Fluid Flow Instrumentation

In the physical world, mechanical engineers are frequently required to monitor or control the flow of various fluids through pipes, ducts and assorted vessels. This fluid can range from thick oils to light gasses. While some techniques work better with some groups of fluids, and less well with others, some are not at all suitable for some applications. In this primer on fluid flow instrumentation we will look at a wide variety of flow transducers and their application in the physical world.

1.0 Fluid flow measurement

Fluid flow measurement can encompass a wide variety of fluids and applications. To meet this wide variety of applications the instrumentation industry has, over many years, developed a wide variety of instruments. The earliest known uses for flow come as early as the first recorded history. The ancient Sumerian cities of UR and Kish, near the Tigris and Euphrates rivers (around 5000 B.C.) used water flow measurement to manage the flow of water through the aqueducts feeding their cities. In this age the a simple obstruction was placed in the water flow, and by measuring the height of the water flowing over the top of the obstruction, these early engineers could determine how much water was flowing. In 1450 the Italian art architect Battista Alberti invented the first mechanical anemometer. It consisted of a disk placed perpendicular to the wind, and the force of the wind caused it to rotate. The angle of inclination of the disk would then indicate the wind velocity. This was the first recorded instrument to measure wind speed. An English inventor, Robert Hooke reinvented this device in 1709, along with the Mayan Indians around that same period of time. Today we would look down our noses at these crude methods of flow measurement, but as you will see, these crude methods are still in use today.

1.1 Types of flow measurement devices

Fluid flow devices fall into a number of device categories as well as fluid classes. In general we can split the fluids into two classes; gasses and liquids. Within these two broad classes are a number of special classes that one should be careful of. Flammable liquids and gasses require special handling, as do those that are at temperature extremes (cold or hot). When selecting a transducer you should be cautious that the device you are selecting is compatible with the fluid and conditions you hare working with. A few examples would be acids, food grade liquids, and DI water. Surprisingly de-ionized water is an extremely harsh liquid that can cause serious headaches.

The physical measurement devices come in a number of classifications. While the following classifications do not match any industry standards, they serve to break the transducers down into some reasonably functional groups. These are:

Obstruction flow meters
Velocity flow meters – Including Moving Member meters
Positive Displacement meters
Variable area meters
Electronic meters

We will spend some time at each category, looking at the particular devices that fall into that category. Some of these devices will work with a wide array of fluids, while others have significant limitations. This tutorial should help you understand what these restrictions are and when to use or not use a particular meter.

2.0 Obstruction flow meters

Obstruction flow meters are the simples and oldest of the measurement classes. One of the first obstruction flow meters was used by the ancient Samarians. In order to measure the amount of water flowing through an aquaduct, they would place a board across the flow, and measure how high the water was when it flowed over the top of the board. In this way they could easily calculate how much water was flowing in the duct. This was modified in later times to a device called a "notch" weir.

2.1 Notch weir

Notch weirs are classified by the shape of their notch; rectangular weirs; triangular, or **V-notch**, weirs; trapezoidal weirs; and parabolic weirs.

http://waterknowledge.colostate.edu/v_notch.htm

The picture above shows a V-notch weir. The edge the water cascades over is called the crest and the overflowing water sheet is called the nappe. Today weirs are still used to determine flows from open water sources such as streams. A typical 90° V-notch will be beveled at 45° so the edge is less than 0.08" thick, and the angle of the notch will be

precisely 90°. Water flow over the weir is calculated by the equation : $Q=2.49h_1^{2.48}$, where h_1 = head on the weir in ft and Q = discharge over weir in ft^3/s.
It is easy to see that this is a simple measurement technique can be used on nearly any open flowing body of water. Its simply a matter of building a large enough weir plate. It is just as obvious that this technique wont work in an enclosed pipe, and it certainly wont work for gasses. The measurement of head is the height of the water above the lowest portion of the weir, and should be made at least four times that height, back from the weir.

2.2 Orifice plate

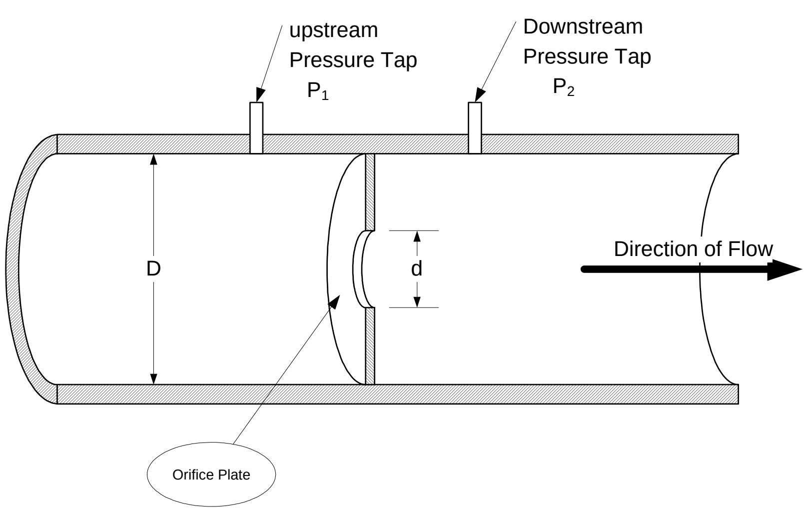
The equivalent of the notch weir in a tube would be an orifice plate. This flow device is created by inserting an obstructing plate, usually with a round hole in the middle, into the pipe and measuring the pressure on each side of the orifice. This is again a very simple device that has been in use for measuring both gas flow and liquid flow for decades.

These plates are generally installed by trapping it between two pipe flanges. Pressure taps on each flange allow you to easily measure the pressure differential across the plate. This pressure differential, along with the dimensions of the plate, are combined with certain fluid properties to determine the flow through the pipe.

The calculation for incompressible (liquid) flow is described by the incompressible Bernoulli equation, as long as the flow is sub-sonic (< mach 0.3).

$$\Delta P = \frac{1}{2}\rho V_2^2 - \rho V_1^2$$

Given the following physical layout, you can modify this formula to take into account the dimensional information rather than the velocity. Also the equation above assumes perfectly laminar flow, which is generally not the case in the real world. Flows in pipe will have a certainly amount of turbulence, which acts to convert kinetic flow energy into heat. This effect is taken into account by adding a new term



to the equation called a *discharge coefficient* (C_d). The resulting equation shows how the area and this new coefficient are applied to get a flow rate (Q).

$$Q = C_d \sqrt{\frac{2(P_1 - P_2)}{\rho}} \times \frac{A_2}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}}$$

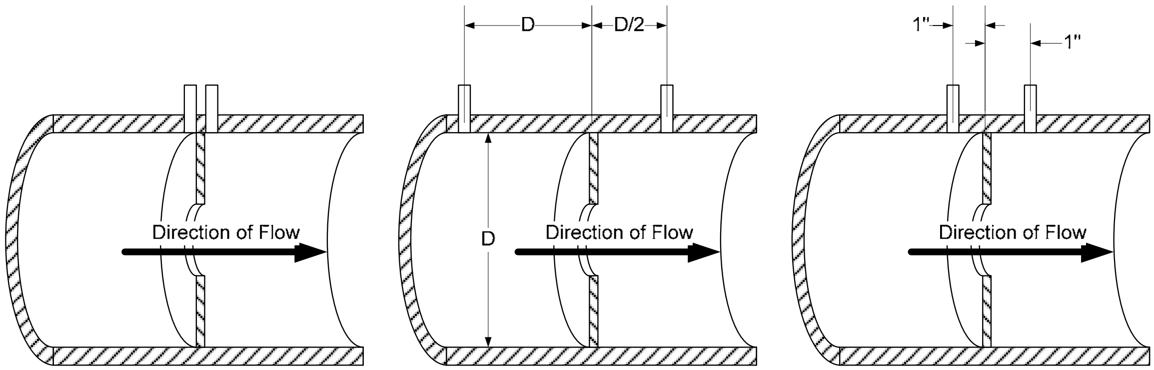
Since the actual flow profile at location 2 (downstream) is quite complex, making the effective value of A_2 uncertain, a substitution is made and a new coefficient C_f is put in place of the area and C_d. The new equation looks like:

$$Q = C_f A_o \sqrt{\frac{2\Delta P}{\rho}}$$

As you can see the formula has been simplified significantly, now only requiring the value of C_f, the area of the orifice (A_o), the density of the fluid and the differential pressure to obtain the volumetric flow rate. The only problem now is the value of C_f. The flow coefficient is found experimentally and is tabulated in numerous reference books. This value ranges from 0.6 to 0.9 for most orifices, and the value depends on the orifice and pipe diameters as well as the Reynolds Number.

Discharge Coefficient - c_d				
Diameter Ratio	Reynolds Number - *Re*			
d / D	104	105	106	107
0.2	0.6	0.595	0.594	0.594
0.4	0.61	0.603	0.598	0.598
0.5	0.62	0.608	0.603	0.603
0.6	0.63	0.61	0.608	0.608
0.7	0.64	0.614	0.609	0.609

This takes care of the incompressible flow, but what about compressible flow, such as air. In this case the orifice flowmeter becomes much more difficult to calculate. The placement of the pressure taps even effect the calculations.



Corner Taps   D and D/2   Flange Taps

Without going into detail here are the equations for calculating the flow for a gas in pipes larger than 5CM in diameter. These are based on ISO 1991 and 1998.

Corner Pressure Taps: $L_1 = L'_2 = 0$
D and D/2 Pressure Taps: $L_1 = 1$ and $L'_2 = 0.47$
Flange Pressure Taps: $L_1 = L'_2 = 0.0254/D$ where D is in meters

$$Q_m = \frac{eC\,A_{throat}\sqrt{2\rho\Delta p}}{\sqrt{1-\beta^4}} \qquad Q_a = \frac{Q_m}{\rho} \qquad Q_s = Q_a\,\frac{P_1 T_{std}}{P_{std}\,T}$$

$$\rho = \frac{P_1}{RT} \qquad e = 1-(0.41+0.35\beta^4)\frac{\Delta P}{K\,P_1} \qquad \beta = \frac{d}{D}$$

$$\mathrm{Re}_D = \frac{V_{pipe}\,D}{\nu} \qquad \mathrm{Re}_d = \frac{V_{throat}\,d}{\nu} \qquad \nu = \frac{\mu}{\rho}$$

$$w = \frac{\sqrt{1-\beta^4} - C\beta^2}{\sqrt{1-\beta^4} + C\beta^2}\,\Delta P \qquad K_m = \frac{2w}{\rho V_{pipe}^2} \qquad V_{pipe} = \frac{Q_a}{A_{pipe}}$$

$$V_{throat} = \frac{Q_a}{A_{throat}} \qquad A_{pipe} = \frac{\pi}{4}D^2 \qquad A_{throat} = \frac{\pi}{4}d^2$$

