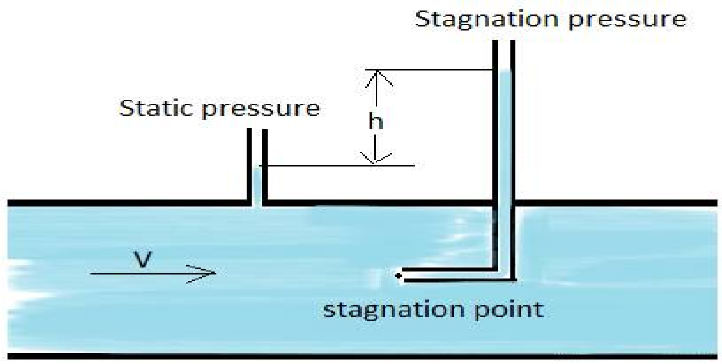

Fig. 5.41 Pitot Tube

[source: https://www.mecholic.com/2017/05/pitot-tube-construction-working-principle.html]

Construction of pitot tube

It is basically a fluid velocity measuring instrument that can also be used for flow measurement of liquids and gases. It consists of two hollow tubes that sense pressure at different places within the pipe. These hollow tubes can be mounted separately in a pipe or installing together in one casing as a single device. One tube measures the stagnation or impact pressure and another tube measures only static pressure usually at the wall of the pipe.

Working principle of Pitot tube

When a solid body is kept centrally, and stationery in a pipeline with flowing fluid, the velocity of the fluid starts reducing (at the same time the pressure fluid increases due to the conversion of kinetic energy into pressure energy) due to the presence of the body. At directly in front of the solid body, the velocity becomes zero. This point is known as the stagnation point. The fluid flow can be measured by measuring the differences between the pressure at the normal flow line (static pressure) and the stagnation point (stagnation pressure).

Pitot tube velocity equation

The equation of velocity is derived by applying Bernoulli's principle; the final equation is given below

Velocity,
g = acceleration due to gravity

Actual velocity,
Cv = Coefficient velocity of pitot tube

The operating principle of pitot tube: conversion of kinetic head into pressure head

Applications of pitot tube

The pitot tube is used in utility streams where high accuracy is not necessary. It is used in the air duct and pipe system. It is used in aircraft to measure air flow velocity. They are used for mapping flow profile in a channel or duct.

Advantages

- Economical to install
- Do not contain moving parts; this minimizes the frictional loss.
- Easy to install. Due to its small size, It can introduce to fluid flow without shutting down the flow.
- Loss of pressure is very small.
- Can be easily installed in extreme environment, high temperature and pressure conditions
- Some types can also be easily removed from the pipeline.

Disadvantages/limitation of pitot tubes

- Low sensitivity and Poor accuracy. It requires high-velocity flow.
- Not suitable for dirty or sticky fluid like sewage disposal.
- Sensitivity disturbed by flow direction
- Pitot tubes have found limited applications in industries because they can easily become clogged with foreign materials in the liquid.
- There is no standardization for pitot tube
- Change in velocity profile may cause significant errors. Due to change in velocity profile, it develops a very low differential pressure which is difficult to measure.

5.4.8 Ultrasonic Flow Meter

Ultrasonic flow meter principle is based on the use and analysis of ultrasonic waves. Such ultrasound is in the range above 20,000 Hz and can reach up to 1000 MHz.

There are several principles of flow rate measurement (it will be described below) but all systems have the same main sensing parts:

- Signal source
- Receiver
- Transducer (controller)

The principle of operation is based on a signal from the source that passes through stream and goes to receiver. Then it goes to the transducer, which analyzes result.

For such work, several pairs of sensors are usually installed. They are located against each other and exchange signals. The most often they are located diagonally from the pipeline axis.

Such an arrangement makes it possible to exchange sound signals both in the direction of the substance flow and against it. When pipeline is empty, both signals pass this distance with the same speed.

When the substance moves through pipe, the sound along the flow accelerates. Such impulse directed against the flow moves more slowly. The greater flow velocity, the greater the time difference between these signals.

The ratio of these values is proportional to the flow rate. Hence, if you know the pipe section dimensions and the substance characteristics, you can determine the flow rate.

Ultrasonic flow meter types

There are three main types of ultrasonic flowmeters depending on their working principle:

- Transit-time
- Doppler

5.4.8.1 Ultrasonic Doppler flow meters

Doppler flow meters are operating, using Doppler Effect. In nutshell, this effect is based on the changing in sound waves coming from moving objects to the stationary position. You can observe this effect too, listening to the changing sound of the passing nearby car's engine.

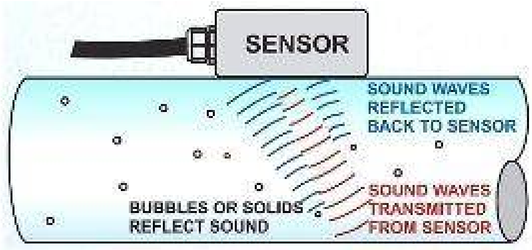

Fig. 5.42 Ultrasonic Doppler flow meters

[source: https://www.nz-online.co.za/industrial-instruments/flow-meters-liquids/clamp-on-ultrasonic-flow-meter-for-liquids-with-bubbles-solids-or-slurries.html]

Doppler flow meter need a presence of solid parts or air bubbles to work. It has emitting transducer (signal source) and receiving transducer (receiver). The emitting transducer generates and sends ultrasound impulse. That impulse reflects from moving by solid parts or bubbles. The form of ultrasonic wave changes depending on velocity of the parts. Then the echo signal returns to the receiver. The device can determine speed of the entire flow by analyzing such waves.

The main plus of Doppler flow meters is their ability to work with solid parts and air bubbles in the stream. They are the most popular as blood and carbonated water flow meters.

54.8.2 Transit time ultrasonic flow meter

Transit time flow meters' measure velocity, calculating time of signal travel signal between two sensors. Such sensors are placed opposite each other and diagonally to the flow axis. There are two main methods:

- Diagonal mode
- Reflection Mode

Diagonal mode is method when sensors send signals directly to each other through the flow.

Reflection mode is method when signals from sensors are first reflected off the pipe's wall and then sent to the opposite sensor.

Let's look at the principle using direct contact (diagonal mode) as an example. Each of the sensors works as a signal source and receiver. They send an ultrasonic pulse through the moving flow.

When sensors send the ultrasonic pulse through the moving flow they have different travel times depending on direction. Such signal accelerates when directed along the flow (upstream) and slows down when directed against it (downstream).

This difference in receiving time (Δ time) between two signals is proportional to the average flow velocity. When there is no flow in pipe, the travel time of both signals will be the same (Δ time = 0).