Discharge Coefficient:

$$C = 0.5961 + 0.0261\beta^2 - 0.216\beta^8 + 0.000521\left(\frac{10^6\ \beta}{\mathrm{Re}_D}\right)^{0.7}$$

$$+\left(0.0188 + 0.0063\left(\frac{19000\,\beta}{\mathrm{Re}_D}\right)^{0.8}\right)\left(\frac{10^6}{\mathrm{Re}_D}\right)^{0.3}\beta^{3.5}$$

$$+\left(0.043 + 0.08e^{-10L_1} - 0.123e^{-7L_1}\right)\left(1 - 0.11\left(\frac{19000\,\beta}{\mathrm{Re}_D}\right)^{0.8}\right)\frac{\beta^4}{1-\beta^4}$$

$$-0.031\left(\frac{2L'_2}{1-\beta} - 0.8\left(\frac{2L'_2}{1-\beta}\right)^{1.1}\right)\beta^{1.3}$$

If $D < 0.07112\,\mathrm{m}$ (2.8 inch), then add the following (where D is in meters):

$$+0.011(0.75-\beta)\left(2.8 - \frac{D}{0.0254}\right)$$

Variables for the above equations:

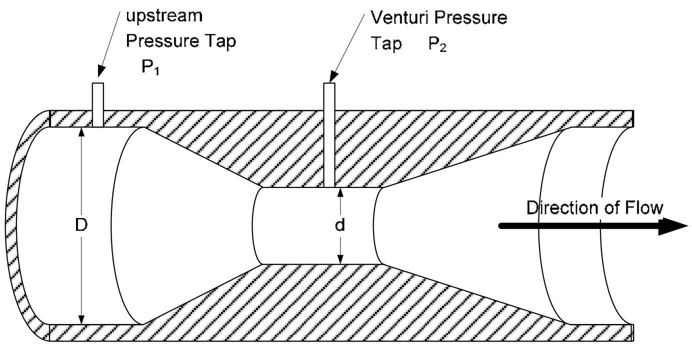
Dimensions: F=Force, L=Length, M=Mass, T=Time, t=temperature

A_{pipe} =Pipe Area [L^2], A_{throat} =Throat Area [L^2], C=Discharge Coefficient
d=Throat Diameter [L], D=Pipe Diameter [L], e=Gas Expansibility
k=Equivalent Roughness of Pipe Material [L]
K=Gas Isentropic Exponent, K_m=Minor Loss Coefficient
M=Mass Flowrate [M/T]
P_1 =Upstream Absolute Pressure [F/L^2], P_2 =Downstream Absolute Pressure [F/L^2]
ΔP =Differential Pressure [F/L^2] = P_1-P_2
P_{std} =Standard Absolute Pressure =14.73 psia = 1.016×10^5 N/m^2
Q_a =Actual Volumetric Flowrate [L^3/T]
Q_s =Volumetric Flowrate at Standard Pressure and Temperature [L^3/T]
R=Gas Constant (used to compute gas density) = 8312/W N-m/kg-K
Re_d =Reynolds Number based on d, Re_D =Reynolds Number based on D
T=Gas Temperature [t] (converted automatically to absolute)
T_{std} =Standard Absolute Temperature=520 ^{o}R=288.9K
V_{pipe}=Gas Velocity in Pipe [L/T], V_{throat} =Gas Velocity in Throat [L/T]
w=Static Pressure Loss [F/L^2], W=Molecular Weight of Gas [gram/mole]
β =Ratio d/D, ρ =Gas Density [M/L^3], μ =Gas Dynamic Viscosity [F-T/L^2]
ν =Gas Kinematic Viscosity [L^2/T]

The primary disadvantage of the orifice type flow meter is that there is a significant pressure drop across the plate, which is not recoverable. For this reason selection of this meter must only be used where you can afford the pressure drop without affecting the rest of the system operations. This is also the reason that the next flow meter type was developed.

2.3 Venturi Flow meter

The venturi flow meter, while considered an obstruction flow meter, is less of an obstruction than the orifice type. It still does have a certain amount of pressure drop, but it is significantly less than the orifice type meter.



Once again, as long as the incompressible fluid velocity is well below the supersonic point (< mach .3), the Bernoulli equation can be used.

$$\Delta P = \frac{1}{2}\rho V_2^2 - \rho V_1^2$$

From continuity we can substitute the throat velocity (V_2) out of the above equation, yielding the following:

$$\Delta P = \frac{1}{2}\rho V_1^2 \left[\left(\frac{A_1}{A_2} \right)^2 - 1 \right]$$

Solving for the upstream velocity and multiplying by the cross sectional area gives the volumetric flow rate Q.

$$Q = \sqrt{\frac{2\Delta P}{\rho}} \frac{A_1}{\sqrt{\left(\frac{A_1}{A_2} \right)^2 - 1}}$$

Ideal fluids would obey this equation, however small amounts of energy are converted into heat within the viscous boundary layers, and tend to lower the actual velocity of real fluids. A discharge coefficient *C* is typically introduced to account for the viscosity of the fluid.

$$Q = C\sqrt{\frac{2\Delta P}{\rho}}\frac{A_1}{\sqrt{\left(\frac{A_1}{A_2}\right)^2 - 1}}$$

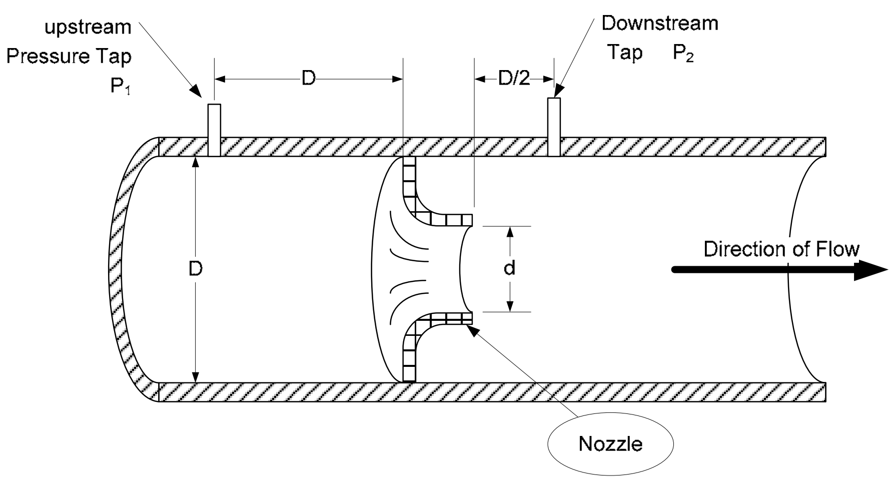
C is found to depend on the Reynolds Number of the flow, and usually lies between .90 and .98 for smoothly tapering venturis.

For air flow you can use the same calculation and assume that the gas is incompressible. The density needs to be adjusted appropriately using the ideal gas formula.

$$\rho = \frac{P}{RT}$$ Where R is the gas constant (287 J/Kg/K for air)

2.4 Nozzle Flow meter

A flow nozzle consists of a restriction with an elliptical contour approach section that terminates in a cylindrical throat section. Pressure drop between the locations one pipe diameter upstream and one-half pipe diameter downstream is measured. Flow nozzles provide an intermediate pressure drop between orifice plates and venturi tubes; also, they are applicable to some slurry systems that would be otherwise difficult to measure.



The flow calculations for the long radius nozzle are similar to that of the orifice plate, with the exception of the values of the discharge coefficient. The following table shows some standard values for this value.

Discharge Coefficient - c_d				
Diameter Ratio	Reynolds Number - *Re*			
d / D	104	105	106	107
0.2	0.968	0.988	0.994	0.995
0.4	0.957	0.984	0.993	0.995
0.6	0.95	0.981	0.992	0.995
0.8	0.94	0.978	0.991	0.995

2.5 References

For more information on obstruction flow meters you can reference the following resources.

American Society of Mechanical Engineers (ASME). 1971. Fluid meters: Their theory and application. Edited by H. S. Bean. 6ed.

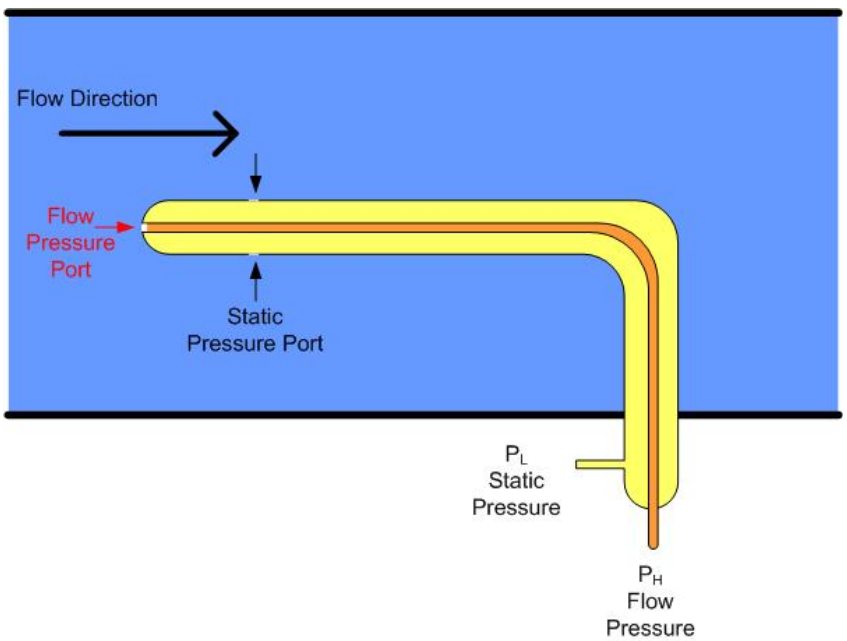
International Organization of Standards (ISO 5167-1). 1991. Measurement of fluid flow by means of pressure differential devices, Part 1: Orifice plates, nozzles, and Venturi tubes inserted in circular cross-section conduits running full. Reference number: ISO 5167-1:1991(E).

3.0 velocity flow measurement devices

Velocity flow measurement techniques allow for the measurement of total flow by measuring the velocity of the fluid within a fixed area duct or pipe. The technique uses a measuring probe to determine the velocity of the fluid in the *center portion* of the pipe. It is important to understand that with all fluid flows, there are boundary layer effects at the interface between the walls of the duct or pipe and the fluid flowing through it. For this technique to provide reasonably accurate results, the velocity measurement of the flow must be made well within the duct, to minimize the effects of the boundary layers. For this reason ducts or piles of small diameter typically do not fair well with this technique. The technique also requires that you be in a laminar flow environment. The results in a turbulent flow area suffer in stability and accuracy. It is possible to calculate the location where the flow in a pipe or duct is fully laminar, but for most applications a general rule of thumb is sufficient. That rule is to make the measurement at least 10 pipe diameters upstream and 20 pipe diameters downstream of any junction, elbow or other flow disturbing point in the pipe.

3.1 Pitot Tube

The Pitot tube is a simple device that allows for the measurement of the flow pressure in a moving fluid. This device is a section of tube that measures the pressure at the tip and the pressure at the side of the tube. Reading this differential pressure and applying Bernoulli's equation will allow for the calculation of the fluid velocity.



The above diagram shows how the Pitot tube is constructed of two tubes, one inside the other, to create a static pressure port and a flow pressure port. Applying Bernoulli's equation we get:

$$P_S + r\left(\frac{V^2}{2}\right) = P_F$$

Where

r = Density
V = Velocity
P_S = Static Pressure
P_F = Flow Pressure

If we solve for the velocity we get the following equation:

$$V^2 = \frac{2(P_F - P_S)}{r}$$

With the velocity of the fluid now known, you can simply multiply it by the area of the duct to get the total volume flow.

This process is extremely useful in locations where there is a significant volume in a large duct or pipe. The differential pressure between the two ports is typically quite small for air flow, and the use of water monometers is a common method of measuring the pressure differential. Small differential pressure transducers are also quite common when an electronic readout is required or desired. Liquid flows can have significantly larger pressure differentials. As with the obstruction flow meters, the fluid that is within the pipe or duct will be on the pressure taps. If this fluid has any nasty properties, you need to take the appropriate steps to protect personnel and equipment. Not all fluids are compatible with all pressure transducers and care must be taken to ensure that an appropriate material is used for all wetted parts.

3.2 Hot Wire / Film probes

While Pitot tubes work well for high flow rates in gasses, and a variety of flow rates in liquids, the technique fails for low air velocities in gasses. To solve this gap in velocity measurement technology, the hot wire and hot film probes were developed.

http://www.omega.com/pptst/HHF42.html

This technique is fairly straight forward in concept, but much more difficult in operation. The theory is that if you place a resistance wire in the flow of air (or other gas) and heat the wire with a fixed current, the voltage across the wire will indicate the resistance of the wire. If you know the properties of the wire you can deduce what its temperature is. Knowing this information, you can determine how much heat is being carried away by the moving stream of gas flowing across the wire or film. Simple… maybe. The difficulty with this is that the density, temperature and actual makeup of the gas flowing affect the heat absorption as well as the flow. This has been handled in a number of ways, but the most straightforward is to use two wires. One in the flow and one out of the flow, and make your measurement based on the difference of these two values. A second method is to make an assumption that the reading is being made in "standard air" which has a known coefficient of absorption. Using this method the only values that are needed are hot wire value and the temperature of the air prior to the hot wire.

Hot wire probes are extremely fast response devices. With a wire size in the micrometers, the probe can respond to temperature changes at rates faster than 1 millisecond. This makes this type of probe ideal for studies of turbulent flows. Scientific level meters are available from a number of companies that will respond to these high rates of change, but the price is generally in the thousands. Smaller hand held units that respond much slower are available for a few hundred dollars and are a good solution to a low flow application. The accuracy of these devices is typically around 1% or so and are generally designed for use in air, although most can be calibrated for other gasses as well.

3.3 Moving Member Meters

Another method of measuring the flow velocity in a duct or pipe is the special class of transducers called "moving member" meters. These fall into two primary classifications, turbines and paddlewheels. Both of these measure the velocity of the fluid in the tube or duct. What makes them different from other velocity measurement devices is that they employ a moving element to determine the flow, unlike the pitot tube and hot wire probes.

3.3.1 Axial Turbine Flow Meter

The axial type turbine flow meter consists of a circular housing with a suspended blade system. This suspended blade is mounted on a shaft or bearing at the center of the housing. As fluid flows past the blades, they are rotated by the fluidic forces. The speed of rotation is proportional to the velocity of the fluid passing through the housing. A method of measuring the speed of rotation is employed, allowing a measurement of fluid velocity. The typical method if measuring the speed of the turbine rotation is to count the blades as they pass a sensor on housing body. This method is extremely accurate and essentially averages the velocity across the whole housing diameter. The construction of these devices can allow insertion into pipes and ducts of varying sizes and can be used with a wide variety of clean fluids over a very wide range of velocities. The design of the housing can be adjusted to allow the use of this type of transducer into a wide range of pressure systems. These systems frequently apply a flow straightener section immediately prior to the blade section. The Blancett model 1100 is typical of this type of flow meter.

http://www.blancett.com/1100_TFM.php

This style flow meter is available in a wide array of sizes and velocity ranges, but is inherently limited to flows that can be totally encapsulated by the body. In large diameter ducts or pipes this type meter becomes impractical due to the extreme velocities that the tips of the blades would be subjected to as the diameters grow.

This type of flow meter has excellent accuracy in both liquids and medium velocity gasses. Since the accuracy of the meter depends on the speed of the impeller, it is imperative that the bearing system that supports the blade remain clean and free to turn. This tends to limit the fluids to "clean" fluids that do not contain significant numbers of abrasive particles. Many installations install 100µ filters upstream of the meter to ensure that the fluid flow does not contain damaging particles. An additional consideration with is the issue of wetted parts. Since the blades and bearing are fully immersed in the fluid, care must be taken to assure that the materials that the meter is made from are compatible with the fluid being measured. Highly corrosive fluids and gasses can have a significant impact on the life of the meter. Additionally these meters are usable with a wide range of viscosities, although certain calibration corrections may need to be applied, depending on the meter, since the amount of "slip" between the fluid and the blade is a factor in its calibration.

As the blades rotate, a mechanism is employed to count the passing of the tips of the blades. In general a magnetic field is induced into the flow field and the disturbance of this field creates a pulse output from the meter. Counting these pulses or measuring the rate of their passage will allow for measurement of flow. Since the meter depends on the magnetic field for operation, it is clear that fluids that effect magnetic fields should be used cautiously with this type of meter.

3.3.2 Radial Turbine Flowmeter

The Axial style turbine flowmeter works well for smaller diameter pipes and ducts. If you have an application in a significantly larger pipe or duct, an alternate configuration will be required. In this alternate style device, a small turbine device is inserted in through the side of the pipe, and the flow across the turbine blades generates a measurement related to the general flow in the pipe, hence the common name of "insertion Turbine flow meter."

The turbine flow meters shown to the left are one form of this type of device. The cartridge unit is inserted into the flow stream with the shaft of the turbine unit parallel to the flow. This allows the flow across the angled turbine element to rotate in proportion to the flow across the blades. This device works well as long as the flow is not turbulent. Since the meter is not actually measuring the full cross section of the flow, only the flow at a single point near the wall of the pipe, excessive turbulence will cause readings that are not representative of the real flow in the pipe. As a result it is best to use these flow meters with caution and if you don't have the real flow characteristics of the pipe, at least use the standard rule of thumb (20 / 10) for your distance from flow disturbances.

Like the Axial device, these flow measurement devices return a pulse output who's frequency is proportional to indicated flow. This frequency is typically fed into a process meter which can be scaled to some particular set of engineering units. Alternately if the intent is to use this with a data acquisition system, a counter / timer input should be used to read the frequency value. Also care should be taken to assure that you are using an appropriate output voltage range for the data acquisition input.

3.3.3 Paddle wheel flowmeter

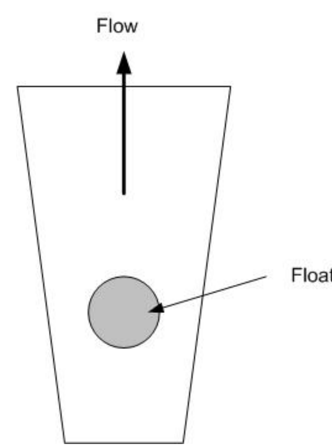
A lower cost alternate to the turbine flowmeter is the paddle wheel flowmeter. This device is somewhat similar to the insertion type turbine flowmeter, but instead of a turbine blade with the flow generating lift forces to cause the rotation, the paddle wheel is perpendicular to the flow and rotates much like an old fashioned steam boat paddlewheel. These devices are usually inserted into a specially made tee in the flow line. The paddlewheel show in the photo, distributed by Omega, is shown inserted into its flow tee. The PVC fitting is then cemented onto two ¾" PVC pipes. In this size pipe, the meter is capable of reading flows from 1.7 to 34 gallons per minute to an accuracy of 1%. The sensor can also be used in pipe sizes from ½" to 36" in diameter for a flow range of 1 to nearly 7000 gallons per minute.

These transducers are extremely economical, running around $400 for the transducer. Like the turbine flowmeter, these also generate a pulse train generated by the paddles passing an internal pickup. The output is a frequency proportional to the flow rate. As with many flow measurement devices, this is also dependent on the stability of flow and significant turbulence will cause significant error. In general, the 20 / 10 rule should be followed to ensure that the flow is fully developed at the transducer location.

4.0 Variable Area flowmeters

There is a class of flow meters which use the pressure drop caused by an obstruction in the flow in a unique way. These meters, call variable area flow meters depend on the flow of the fluid to carry an object along. In a fixed diameter pipe, the object would be carried along with the flow based on the resistance to that flow. If the flow is moving in a variable diameter pipe, the force on that object changes with changes in the pipe diameter, and hence, the clearance between the sides of the object and the sides of the pipe. This class of flowmeters is generally represented by two main types; Rotameters and spring – plunger meters.

4.1 Rotameters



The rotameter is a variable area meter that employs a vertical tube of varying diameter, with an object inserted in it. This object is known as the float. This type meter is used only in a vertical position, as gravity is a primary force involved in the calibration of the device. The float is moved vertically in the variable diameter tube by a combination of buoyancy forces and flow pressure forces. The flow pressure forces are created by the fluid trying to move around the float, by using the gap between the float and the sides of the tube. As the forces move the float up the tube, the widening gap between the tube and the float allow these forces to be reduced, and gravity tends to force the float back down the tube toward the bottom. At the equilibrium point for a given flow, the forces of flow and buoyancy in the vertical direction are balanced by the mass of the float being pulled down by gravity.

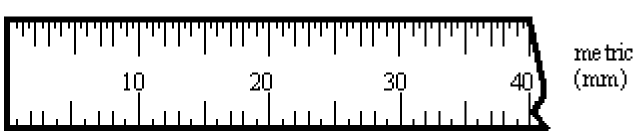
UNIT-II
LINEAR AND ANGULAR MEASUREMENTS

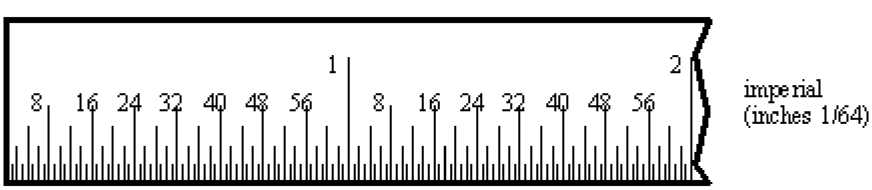
MEASUREMENT OF ENGINEERING COMPONENTS:

- Measurement systems are mainly used in industries for quality control management.
- Often quality control engineers are applying some the measuring systems such as linear and angular measurements.
- These measurements are very much useful to compare the actual measurements with already existing standard measurements.
- The linear measurement includes the measurement of lengths, diameters, heights and thickness.
- The basic principle of linear measurement is that of comparison with standard dimensions on a suitably engraved instrument or device.
- The various devices used for measuring the linear measurements are
  - Vernier calipers
  - Micrometers
  - Slip gauge or gauge blocks
  - Comparators
- Angular measurement is another important element in measuring.
- This involves the measurement of angles of tapers and similar surfaces. In angular measurements t types of angle measuring devices are used.
- They are angle gauges corresponding to slip gauges and divided scales corresponding to line standards. The most common instrument is sine bar.
- The main difference between linear and angular measurement is that no absolute standard is required for angular measurement.