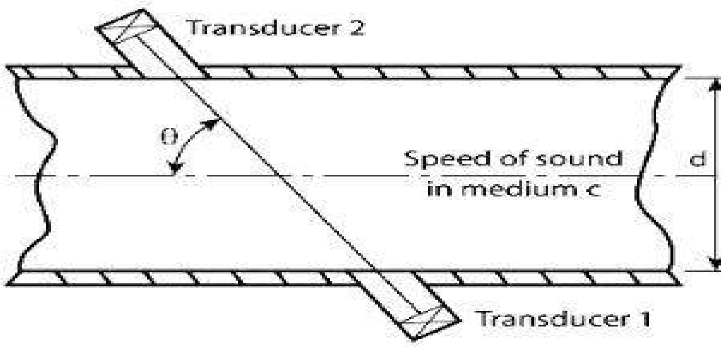

Fig. 5.43 Transit time ultrasonic flow meter

[source: https://eltra-trade.com/blog/what-is-ultrasonic-flow-meter]

Transit time flow meters is an ideal solution for pure liquids or gases. The presence of solid parts or bubbles effects on its results. Transit time flow meters are used to measure gas, steam and vapours.

5.4.9 Other Flow Measurements

5.4.9.1 Current Meter.

A current meter is used to measure the velocity of flow in the channel. it consists of a wheel or revolving element on which the conical buckets of V shaped vanes are fixed. So, the current meters are classified on the basis of revolving element such as

1. Cup type current meter
2. Screw or propeller type current meter

5.4.9.1.1 Cup type current meter

In this case, series of conical cups called revolving element are mounted on a spindle vertically at right angle to the direction of flow.

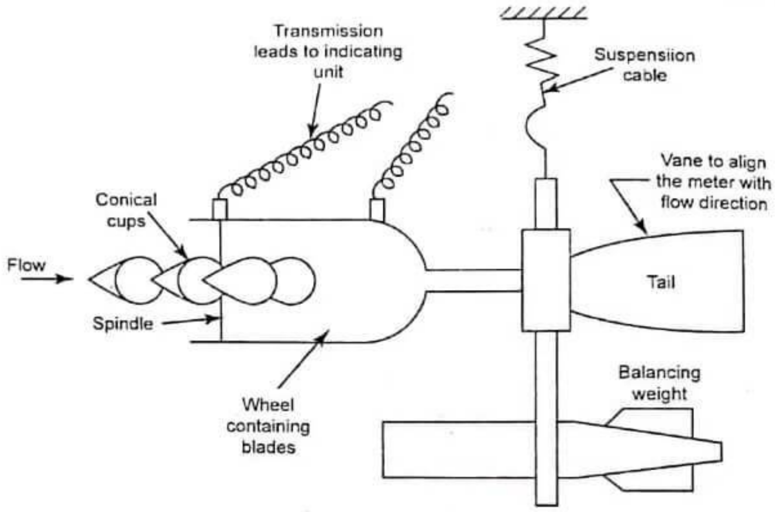

Fig. 5.44 Cup type current meter

[source: https://theteche.com/current-meter-is-used-to-measure/]

5.4.9.1.2 Screw or Propeller Type Current Meter

In a screw or propeller type current meter, the revolving element has of a shaft with its axis parallel to the direction of flow. It has a number of curved vanes or propeller blades mounted around the periphery of the shaft. The current meter unit is immersed or suspended vertically to the required depth in flowing stream of water by cables.

It means, the revolving element is placing to face towards the upstream direction. Due to the dynamic thrust exerted on the wheel, it is rotated. So, the number of per unit time is proportional to the velocity of the revolutions of the wheel flowing water. Then the number of revolutions of the wheel per unit time is noted. It is further calibrated to obtain the velocity of flow of water. To count the number of revolutions of the wheel, an electrical transmission system is adopted.

5.4.10 Laser Doppler Anemometer (LDA)

Laser Doppler Anemometer enables the measurement of instantaneous velocity of a gas or a liquid flowing in a glass walled channel. It offers the non-disturbance advantages of optical methods while affording a very precise quantitative measurement of local flow velocity. This instrument is the most recent advancement in the area of flow measurement especially measurement of high frequency turbulence fluctuations.

The theory of Laser Doppler Anemometer (LDA) is based on the principle of Doppler shift. It involves the focusing of laser beams at the point where the velocity is to be measured and then sensing with a photo detector the light scattered by thin particles carried along with the fluid as it passes through the laser focal point. The velocity of particles which is assumed to be equal to the fluid velocity causes a Doppler shift of the frequency of the scattered light a and produces a photo detector signal related to the velocity.

It is not necessary to insert artificial tracer particles always to function this instrument because normally microscopic particles are present in liquids may be sufficient. However, it may become essential to insert artificial particles from outside in case of gases. It is obvious that the Laser Doppler Anemometer measures the velocity of scattering particles. Under extreme conditions, particles may not perfectly follow the flow and therefore there may be errors in measurement of flow velocity. By providing smaller particles, almost accurate indication of fluid velocity may be obtained as the slip velocity between particles and fluid will be small.

There are two distinct approaches in vogue to explain the working of an LDA. These are:

i. Reference beam mode, and
ii. Interference fringe mode.

5.4.10.1 Reference beam mode

In this mode, laser light is split into two beams which are directed at the point of measurement in the field at an angle θ. The light scattered in the direction of reference beam is picked up and photo-mixed in the Photo-Multiplier Tube (PMT) with the reference beam propagating in the same direction as shown in fig.

The photo multiplier tube yields a signal at the Doppler frequency. The reference beam need not traverse through the same volume but it can be added to the scattered beam at PMT. The reference beam strength is considerably smaller than that of the other beam so that scattered beam is relatively stronger and a good heterodyne signal from PMT is obtained.

This mode of operation can be used with advantages when the suspension density is fairly high. Further, the alignment tolerance required for the heterodyne process is not so critical. Thus, this mode of operation is relatively easy to use.

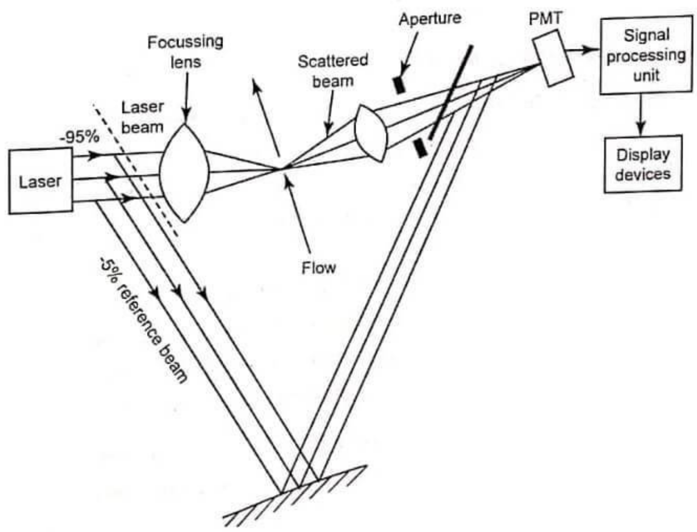

Fig. 5.45 Reference beam mode of LDA

[source: https://theteche.com/laser-doppler-anemometer-lda/]

5.4.10.2 Interference fringe mode

Working principle of the interference fringe mode gives a better insight of the appearance of Doppler signal. Fig. shows the diagram of fringe mode anemometer. In this anemometer, the laser beam is split into two equal intensity such as parallel beams with the help of two coated optical flat (called beam splitter). A lens focuses the beams at a point where the velocity of flow fluid is to be measured. The scattered beam of light moving through the fringe pattern is selectively collected by a combination of lens and the hole aperture. It is then detected by a PMT. The light intensity verses time is displayed on a display device.