SCALES:

- The most common tool for crude measurements is the scale (also known as **rules, or rulers**)
- Although plastic, wood and other materials are used for common scales, precision scales use tempered steel alloys, with graduations scribed onto the surface.
- These are limited by the human eye. Basically they are used to compare two dimensions.
- The metric scales use decimal divisions, and the imperial scales use fractional divisions.





- Some scales only use the fine scale divisions at one end of the scale.
- It is advised that the end of the scale not be used for measurement. This is because as they become worn with use, the end of the scale will no longer be at a `zero' position. Instead the internal divisions of the scale should be used.
- Parallax error can be a factor when making measurements with a scale.

CALIPERS:

- A tool used to transfer measurements from a part to a scale, or other instrument.
- Calipers may be difficult to use, and they require that the operator follow a few basic rules, do not force them, they will bend easily, and invalidate measurements made.
- If measurements are made using calipers for comparison, one operator should make all of the measurements (this keeps the feel factor a minimal error source).
- These instruments are very useful when dealing with hard to reach locations that normal measuring instruments cannot reach.
- Obviously the added step in the measurement will significantly decrease the accuracy

(A)Vernier Calipers

- Vernier calipers have two scales namely, the main scale and vernier scale. The vernier scale moves along the main scale. Verifiers are used to measure both internal and external dimensions.
- The caliper is placed on the object to be measured and the fine adjustment screw is rotated until the jaws fit tightly against the work piece. The readings from the main and vernier scales are taken.

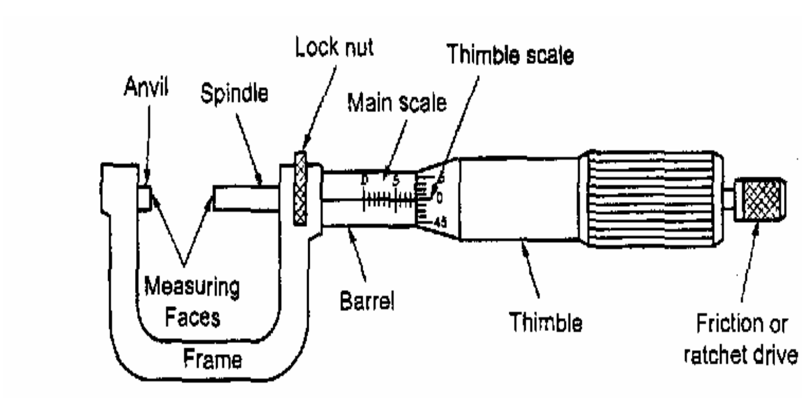
MICROMETERS

There are two types in it.

(i) Outside micrometer —To measure external dimensions.

(ii) Inside micrometer —To measure internal dimensions.

An outside micrometer is shown in Fig.1. It consists of two scales, main scale and thimble scale. While the pitch of barrel screw is 0.5 mm the thimble has graduation of 0.01 mm. The **least count** of this micrometer is 0.01 mm.



COMPARATORS:

- Comparators are one form of linear measurement device which is quick and more convenient for checking large number of identical dimensions.
- Comparators normally will not show the actual dimensions of the work piece. They will be shown only the deviation in size. i.e. During the measurement a comparator is able to give the deviation of the dimension from the set dimension.
- This cannot be used as an absolute measuring device but can only compare two dimensions.
- Comparators are designed in several types to meet various conditions. Comparators of every type incorporate some kind of magnifying device.
- The magnifying device magnifies how much dimension deviates, plus or minus, from the standard size.
- The comparators are classified according to the principles used for obtaining magnification.
- The common types are:
    1) Mechanical comparators.
    2) Electrical comparators.
    3) Optical comparators.
    4) Pneumatic comparators.

1. **MECHANICAL COMPARATORS**:

- Mechanical comparator employs mechanical means for magnifying small deviations.
- The method of magnifying small movement of the indicator in all mechanical comparators are effected by means of levers, gear trains or a combination of these elements.
- Mechanical comparators are available having magnifications from 300 to 5000 to 1. These are mostly used for inspection of small parts machined to close limits.

1. Dial indicator:

- A dial indicator or dial gauge is used as a mechanical comparator. The essential parts of the instrument are like a small clock with a plunger projecting at the bottom as shown in fig.
- Very slight upward movement on the plunger moves it upward and the movement is indicated by the dial pointer.
- The dial is graduated into 100 divisions. A full revolution of the pointer about this scale corresponds to 1mm travel of the plunger.
- Thus, a turn of the pointer b one scale division represents a plunger travel of 0.01 mm.

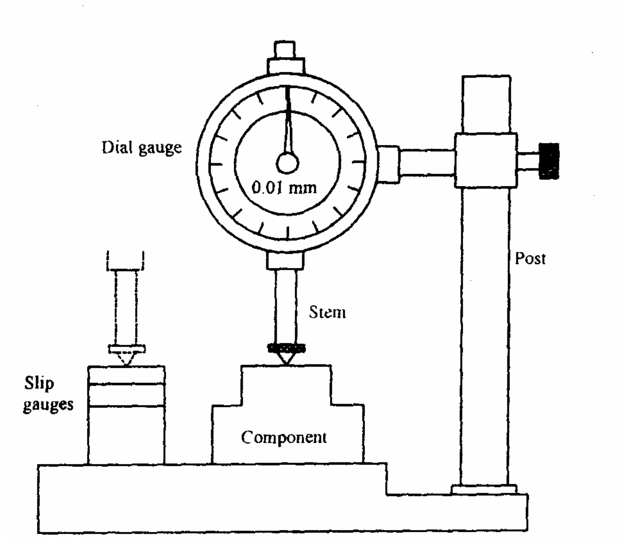
Experimental setup:

- The whole setup consists of worktable, dial indicator and vertical post.
- The dial indicator is fitted to vertical post by on adjusting screw as shown in fig.
- The vertical post is fitted on the worktable, The top surface of the worktable is finely finished.
- The dial gauge can be adjusted vertically and locked in position by a screw.

How to use?

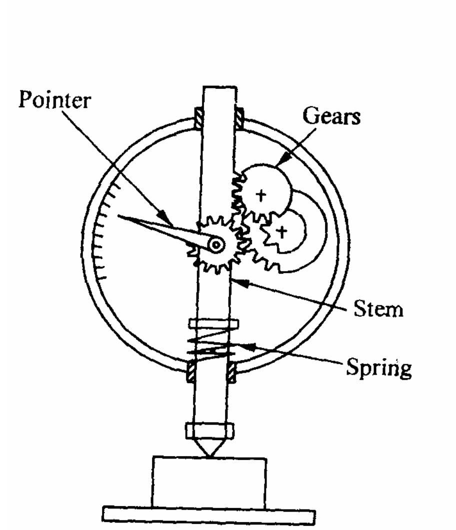
- Let us assume that the required height of the component is 32.5mm. Initially this height is built up with slip gauges.
- The slip gauge blocks are placed under the stem of the dial gauge.

- The pointer in the dial gauge is adjusted to zero. The slip gauges are removed.
- Now the component to be checked is introduced under the stem of the dial gauge. If there is any deviation in the height of the component, it will be indicated by the pointer.



Mechanism:

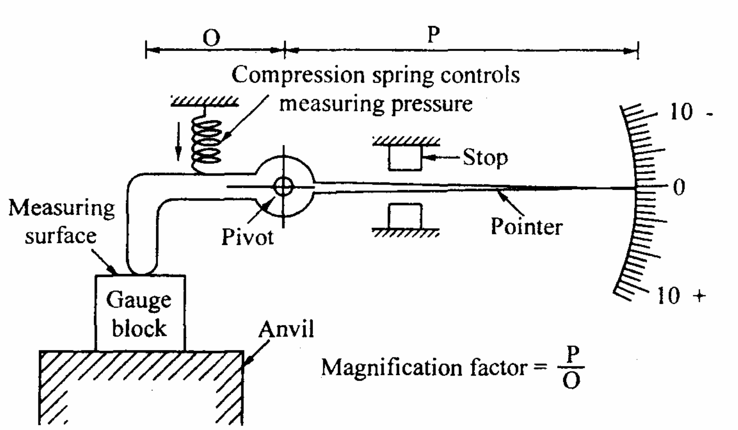
- The mechanism of such an instrument is. illustrated in figure.
- The stem has rack teeth. A set of gears engage with the rack.
- The pointer is connected to a small pinion.
- The small pinion is independently hinged. i.e. it is not connected to the stern.
- The vertical movement of the stem is transmitted to the pointer through a set of gears. A spring gives a constant downward pressure to the stem.



2. Read type mechanical comparator:

- In this type of comparator, the linear movement of the plunger is specified by means of read mechanism. The mechanism of this type is illustrated in fig.
- A spring-loaded pointer is pivoted. Initially, the comparator is set with the help of a known dimension eg. set of slip gauges as shown in fig.

- Then the indicator reading is adjusted to zero. When the part to be measured is kept under the pointer, then the comparator displays the deviation of this dimension either in ± or —side of the set dimension.



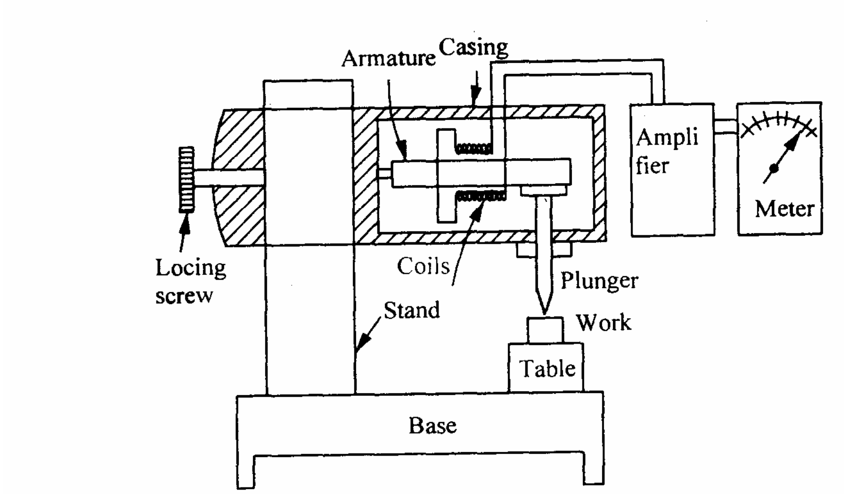
Advantages:

1) It is usually robust, compact and easy to handle.
2) There is no external supply such as electricity, air required.
3) It has very simple mechanism and is cheaper when compared to other types.
4) It is suitable for ordinary workshop and also easily portable.

Disadvantages:

1) Accuracy of the comparator mainly depends on the accuracy of the rack and pinion arrangement. Any slackness will reduce accuracy.
2) (ii) It has more moving parts and hence friction is more and accuracy is less.
3) (iii) The range of the instrument is limited since pointer is moving over a fixed scale.

2. ELECTRICAL COMPARATOR:



An electrical comparator consists of the following three major part such as

1) Transducer
2) Display device as meter
3) Amplifier

Transducer:

- An iron armature is provided in between two coils held by a lea spring at one end. The other end is supported against a plunger.
- The two coils act as two arms of an A.C. wheat stone bridge circuit.

Amplifier:

- The amplifier is nothing but a device which amplifies the give input signal frequency into magnified output

Display device or meter:

- The amplified input signal is displayed on some terminal stage instruments. Here, the terminal instrument is a meter.

Working principle:

- If the armature is centrally located between the coils. the inductance of both coils will be equal but in opposite direction with the sign change.
- Due to this, the bridge circuit of A.C. wheatstone bridge is balanced. Therefore, the meter will read zero value. But practically, it is not possible. In real cases, the armature may be lifted up or lowered down by the plunger during the measurement.
- This would upset the balance of the wheatstone bridge circuit. Due to this effect, the change in current or potential will be induced correspondingly.
- On that time, the meter will indicate some value as displacement. This indicated value may be either for larger or smaller components.
- As this induced current is too small, it should be suitably amplified before being displayed in the meter.

Checking of accuracy:

- To check the accuracy of a given specimen or work, first a standard specimen is placed under the plunger.
- After this, the resistance of wheatstone bridge is adjusted so that the scale reading shows zero. Then the specimen is removed.
- Now, the work is introduced under the plunger. If height variation of work presents, it will move the plunger up or down.
- The corresponding movement of the plunger is first amplified by the amplifier then it is transmitted to the meter to show the variations.
- The least count of this electrical comparator is **0.001mm (one microns).**

3.ELECTRONIC COMPARATOR:

- In electronic comparator, transducer induction or the principle of application of frequency modulation or radio oscillation is followed.

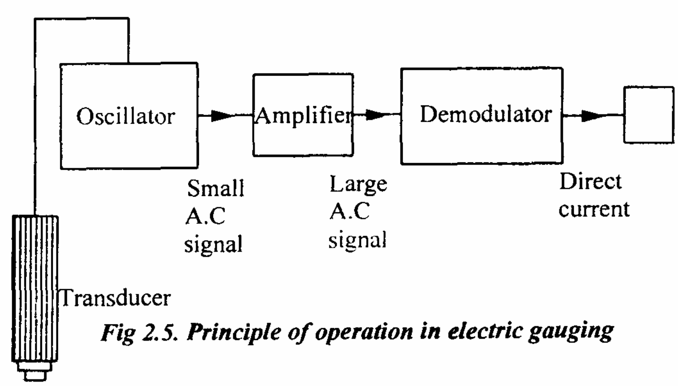


Fig 2.5. Principle of operation in electric gauging

Construction details:

In the electronic comparator, the following components are set as follows:

i. Transducer
ii. Oscillator
iii. Amplifier
iv. Demodulator
v. Meter

(i) Transducer: -

It converts the movement of the plunger into an electrical signal. It is connected with oscillator.

(ii) Oscillator: -

The oscillator which receives electrical signal from the transducer and raises the amplitude of frequency wave by adding carrier frequency called as modulation.

(iii) Amplifier: -

An amplifier is connected in between oscillator and demodulator. The signal coming out of the oscillator is amplified into a required level.

(iv) Demodulator: -

Demodulator is nothing but a device which cuts off external carrier wave frequency. i.e. It converts the modulated wave into original wave as electrical signal.

(v) Meter:

This is nothing but a display device from which the output can be obtained as a linear measurement.

Principle of operation:

- The work to be measured is placed under the plunger of the electronic comparator. Both work and comparator are made to rest on the surface plate.
- The linear movement of the plunger is converted into electrical signal by a suitable transducer. Then it sent to an oscillator to modulate the electrical signal by adding carrier frequency of wave.
- After that the amplified signal is sent to demodulator in which the carrier waves are cut off.
- Finally, the demodulated signal is passed to the meter to convert the probe tip movement into linear measurement as an output signal.
- A separate electrical supply of D.C. is already given to actuate the meter.

Advantages of Electrical and Electronic comparator:

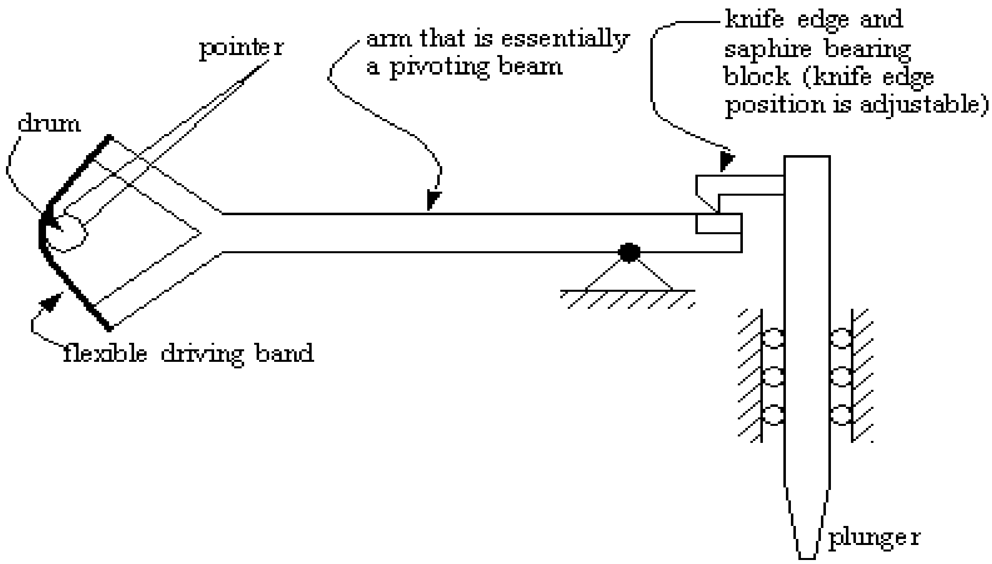
1) It has less number of moving parts.
2) Magnification obtained is very high.
3) Two or more magnifications are provided in the same instrument to use various ranges.
4) The pointer is made very light so that it is more sensitive to vibration.
5) The instrument is very compact.

Disadvantages of Electrical and Electronic comparator:

1) External agency is required to meter for actuation.
2) Variation of voltage or frequency may affect the accuracy of output.
3) Due to heating coils, the accuracy decreases.
4) It is more expensive than mechanical comparator.

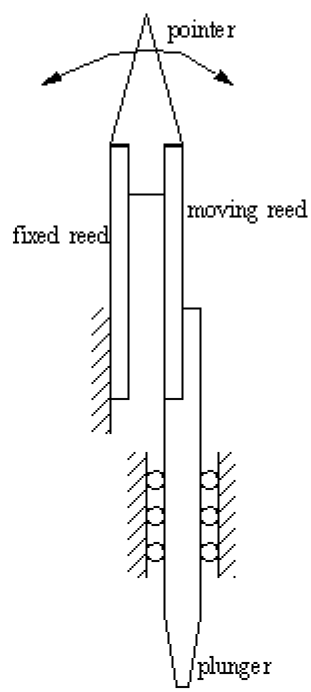
4.SIGMA MECHANICAL COMPARATOR

- The Sigma Mechanical Comparator uses a partially wrapped band wrapped about a driving drum to turn a pointer needle.



5. MECHANICAL AND OPTICAL COMPARATORS

- The Eden-Rolt Reed system uses a pointer attached to the end of two reeds.
- One reed is pushed by a plunger, while the other is fixed.
- As one reed moves relative to the other, the pointer that they are commonly attached to will deflect.



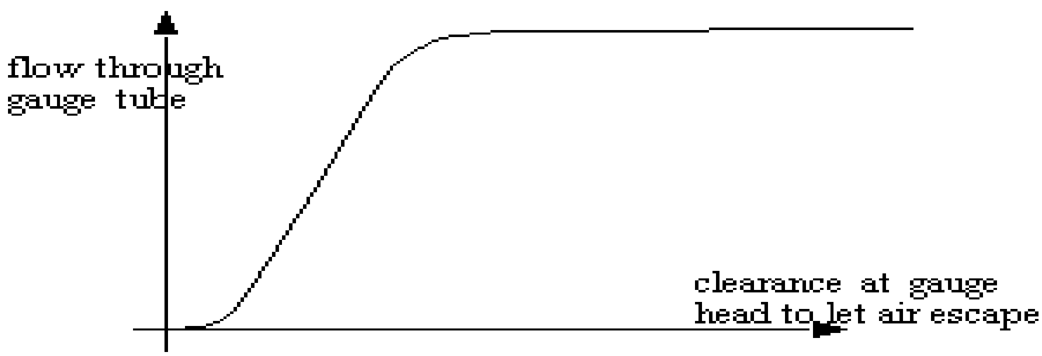
6. PNEUMATIC COMPARATORS:

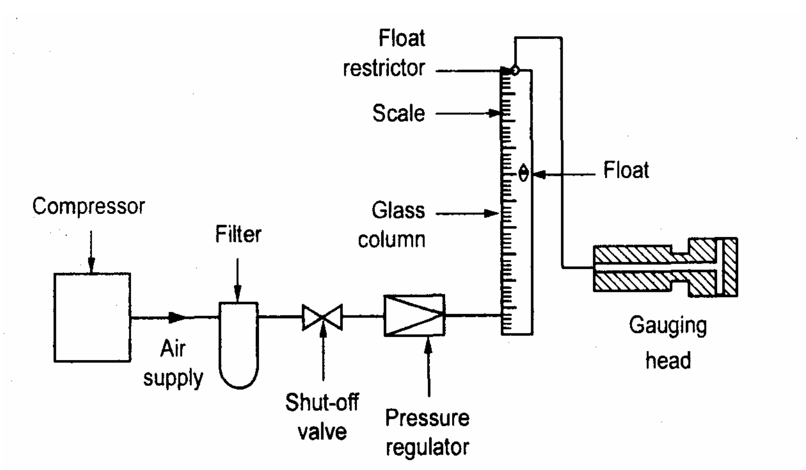
- The term pneumatic associates with pressurised air.
- The pressurized air is used as the working medium in pneumatic comparator.

- Based on the physical phenomena, the pneumatic comparators are classified into two types.
  1) Flow or Velocity type.
  2) Back pressure type.

1. Flow type

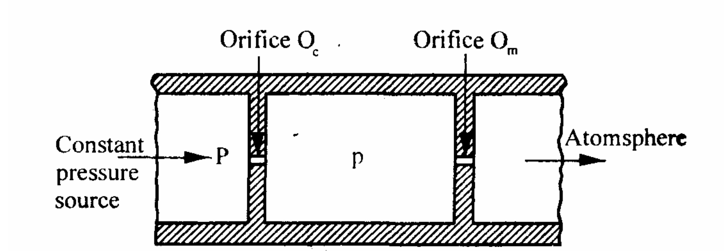
- - the float height is essentially proportional to the air that escapes from the gauge head
- - master gauges are used to find calibration points on the scales
- - the input pressure is regulated to allow magnification adjustment
- - a pressure bleed off valve allows changes to the base level for offset
- - The pressure is similar to that shown in the graph below,





2.Back pressure type

- The Soloflex Back Pressure System uses an orifice with the venturi effect to measure air flow. If the gas is not moving, the pressure on both sides of the orifice will be equal.