In both the cases, the laser source employed is usually helium-neon (He-Ne) gas laser although argon ion lasers provide a more intense beam output.

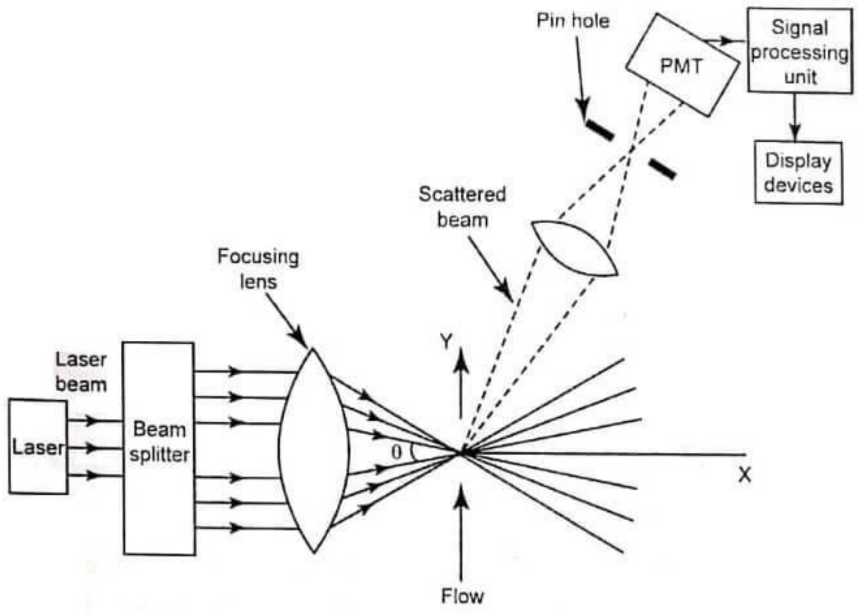

Fig. 5.46 Interference fringe mode of LDA

[source: https://theteche.com/laser-doppler-anemometer-lda/]

Advantages

1. It measures only the velocity.
2. Volume of sensing part is very small.
3. There is no addition of physical object to avoid disturbances.
4. It has very high accuracy.
5. It has a high frequency response.
6. It is used to measure both the flow of liquids and gases.

Disadvantages

1. It involves the use of transparent channels.
2. There is no using of tracer particles to divert the light beam.
3. Cost is high and it has a high degree of complexity.

Applications

1. For investigating the boundary layers and shock wave interaction.
2. For determining the 3-D wing tip vortices near tips of wings of aircrafts.

3. For measuring the flow between blades of a turbine.
4. Combustion and flame phenomena in gas turbines.
5. Jet propulsion systems.
6. For measuring the blood flows.
7. In remote sensing of wind velocities.

5.5 TEMPERATURE MEASUREMENT

Measurement of temperature cannot be accomplished by direct comparison with basic standards such as length and mass. A standardized calibrated device or system is necessary to determine temperature. In order to measure temperature, various primary effects that cause changes in temperature can be used. The temperature may change due to changes in physical or chemical states, electrical property, radiation ability, or physical dimensions. The response of the temperature-sensing device is influenced by any of the following factors:

1. Thermal conductivity and heat capacity of an element
2. Surface area per unit mass of the element
3. Film coefficient of heat transfer
4. Mass velocity of a fluid surrounding the element
5. Thermal conductivity and heat capacity of the fluid surrounding the element

Temperature can be sensed using many devices, which can broadly be classified into two categories: contact- and non-contact-type sensors. In case of contact-type sensors, the object whose temperature is to be measured remains in contact with the sensor. Inference is then drawn on the assessment of temperature either by knowing or by assuming that the object and the sensor are in thermal equilibrium. Contact-type sensors are classified as follows:

1. Thermocouples
2. Resistance temperature detectors (RTDs)
3. Thermistors
4. Liquid-in-glass thermometers
5. Pressure thermometers
6. Bimetallic strip thermometers

In case of non-contact-type sensors, the radiant power of the infrared or optical radiation received by the object or system is measured. Temperature is determined using instruments such as radiation or optical pyrometers. Non-contact-type sensors are categorized as follows:

1. Radiation pyrometers
2. Optical pyrometers
3. Fibre-optic thermometers

5.5.1 THERMOCOUPLES

Thermocouples are active sensors employed for the measurement of temperature. The thermoelectric effect is the direct conversion of temperature differences to an electric voltage. In 1821, Thomas Johan See beck discovered that when two dissimilar metals are joined together to form two junctions such that one junction (known as the hot junction or the measured junction) is at a higher temperature than the other junction (known as the cold junction or the reference junction), a net emf is generated. This emf, which also establishes the flow of current, can be measured using an instrument connected as shown in Fig. The magnitude of emf generated is a function of the junction temperature. It is also dependent on the materials used to form the two junctions. The thermoelectric emf is a result of the combination of two different effects the Peltier effect and the Thomson effect.

The French physicist Jean Charles Athanase Peltier discovered that if two dissimilar metals are connected to an external circuit in a way such that a current is drawn, the emf may be slightly altered owing to a phenomenon called Peltier effect. A potential difference always exists between two dissimilar metals in contact with each other. This is known as the Peltier effect.

Thomson found out that the emf at a junction undergoes an additional change due to the existence of a temperature gradient along either or both the metals. The Thomson effect states that even in a single metal a potential gradient exists, provided there is a temperature gradient.

Both these effects form the basis of a thermocouple, which finds application in temperature measurement. The flow of current through the circuit is spontaneous when two dissimilar metals are joined together to form a closed circuit, that is, a thermocouple, provided one junction is maintained at a temperature different from the other. This effect is termed the See beck effect.