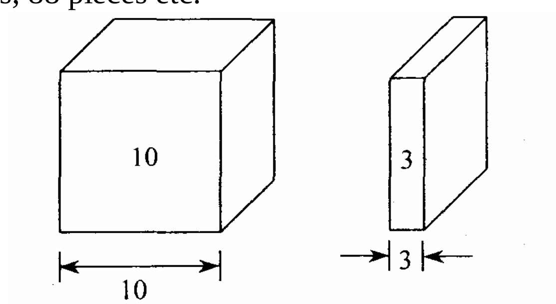


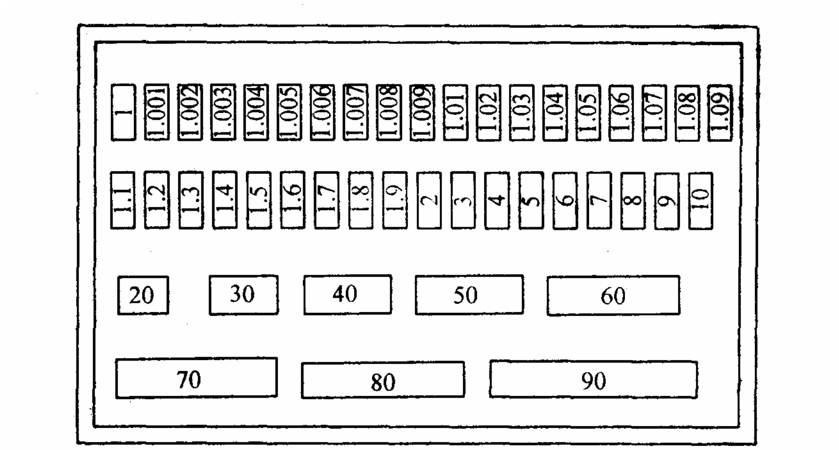
- If the flow is moving quickly, the air pressure on the downstream side of the orifice will be at a lower pressure.

- A Differential Back Pressure system uses a split flow channel, one flow goes to the gauge head, the other goes to a zero offset valve.
- A meter measures the difference in pressures, and thus gives the differences in pressure.

SLIP GAUGES

- Slip gauges are used as measuring blocks.
- It is also called as precision gauge blocks.
- They are made of hardened alloy steel of rectangular cross-section.
- The surfaces of slip gauges are made to a high degree of accuracy.
- The distance between the two opposite faces indicates the size of the gauge. But all slip gauges are made to same thickness to perform wringing.
- **Wringing or Sliding** is nothing but combining the faces of slip gauges one over the other. Due to adhesion property of slip gauges, they will stick together. This is because of very high degree of surface finish of the measuring faces.
- They are used in comparators and sin bars. They are mainly used as testing and calibrating instruments in metrology.
- Different sets of slip gauges are manufactured in standard sets of
- 32 pieces, 45 pieces, 88 pieces etc.





A normal set of slip gauges has 45 pieces as shown in fig.

- The slip gauges should be stored carefully in a box. For obtaining higher accuracy. They are stored in a temperature-controlled room.
- **For example**, a slip gauge set of 56 slips is made up as follows:
  - 9 slips 1.001 to 1.009 in steps of 0.001mm
  - 9 slips 1.01 to 1.09 in steps of 0.01mm
  - 9 slips 1.1 to 1.9 in steps of 0.1mm
  - 25 slips I to 25 in steps of 1mm
  - 3 slips 25 to 75 in steps of 25mm
  - One slip of 1.0005mm

CLASSIFICATION OF SLIP GAUGES:

Slip gauges are classified into various types according to their use as follows:

1) Grade 2
2) Grade 1
3) Grade 0
4) Grade 00
5) Calibration grade.

1) Grade 2:

It is a workshop grade slip gauges used for setting tools, cutters and checking dimensions roughly.

2) Grade 1:

The grade I is used for precise work in tool rooms.

3) Grade 0:

It is used as inspection grade of slip gauges mainly by inspection department.

4) Grade 00:

Grade 00 mainly used in high precision works in the form of error detection in instruments.

5) Calibration grade:

The actual size of the slip gauge is calibrated on a chart supplied by the manufactures.

MANUFACTURE OF SLIP GAUGES:

The following additional operations are carried out to obtain the necessary qualities in slip gauges during manufacture.

i. First the approximate size of slip gauges is done by preliminary operations.
ii. The blocks are hardened and wear resistant by a special heat treatment process.
iii. To stabilize the whole life of blocks, seasoning process is done.
iv. The approximate required dimension is done by a final grinding process.
v. To get the exact size of slip gauges, lapping operation is done.
vi. Comparison is made with grand master sets.

Calibration of slip gauges

Comparators are used to calibrate the slip gauges.

SLIP GAUGES ACCESSORIES:

The application slip gauges can be increased by providing accessories to the slip gauges. The various accessories are

- Measuring jaw
- Scriber and Centre point.
- Holder and base.

1. Measuring jaw:

It is available in two designs specially made for internal and external features.

2. Scriber and Centre point:

It is mainly formed for marking purpose.

3. Holder and base:

- Holder is nothing but a holding device used to hold combination of slip gauges.
- Base in designed for mounting the holder rigidly on its top surface.

ODD TOPICS

- There are also a number of angular gauge blocks for the measurement of angles. The two common sets are, 16 piece set

degrees	45°, 30°, 15°, 5°, 3°, 1°
minutes	30’, 20’, 5’, 3’, 1’
second	30”, 20”, 5”, 3”, 1”

13 piece set

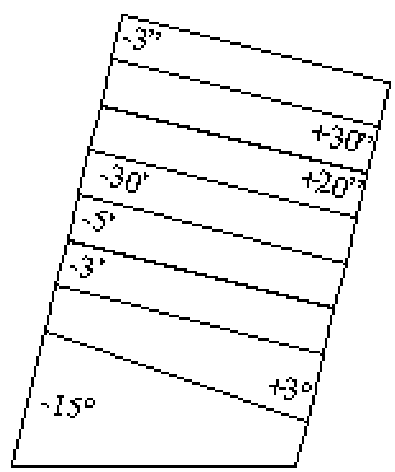
degrees	1°, 3°, 9°, 27°, 41°, 90°
minutes	1’, 3’, 9’, 27’, 0.1’, 0.3’, 0.5’

tool room accuracy ±1 second
laboratory accuracy ± 0.25 seconds

- The selection of angular gauge blocks is similar to the selection of linear gauge blocks, except that subtraction may also be required. (When the blocks are stacked, then angles are simply reversed.)

For the angle 12°37’13”, find the angular gauge block stack using the 16 piece set.

12°37’13”
-3”
___
12°37’10”
+30”
___
12°37’40”
+20”
___
12°38’
-30’
___
12°8’
-5’
___
12°3’
-3’
___
12°
+3°
___
15°
-15°
___
0

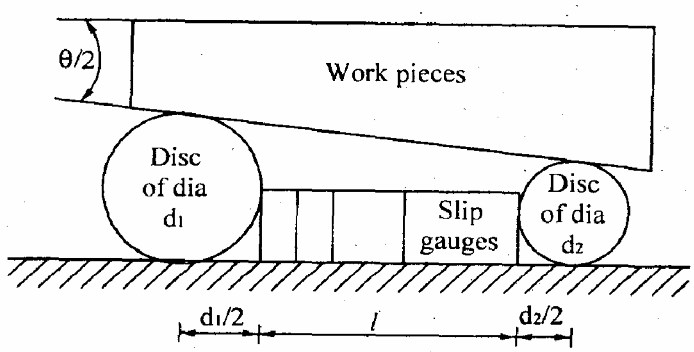


ROLLERS:

- Rollers are precisely manufactured with high accuracy for metrological applications.
- It is used to determine both linear and angular dimensions in conjunction with gauge blocks.
- These are made of good quality steel and are hardened and tapered. The length of the roller is equal to the diameter.
- The use of precision rollers for determining both linear and angular dimensions is explained with the help of following examples.

1. Measurement of angle by using rollers:

- Angle of the right-tapered piece can be measured by using two rollers of different sizes, slip gauges and a dial indicator.
- The two rollers whose diameters are known and slip gauges are placed on a surface plate as shown in fig.
- The rollers may be clamped in position against an angle plate by C-clamps. The work is then placed on top of rollers and clamped against the angle plate C-clamp.
- If the angle of the piece is all right, then the top edge will be parallel to surface plate. The dial indicator will show no variation when traversed along its surface.



From fig., the triangle $O_1 A O_2$

$$\tan\theta/2 = \frac{O_1 A}{O_2 A} = \frac{\frac{d_2}{2} - \frac{d_1}{2}}{l + \frac{d_1}{2} + \frac{d_2}{2}} = \frac{d_1 - d_2}{2l + d_1 + d_2}$$

Where, l = Length of slip gauge pile and

d_1 & d_2 = Diameters of rollers

From the above equation

$$l = \frac{\frac{d_2 - d_1}{2}}{\tan(\theta/2)} - \left(\frac{d_1 + d_2}{2}\right)$$

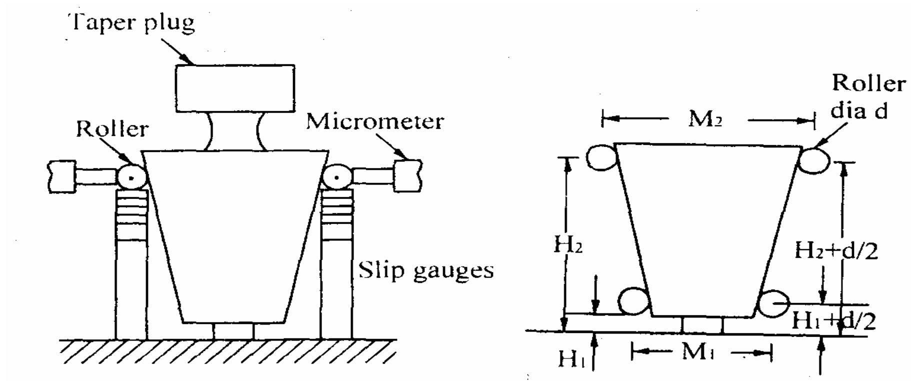
- Thus, initially the length of the slip gauges is calculated by the above equation and the rollers are placed in contact with the slip gauges.

2. Checking the angle of taper using rollers:

- Method of checking the angle of a taper plug gauge using rollers.
- Micrometer and slip gauges are illustrated by fig.
- Taper plug is placed on a surface plate. First two rollers of equal diameters are placed touching on the opposite sides of the lower surface of the plug on the slip gauge combinations of equal heights (H) The distance (M) between the ends of the roller is measured with a micrometer.
- Then the rollers are placed on slip .gauge combinations of height touching on the opposite sides of the top portion of the plug.
- The distance between the ends of the rollers in this new position is again measured by means of micrometer.
- The half of the taper angle of the plug is then calculated as follows:
- If d= diameter of rollers, then

$$\tan\theta/2 = \frac{\left[\left(\frac{M_2-d}{2}\right)-\left(\frac{M_1-d}{2}\right)\right]}{\left(H_2+\frac{d}{2}\right)-\left(H_1+\frac{d}{2}\right)}$$

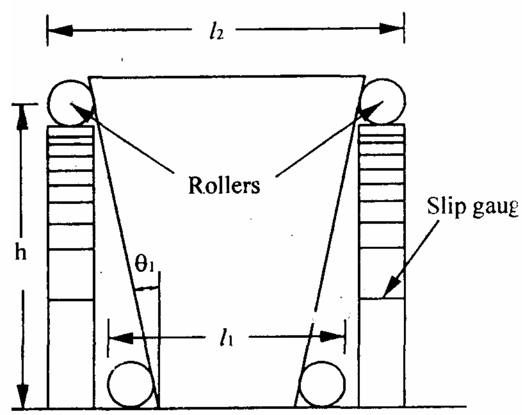
$$\therefore \tan\theta/2 = \frac{M_2-M_1}{2(H_2-H_1)}$$



3. Measuring of included tingle o/an internal dovetail:

- Dovetail slides are widely used in machine tools as a guide ways.
- The sloping side of the dovetail slide act as guide and prevent the lifting of the female mating part during sliding operation.
- This angle can be measured by using two rollers of equal size, slip gauges and a micrometer.
- The two rollers of equal diameters are placed. One each at the two corners and distance i is measured across the rollers with a micrometer.
- Then the rollers equal size slip gauge blocks and the distance is measured. It should be noted that the rollers do not extend above the top surface of' dovetail.
- Let the height of slip gauges be h, then

$$\tan\theta = \frac{\frac{l_2-l_1}{2}}{h}$$

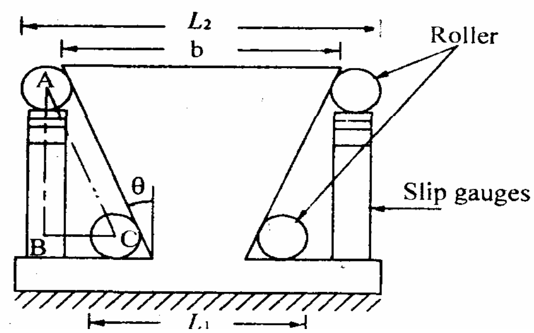


4. Measuring external dovetail slide:

- Figures shows an external dovetail slide with angle of dovetail 0.
- To check the width of opening b as shown in fig., two rollers of equal diameter d are placed one each in the two corners.

- Then the length L is obtained by trial and error with the help of slip gauges or end bars if L is greater than 250mm.
- Then the width ' b' can he calculated by the relation

$$b = l + d + d\,Cot\theta/2$$



LIMIT GAUGES:

- A limit gauge is not a measuring gauge. Just they are used as inspecting gauges.
- The limit gauges are used in inspection by methods of attributes.
- This gives the information about the products which may be either within the prescribed limit or not.
- By using limit gauges report, the control charts of P and C charts are drawn to control invariance of the products.
- This procedure is mostly performed by the quality control department of each and every industry.
- Limit gauge are mainly used for checking for cylindrical holes of identical components with a large numbers in mass production.

Purpose of using limit gauges:

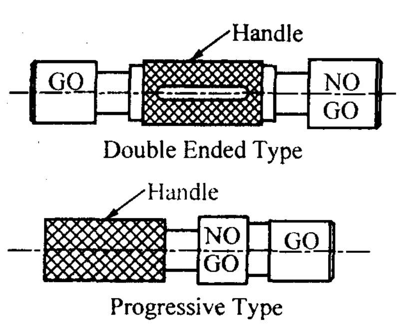
- Components are manufactured as per the specified tolerance limits, upper limit and lower limit. The dimension of each component should be within this upper and lower limit.
- If the dimensions are outside these limits, the components will be rejected.
- If we use any measuring instruments to check these dimensions, the process will consume more time. Still we are not interested in knowing the amount of error in dimensions.
- It is just enough whether the size of the component is within the prescribed limits or not. For this purpose, we can make use of gauges known as limit gauges.

The common types are as follows:

1) Plug gauges.
2) Ring gauges.
3) Snap gauges.

PLUG GAUGES:

- The ends are hardened and accurately finished by grinding. One end is the GO end and the other end is NOGO end.
- Usually, the GO end will be equal to the lower limit size of the hole and the NOGO end will be equal to the upper limit size of the hole.



- Ø If the size of the hole is within the limits, the GO end should go inside the hole and NOGO end should not go.
- Ø If the GO end and does not go, the hole is under size and also if NOGO end goes, the hole is **over size**. Hence, the components are rejected in both the cases.

Now, we are having two chances to make plug gauges.

1. Double ended plug gauges:

In this type, the GO end and NOGO end are arranged on both the ends of the plug. This type has the advantage of easy handling.

2. Progressive type of plug gauges:

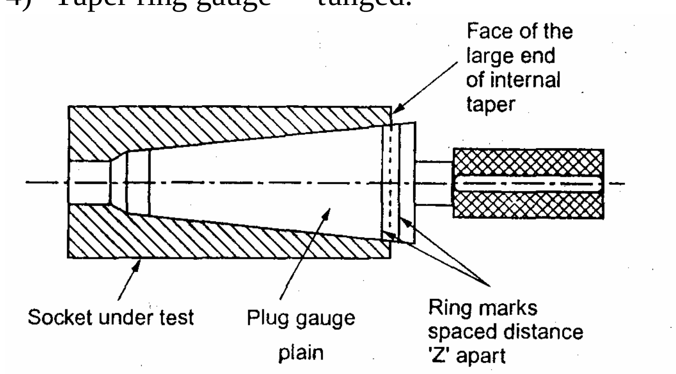
In this type both the GO end and NOGO end are arranged in the same side of the plug. We can use the plug gauge ends progressively one after the other while checking the hole. It saves time. Generally, the GO end is made larger than the NOGO end in plug gauges.

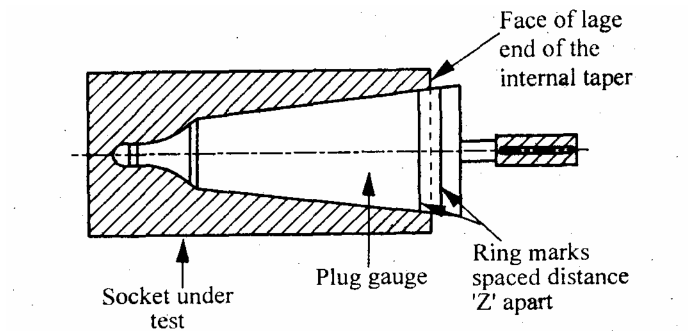
TAPER PLUG GAUGE:

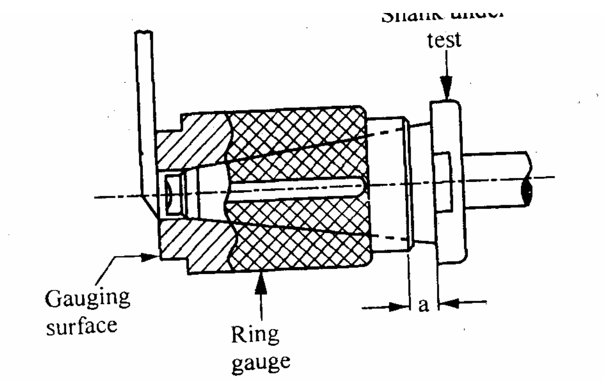
- v Taper plug gauges are used to check tapered holes. It has two check lines. One is a GO line and another is a NOGO line.
- v During the checking of work, NOGO line remains outside the hole and GO line remains inside the hole.

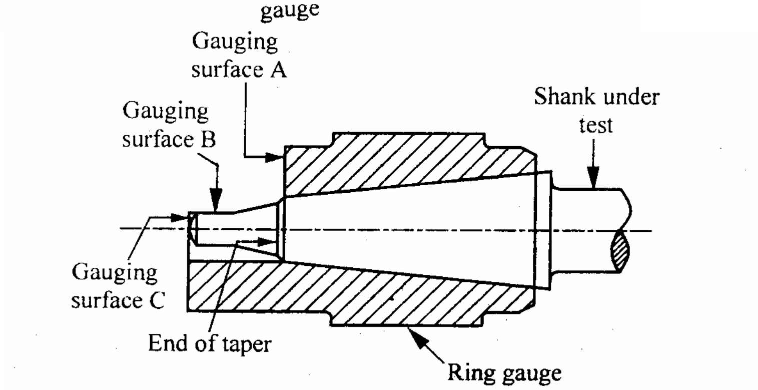
They are various types taper plug gauges are available as shown in fig. Such as

1) Taper plug gauge —plain
2) Taper plug gauge —tanged.
3) Taper ring gauge plain
4) Taper ring gauge —tanged.



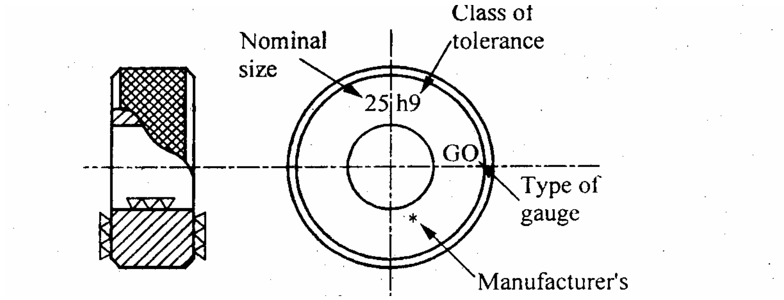






RING GAUGES:

- Ring gauges are mainly used for checking the diameter of shafts having a central hole. The hole is accurately finished by grinding and lapping after taking hardening process.
- The periphery of the ring is knurled to give more grips while handling the gauges. We have to make two ring gauges separately to check the shaft such as GO ring gauge and NOGO ring gauge.
- But the hole of GO ring gauge is made to the upper limit size of the shaft and NOGO for the lower limit.
- While checking the shaft, the GO ring gauge will pass through the shaft and NOGO will not pass.
- To identify the NOGO ring gauges easily, a red mark or a small groove cut on its periphery.