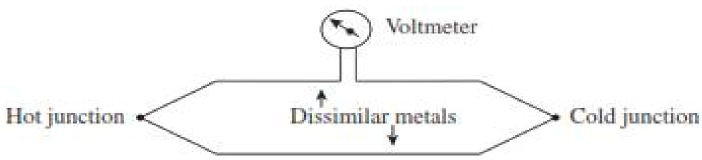

Fig. 5.47 Basic thermocouple circuit

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 367]

If temperatures at the hot junction (T_1) and the cold junction (T_2) are equal and at the same time opposite, then there will not be any flow of current. However, if they are unequal, then the emfs will not balance and hence current will flow. It is to be mentioned here that the voltage signal is a function of the junction temperature at the measured end and the voltage increases as the temperature rises. Variations in emf are calibrated in terms of temperatures; the devices employed to record these observations are termed thermocouple pyrometers.

Laws of Thermocouples

Apart from the Peltier and Thomson effects, which form the basis of thermoelectric emf generation, three laws of thermocouples that govern this phenomenon are required to be studied in order to understand their theory and applicability. They also provide some useful information on the measurement of temperature.

Law of Homogeneous Circuit

This law states that a thermoelectric current cannot be sustained in a circuit of a single homogenous material, regardless of the variation in its cross section and by the application of heat alone. This law suggests that two dissimilar materials are required for the formation of any thermocouple circuit.

Law of Intermediate Metals

If an intermediate metal is inserted into a thermocouple circuit at any point, the net emf will not be affected provided the two junctions introduced by the third metal are at identical temperatures. This law allows the measurement of the thermoelectric emf by introducing a device into the circuit at any point without affecting the net emf, provided that additional junctions introduced are all at the same temperature.

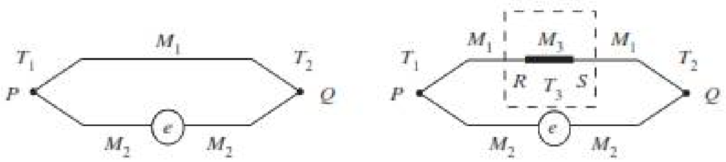

Fig. 5.48 Basic thermocouple circuit

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 368]

It is clear from Fig. that when a third metal, M_3, is introduced into the system, two more junctions, R and S, are formed. If these two additional junctions are maintained at the same temperature, say T , the net emf of the thermocouple circuit remains unaltered.

Law of Intermediate Temperatures

If a thermocouple circuit generates an emf e_1 when its two junctions are at temperatures T_1 and T_2, and e_2 when the two junctions are at temperatures T_2 and T_3, then the thermocouple will generate an emf of $e_1 + e_2$ when its junction temperatures are maintained at T_1 and T_3.

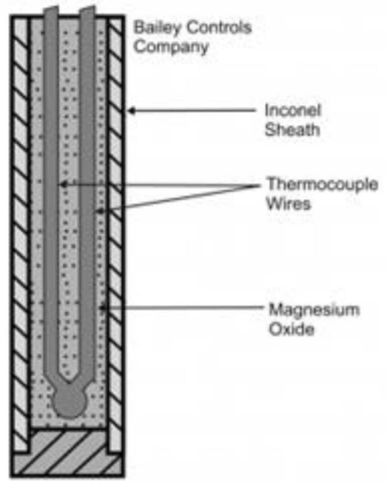

Fig. 5.49 Law of intermediate temperatures

[source: https://www.elprocus.com/what-is-a-thermocouple-definition-working-principle-diagram-applications/]

This law pertains to the calibration of the thermocouple and is important for providing reference junction compensation. This law allows us to make corrections to the thermocouple readings when the reference junction temperature is different from the temperature at which the thermocouple was calibrated. Usually while preparing the calibration chart of a thermocouple, the reference or cold junction temperature is taken to be equal to 0 °C. However, in practice, the reference junction is seldom maintained at 0 °C; it is usually maintained at ambient conditions. Thus, with the help of the third law, the actual temperature can be determined by means of the calibration chart.

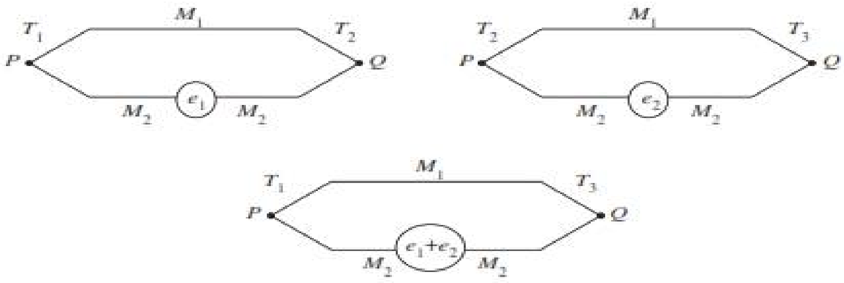

Fig. 5.50 Law of intermediate temperatures

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 369]

Advantages

The advantages of thermocouples include the following.

- Accuracy is high
- It is Robust and can be used in environments like harsh as well as high vibration.
- The thermal reaction is fast
- The operating range of the temperature is wide.
- Wide operating temperature range
- Cost is low and extremely consistent

Disadvantages

The disadvantages of thermocouples include the following.

- Nonlinearity
- Least stability
- Low voltage
- Reference is required
- least sensitivity
- The thermocouple recalibration is hard

Applications

Some of the **applications of thermocouples** include the following.

- These are used as the temperature sensors in thermostats in offices, homes, offices & businesses.

- These are used in industries for monitoring temperatures of metals in iron, aluminium, and metal.
- These are used in the food industry for cryogenic and Low-temperature applications. Thermocouples are used as heat pumps for performing thermoelectric cooling.
- These are used to test temperature in chemical plants, petroleum plants.
- These are used in gas machines for detecting the pilot flame.

5.5.2 Thermopiles

An extension of thermocouples is known as a thermopile. A thermopile comprises a number of thermocouples connected in series, wherein the hot junctions are arranged side by side or in a star formation. In such cases, the total output is given by the sum of individual emfs. The advantage of combining thermocouples to form a thermopile is that a much more sensitive element is obtained. For example, a sensitivity of 0.002 °C at 1 mV/°C can be achieved with a chromel–constantan thermopile consisting of 14 thermocouples. If n identical thermocouples are combined to form a thermopile, then the total emf will be n times the output of the single thermocouple.

For special-purpose applications such as measurement of temperature of sheet glass, thermopiles are constructed using a series of semiconductors. For average temperature measurement, thermocouples can be connected in parallel. During the formation of a thermopile, one has to ensure that the hot junctions of the individual thermocouples are properly insulated from one another.

A thermopile having a series connection and one having a star connection

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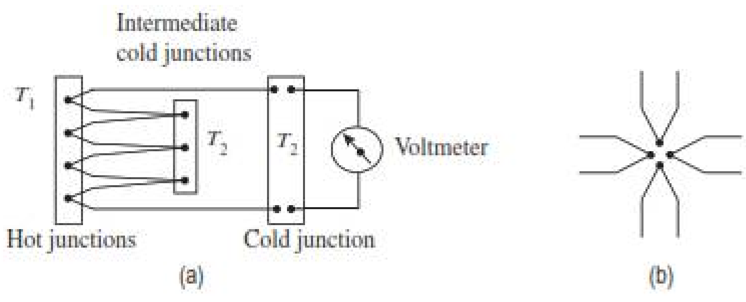

Fig. 5.51 Thermopiles (a) Series connection (b) Star connection

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 371]

5.5.3 RESISTANCE TEMPERATURE DETECTORS(RTDs)

RTDs are also known as resistance thermometers. The American Society for Testing and Materials has defined the term resistance thermometer as follows: RTD is ‘a temperature measuring device composed of a resistance thermometer element, internal connecting wires, a protective shell with or without means for mounting a connection head, or connecting wire or other fittings, or both’.

We know that the electrical conductivity of a metal is dependent on the movement of electrons through its crystal lattice. An RTD is a temperature sensor that works on the principle that the resistance of electrically conductive materials is proportional to the temperature to which they are exposed. Resistance of a metal increases with an increase in temperature. Hence, metals can be classified as per their positive temperature coefficient (PTC).

When temperature measurement is performed by a resistance thermometer using metallic conductors, it is called a resistance temperature detector (RTD); on the other hand, semiconductors used for temperature measurement are called thermistors.

We know that an RTD measures temperature using the principle that the resistance of a metal changes with temperature. In practice, the RTD element or resistor that is located in proximity to the area where the temperature is to be measured transmits an electrical current.

Then, using an instrument, the value of the resistance of the RTD element is measured. Further, on the basis of known resistance characteristics of the RTD element, the value of the resistance is correlated to temperature. RTDs are more rugged and have more or less linear characteristics over a wide temperature range.

The range of RTDs is between 200 and 650°C. Many materials are commonly used for making resistance thermometers, such as platinum, nickel, and copper, which are contained in a bulb.

However, platinum is the most popular and internationally preferred material. When platinum is employed in RTD elements, they are sometimes termed platinum resistance thermometers.

The popularity of platinum is due to the following factors:

1. Chemical inertness

2. Almost linear relationship between temperature and resistance

3. Large temperature coefficient of resistance, resulting in readily measurable values of resistance changes due to variations in temperature

4.Greater stability because the temperature resistance remains constant over a long period of time

Selection of a suitable material for RTD elements depends on the following criteria:

1. The material should be ductile so that it can be formed into small wires.

2. It should have a linear temperature-versus-resistance graph.

3. It must resist corrosion.

4. It should be inexpensive.

5. It should possess greater stability and sensitivity.

6. It must have good reproducibility.

RTDs essentially have the following three configurations:

1. A partially supported wound element: A small coil of wire inserted into a hole in a ceramic insulator and attached along one side of that hole.

2. Wire-wound RTD: Prepared by winding a platinum or metal wire on a glass or ceramic bobbin and sealed with a coating on molten glass known as wire-wound RTD elements.

3.Thin film RTD: Prepared by depositing or screening a platinum or metal glass slurry film onto a small flat ceramic substrate called thin film RTD elements.

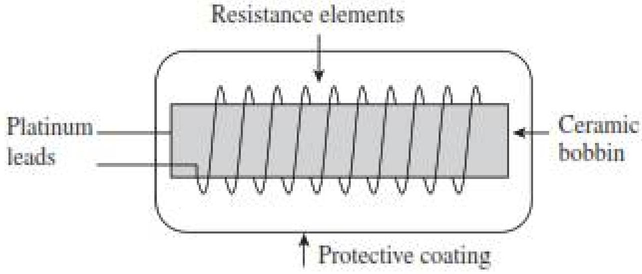

Fig. 5.52 Wire-wound RTD

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 373]

Advantages

Compared to other types of temperature sensors, RTDs have the following advantages:

1. The resistance versus temperature linearity characteristics of RTDs are higher.

2. They possess greater accuracy (as high as ±0.1 °C). Standard platinum resistance thermometers have ultra-high accuracy of around ±0.0001 °C.

3. They have excellent stability over time.

4. Resistance elements can be used for the measurement of differential temperature.

5.Temperature-sensitive resistance elements can be replaced easily.

Disadvantages

RTDs are also associated with some disadvantages. They are as follows:

1. The use of platinum in RTDs makes them more expensive than other temperature sensors.

2. The nominal resistance is low for a given size, and the change in resistance is much smaller than other temperature sensors.

3. Although its temperature sensitivity is high, it is less than that of thermistors.

5.5.4 THERMISTORS

Semiconductors that are used to measure temperature are called thermistors. When a thermistor is employed for temperature measurement, its resistance decreases with increase in temperature. The valence electrons, which are mutually shared by the metal atoms, move continuously and freely through the metal during their movement from atom to atom. The vibration in the crystal lattice of atoms increases with the increase in temperature.

The free movement of electrons becomes restricted due to an increase in the volume of space occupied by the atoms. In case of thermistors, the valence electrons are attached more firmly to the atoms; some of the electrons are detached and flow due to the increase in temperature, which decreases electrical resistance facilitating the easy flow of electrons. Materials used in thermistors for temperature measurements have very high temperature coefficients (8–10 times higher than platinum and copper) and high resistivity (higher than any pure metal).

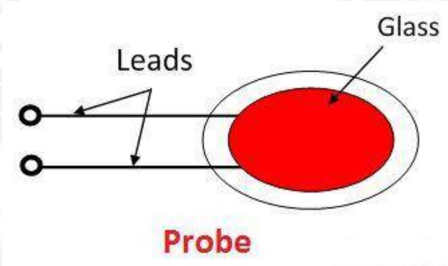

Fig. 5.53 Thermistors

[source: https://circuitglobe.com/thermistor.html]

The temperature coefficient of platinum at 25 °C is +0.0036/K and, for thermistors, it is generally around −0.045/K, which is more than 10 times sensitive when compared to platinum. A variety of ceramic semiconductor materials qualify as thermistor materials. Among them, germanium containing precise proportions of arsenic, gallium, or antimony is most preferred. The temperature measurement range of thermistors is −250 to 650 °C.

The oxides are milled into powder form and mixed with a plastic binder, which are then compressed into desired forms such as disks or wafers. Disks are formed by compressing the mixtures using pelleting machines, and the wafers are compression moulded. They are then sintered at high temperatures to produce thermistor bodies. Depending on their intended application, leads are then added to these thermistors and coated if necessary. To achieve the required stability, the thermistors so formed are subjected to a special ageing process.

Advantages

The use of thermistors as temperature sensors has several advantages:

1. Thermistors possess very high sensitivity, which is much higher than that of RTDs and thermocouples, and hence have the capability to detect very small changes in temperature.

2. Their response is very fast, and hence, they are employed for precise control of temperature.

3. They are inexpensive.

Disadvantages

Thermistors also have certain disadvantages:

1. They have highly non-linear resistance temperature characteristics.

2. The temperature range is narrow.

3. Low fragility is often a problem.

4. High-temperature performance of thermistors is not good and they exhibit instability with time.

5. They are prone to self-heating errors.

5.5.5 LIQUID-IN-GLASS THERMOMETERS

The liquid-in-glass thermometer is the most popular and is widely used for temperature measurement. It comprises a bulb that contains a temperature-sensing liquid, preferably mercury. Alcohol and pentane, which have lower freezing points than mercury and do not contaminate if the bulb is broken, are also used. Since alcohol has a better expansion coefficient than mercury, it is also used. A graduated capillary tube is connected to the bulb. At the top of the capillary, a safety or expansion bulb is provided.

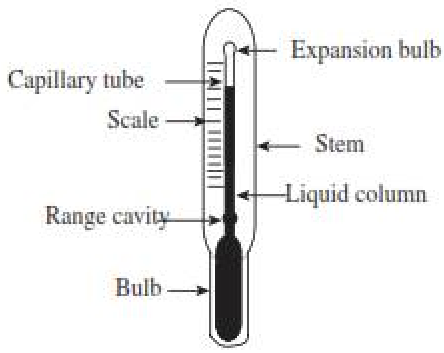

Fig. 5.54 Liquid-in-glass thermometer

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 375]

Figure shows a liquid-in-glass thermometer. A range cavity is provided just above the bulb to accommodate the range variation. The walls of the bulb should be thin in order to facilitate quick transfer of heat. Further, for the response to be quick, the volume of liquid should be small. However, the larger the volume of the liquid, the higher the sensitivity. Since speed of response depends on the volume of the liquid, a compromise needs to be made between sensitivity and response.

The entire assembly is enclosed in a casing to provide protection from breakage. An extra-long stem may be provided to facilitate easy dipping into hot liquids. Calibration of thermometers has to be carried out for better results. Liquid-in-glass thermometers are simple, portable, and inexpensive. However, they are fragile and not suitable for remote applications and sensing surface temperature. Under optimal conditions, the accuracy of this type of thermometers is around 0.1°C.

5.5.6 BIMETALLIC STRIP THERMOMETERS

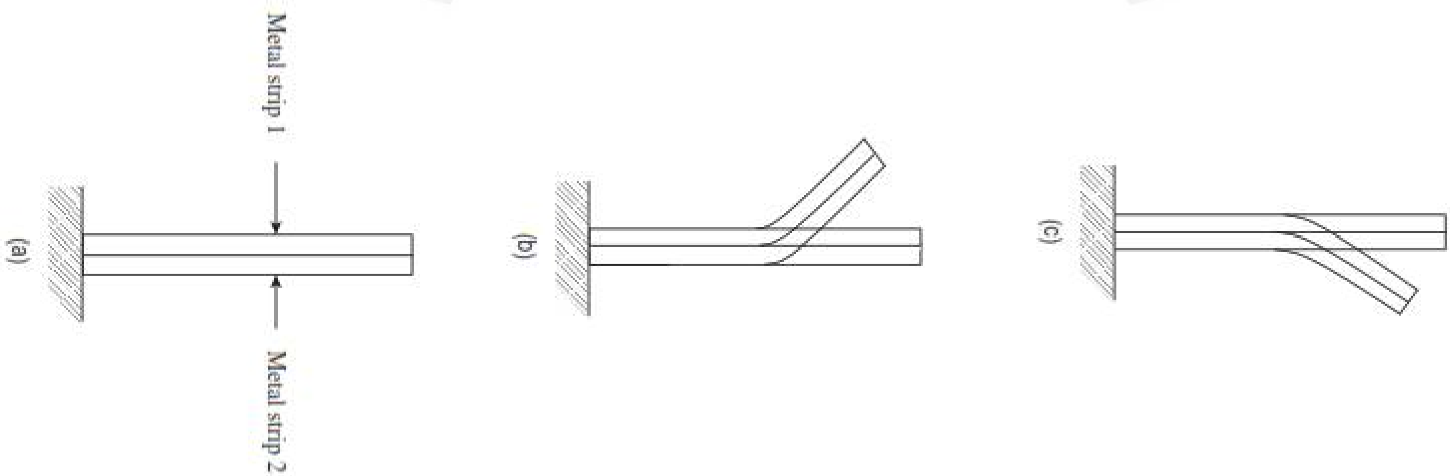

Fig. 5.55 Deflection of a bimetallic strip (a) Normal condition (b) Cold condition (c) Hot condition

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 377]

A bimetallic strip thermometer works on the well-known principle that different metals expand and contract to different degrees, depending on the coefficient of expansion of the individual metals.

For example, if two strips of two different metals (steel and copper) are firmly welded, riveted, or brazed together and subjected to temperature changes, either cooling or heating, the degree of contraction or expansion of the metals differ depending on their coefficient of expansion.

The metal strips tend to bend owing to their different coefficients of expansion; the contraction or expansion of one strip will be greater than that of the other. The difference in the expansion of two metals, which makes the strip bend, is a measure of temperature, and since two different metal strips are employed, it is called a bimetallic strip thermometer.

Bimetallic strips are manufactured in different shapes: cantilever type, flat form, U form, and helical and spiral shapes. In bimetallic strips, the lateral displacement in both the metals is much larger than the small longitudinal expansion. This effect is made use of in mechanical and electrical devices. For industrial use, the strips are wrapped around a spindle into a helical coil. Due to its coil form, the length of the bimetallic strip increases, which in turn increases its sensitivity. Bimetallic strip thermometers are preferred for their ruggedness and availability in suitable forms. These thermometers are used for sensing temperature of hot water pipes, steam chambers, etc. They are also used in temperature compensation clocks and circuit breakers.

Advantages

- The bimetallic thermometer is easily installed and maintained.
- Wide temperature ranges are available.
- The bimetallic thermometer has good accuracy.

• The cost is very low.

• It has nearly linear response

Disadvantages

• It is suitable at local mounting only.

• Indicators are used to display.

• Calibration is disturbed if roughly handled.

5.5.7 PYROMETERS

If the temperature of a very hot body has to be measured, contact-type temperature-measuring devices will not be suitable, because they are liable to be damaged when they come in contact with the hot body. Hence, the use of non-contact-type temperature-measuring devices become imperative. When such devices are employed for high-temperature measurement, the distance between the source of the temperature and the instrument has no effect on the measurement. These non-contact-type devices are called pyrometers.

Pyrometers are classified into two distinct categories:

1. Total Radiation Pyrometers and
2. Optical Pyrometers

5.5.7.1 TOTAL RADIATION PYROMETER

A total radiation pyrometer gives a measure of temperature by evaluating the heat radiation emitted by a body. All the radiations emitted by a hot body or furnace are measured and calibrated for black-body conditions. A total radiation pyrometer comprises an optical system that includes a lens, a mirror, and an adjustable eyepiece. The heat energy emitted from the hot body is focused by an optical system onto the detector. The heat energy sensed by the detector, which may be a thermocouple or a thermopile, is converted to its analogous electrical signal and can be read on a temperature display device.

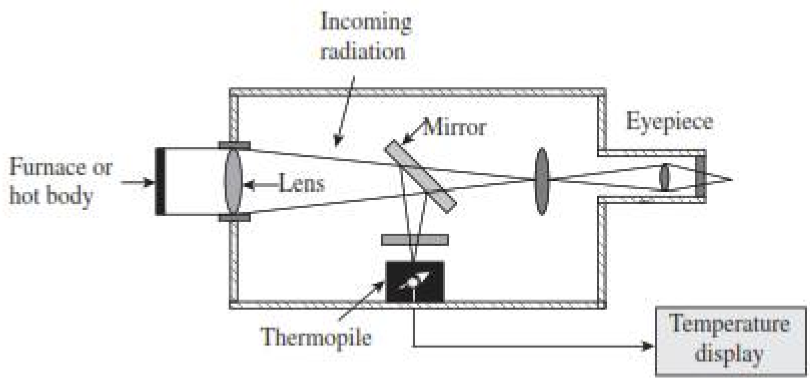

Fig. 5.56 Total radiation pyrometer

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 380]

The pyrometer has to be aligned properly such that it is in line with the furnace or hot body and is placed as close to it as possible. This is essential to minimize the absorption of radiation by the atmosphere. Radiation pyrometers find applications in the measurement of temperature in corrosive environments and in situations where physical contact is impossible. In addition, radiations of moving targets and invisible rays can also be measured. It is also used for temperature measurement when sources under consideration have near-black body conditions.

Advantages

The following are the advantages of radiation pyrometers:

1. It is a non-contact-type device.

2. It gives a very quick response.

3. High-temperature measurement can be accomplished.

Disadvantages

Radiation pyrometers also have certain disadvantages. They are as follows:

1. Errors in temperature measurement are possible due to emission of radiations to the atmosphere.

2. Emissivity errors affect measurements.

5.5.7.2 Optical Pyrometer

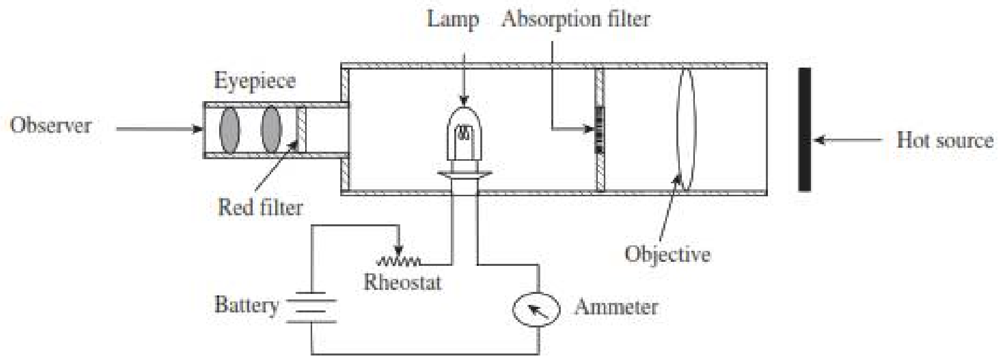

Fig. 5.57 Optical pyrometer

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 380]

Optical pyrometers work on the disappearing filament principle. In order to measure temperature, the brightness generated by the radiation of the unknown source or hot body whose temperature is to be determined is compared with that of the reference lamp. The brightness of the reference lamp can be adjusted so that its intensity is equal to the brightness of the hot body under consideration. The light intensity of the object depends on its temperature, irrespective of its wavelength. A battery supplies the current required for heating the filament. The current flowing through the filament is adjusted by means of a rheostat and an ammeter is used to measure it. The current passing through the circuit is proportional to the temperature of the unknown source.

An optical pyrometer essentially consists of an eyepiece, by means of which the filament and the source are focused so that they appear superimposed, enabling a clear view for the observer. Between the eyepiece and the reference lamp, a red filter is positioned, which helps narrow down the wavelength band and attain monochromatic conditions. An absorption filter helps operate the lamp at reduced intensity, thereby enhancing the life of the lamp.

The current in the reference lamp can be varied by operating the rheostat and can be measured using the ammeter. Thus, the intensity of the lamp can be altered. The following three situations arise depending on the current passing through the filament or lamp:

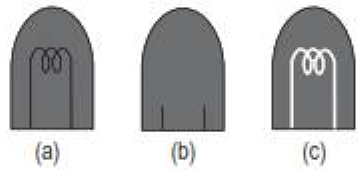

Fig. 5.58 Disappearing filament principle (a) Current passing though the filament is low (b) Current passing though the filament is exact (c) Current passing though the filament is high

[source: Engineering Metrology and Measurements, N.V. Raghavendra, Pg. No 381]

1. When the current passing through the filament is very low, the radiation emitted by the filament is of a lesser intensity than that of the source, and the filament appears dark against a bright backdrop.

2. When the current passing through the filament is exact, the intensity of the radiation emitted by the filament is equal to that of the source and hence the filament disappears into the background.

3. When the current passing through the filament is very high, the radiation emitted by the filament is of higher intensity than that of the source and the filament appears brighter than the background, as When the filament disappears, the current that flows in the circuit is measured. The value at which the filament disappears is a measure of the temperature of the radiated light in the temperature source, when calibrated.

Advantages

The advantages associated with optical pyrometers are as follows:

1. They are simple in construction and portable.

2. Optical pyrometers are flexible and easy to operate.

3. They provide very high accuracy of up to ±5 °C.

4. Since they are non-contact-type sensors, they are used for a variety of applications.

5. They can be used for remote-sensing applications, since the distance between the source and the pyrometer does not affect the temperature measurement.

6. Optical pyrometers can be employed for both temperature measurement and for viewing and measuring wavelengths that are less than 0.65 μm.

Disadvantages

The following are the disadvantages of optical pyrometers:

1. Optical pyrometers can be employed for measurement only if the minimum temperature is around 700 °C, since it is based on intensity of light.

2. Temperature measurement at short intervals is not possible.

3. Emissivity errors may affect measurement.

4. Optical pyrometers are used for the measurement of clean gases only.

5.5.8 Calibration of Temperature Measuring Devices

For calibration of temperature measuring devices, a constant temperature source should be provided. The temperature source should as a minimum be stable enough to provide a constant temperature. (approximately ±0.2°F) for a short length of time at any temperature. The temperature source should have a zone of uniform temperature into which the temperature measuring devices may be inserted. The length of the temperature source must be adequate to permit a depth of immersion sufficient to assure that the measuring junction temperature is not affected by a temperature gradient along the thermocouple wires.

These are two methods used to calibrate the temperature measuring devices.

(i) Cold temperature or ice bath check

(ii) Hot temperature check

5.5.8.1 Cold Temperature or Ice Bath Check

One of the most common methods of calibrating the temperature measuring devices is the ice bath or cold temperature check. Here, the methods of calibrating thermocouple and thermometer are given under.

The ice bath is made up of a mixture of melting shaved or crushed ice and water. The ice bath is a convenient and inexpensive way to achieve an ice point (i.e., reference junction or temperature source), it can be reproduced with ease and with exceptional accuracy.

Junctions formed between the thermocouple materials and instrument leads can be simply immersed into such mixture, or alternatively glass 'U' tubes containing a quantity of mercury approximately ¾" to 1" depth can be placed into the slush mixture. Quick electrical connection can then be made between thermocouple and instrument leads through the mercury as shown in fig,

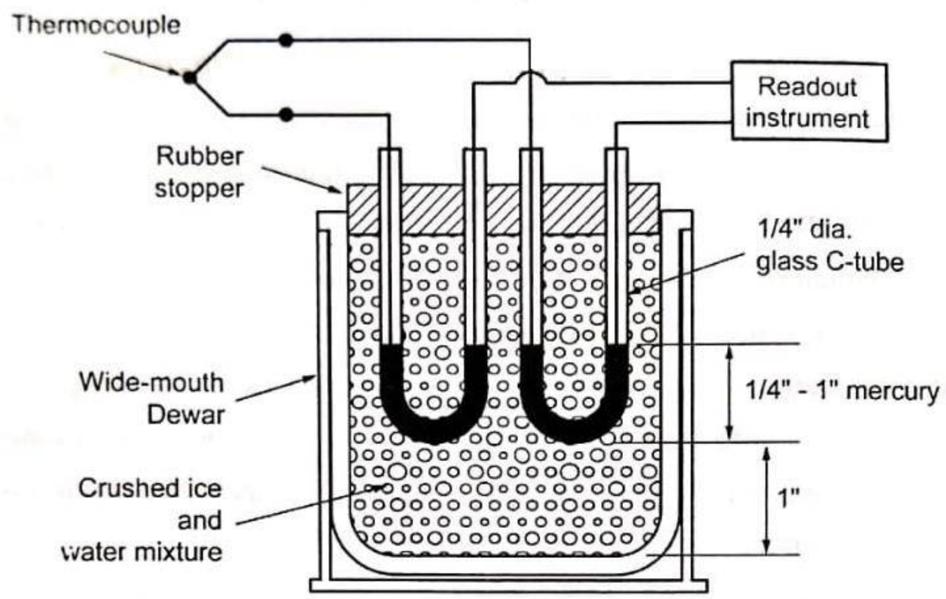

Fig. 5.59 Ice Bath Check

[source: https://theteche.com/calibration-of-temperature-measuring-devices/]

The same set up can be used to calibrate thermometer with slight modification. Place the thermometer at the centre of the container to a depth of at least 50mm and should be frequently agitated with agitator. The temperature should be noted after the reading has stabilized (after about 3 minutes) and must be between 30° to 34°F or -0.5°C to +0.5°C,

5.5.8.2 Hot Temperature Check

In this method of calibration of thermocouple, both reference thermocouple and thermocouple to be calibrated are inserted in a hot temperature source. The temperature source is a electrical furnace in which the copper blocks are kept to inert both thermocouples. The copper block is shielded by radiation resistant material to avoid radiations of the furnace walls. The electrical furnace is switched on and kept for some time for attaining constant temperature. Now, the temperature of both the thermocouple are noted and compared for calibration. The difference in temperature must be ±0.5°C.

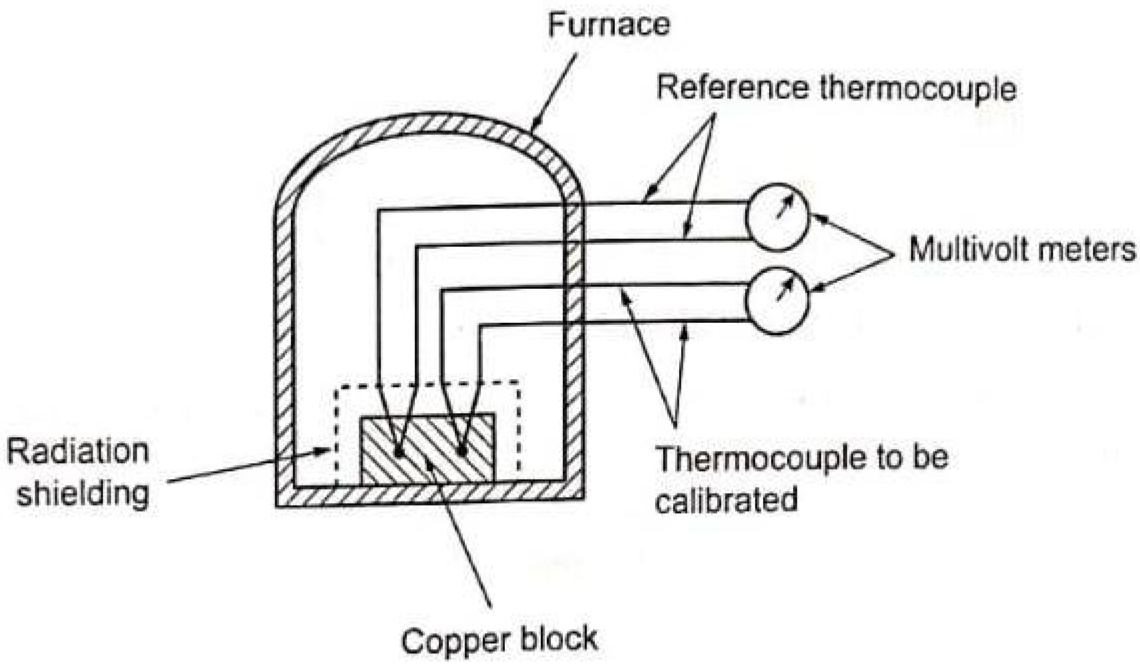

Fig. 5.60 Hot Temperature Check

[source: https://theteche.com/calibration-of-temperature-measuring-devices/]

For calibrating thermometer, a 25cm deep container of water should be brought to a rolling boil on a stove or other sources of constant heat. The thermometer to be calibrated is immersed in the water. The temperature should be noted after the reading has stabilized (after about 3 min.) and must be between 210°F to 214°F or 99.5°C to 100.5°C.