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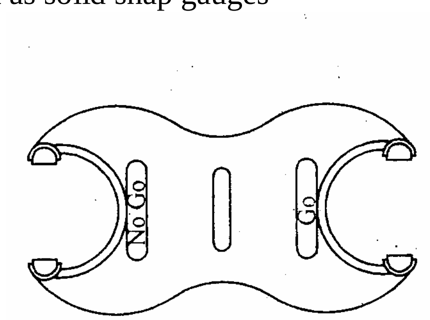
SNAP GAUGE:

- Snap gauges are used for checking external dimensions. They are also called as gap gauges. The different types of snap gauges are:

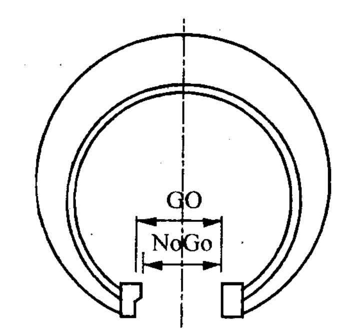
1. DOUBLE ENDED SNAP GAUGE:

- This gauge is having two ends in the form of anvils.
- Here also, the GO anvil is made to lower limit and NOGO anvil is made to upper limit of the shaft.
- It is also known as solid snap gauges



2. PROGRESSIVE SNAP GAUGE:

- This type of snap gauge is also called caliper gauge.
- It is mainly used for checking large diameters up to 100mm. Both GO and NOGO anvils at the same end. The GO anvil should be at the front and NOGO anvil at the rear.
- So, the diameter of the shaft is checked progressively by these two ends.
- This type of gauge is made of horse shoe shaped frame with I section to reduce the weight of the snap gauges



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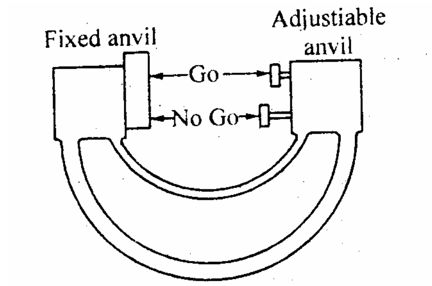
3. ADJUSTABLE SNAP GAUGE:

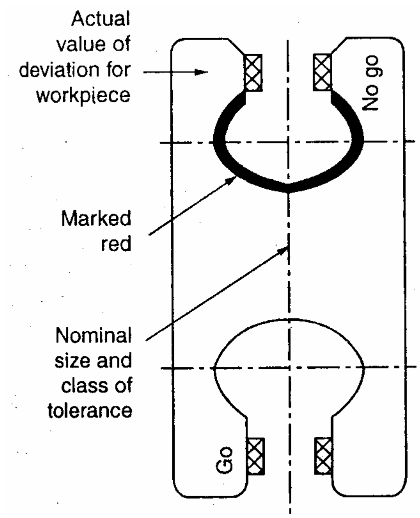
- Adjustable snap gauges are used for checking large size shafts made with horseshoe shaped frame of I section.

- It has one fixed anvil and two small adjustable anvils. The distance between the two anvils is adjusted by adjusting the adjustable anvils by means of setscrews.
- This adjustment can be made with the help of slip gauges for specified limits of size.



4. PLATE TYPE DOUBLE ENDED SNAP GAUGE:

This type is used for sizes from 2mm to 100mm as shown in fig



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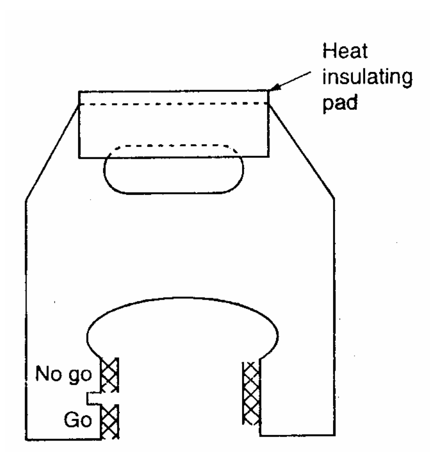
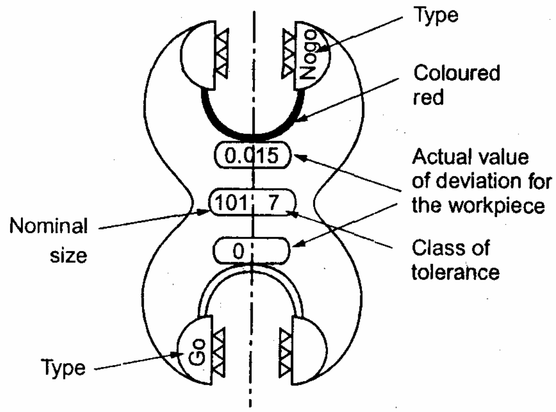
5. PLATE TYPE SINGLE ENDED PROGRESSIVE SNAP GAUGE:

This type is used for sizes from 100mm to 250mm as shown in fig.



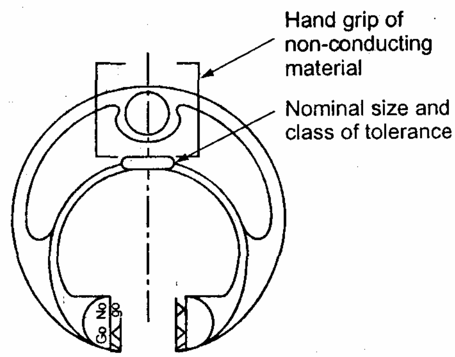
6. COMBINED LIMIT GAUGES:

- A spherical projection is provided with GO and NOGO dimension marked in a single gauge.
- While using GO gauge the handle is parallel to axes of the hole and normal to axes for NOGO gauge.



7. POSITION GAUGE:

- It is designed for checking the position of features in relation to another surface.
- Other types of gauges are also available such as contour gauges, receiver gauges, profile gauges etc.



TAYLOR' S PRINCIPLE:

- It states that GO gauge should check all related dimensions. Simultaneously whereas NOGO gauge should check only one dimension at a time.

Maximum metal condition:

It refers to the condition of hole or shaft when maximum material is left on i.e. high limit of shaft and low limit of hole.

Minimum metal condition:

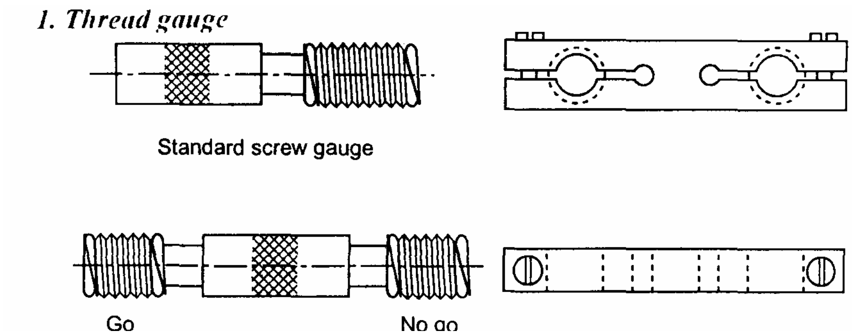
If refers to the condition of hole or shaft when minimum material is left on such as low limit of shaft and high limit of hole.

APPLICATIONS OF LIMIT GAUGES:

1.Thread gauges
2.Form gauges
3.Serew pitch gauges
4. Radius and fillet gauges
5. Feeler gauges
6. Plate gauge and Wire gauge

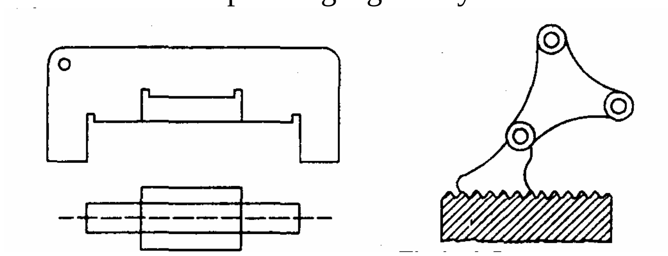
1. THREAD GAUGES

- Threads are checked with the help of thread gauges.
- For checking internal threads, (nuts, bushes) plug thread gauges are used. Similarly, ring thread gauges are used for checking external threads (bolts, screw s).



2. FORM GAUGES:

- Form gauges may be used to check the contour of a profile of a work piece.
- Form gauges are nothing but template gauges made of sheet steel.
- A profile gauges may contain two outlines which indicates the limits of a profile.

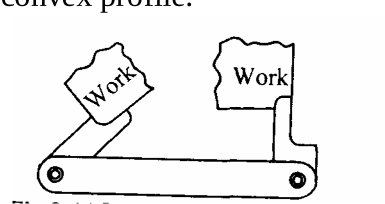


3. SCREW PITCH GAUGES:

- Screw pitch gauges are used to check the pitch of the thread immediately. It is very much in everyday tool used to pick out a required screw.
- The number of flat blades with different pitches is pivoted in a holder. The pitch value is marked on each blade.

4. RADIUS AND FILLET GAUGES:

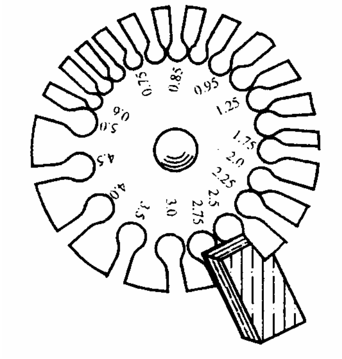
- The radius of curvature can he measure by using these gauges. The radius may be either outer or inner radius.
- According to the type of radius to be measured, the end of the blade is made to either concave or convex profile.

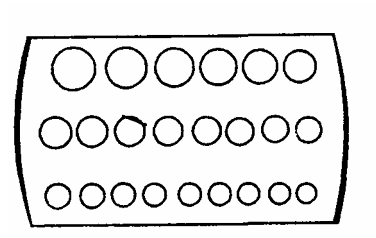


5. FEELER GAUGES:

- Feeler gauges are used for checking the clearance between mating surfaces.
- They are mainly used in adjusting the valve clearance in automobiles.
- They are made from 0.03to 1.0mm thick of 100mm long. The blades are pivoted in a holder.

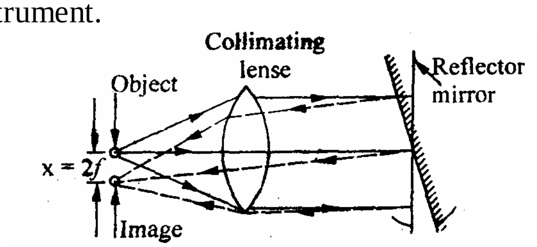
6. PLATE GAUGE AND WIRE GAUGE:





AUTO- COLLIMATOR:

- Auto-collimator is an optical instrument used for the measurement of small angular differences, changes or deflection, plane surface inspection etc.
- For small angular measurements, autocollimator provides a very sensitive and accurate approach.
- An auto-collimator is essentially an infinity telescope and a collimator combined into one instrument.



Basic principle:

- If a light source is placed in the flows of a collimating lens, it is projected as a parallel beam of light.
- If this beam is made to strike a plane reflector, kept normal to the optical axis, it is reflected back along its own path and is brought to the same focus.
- If the reflector is tilted through a small angle ‘ 0’ . Then the parallel beam is deflected twice the angle and is brought to focus in the same plane as the light source.
- The distance of focus from the object is given by

$$x = 2\theta . f$$

Where, f = Focal length of the lens

θ = Fitted angle of reflecting mirror.

Note:

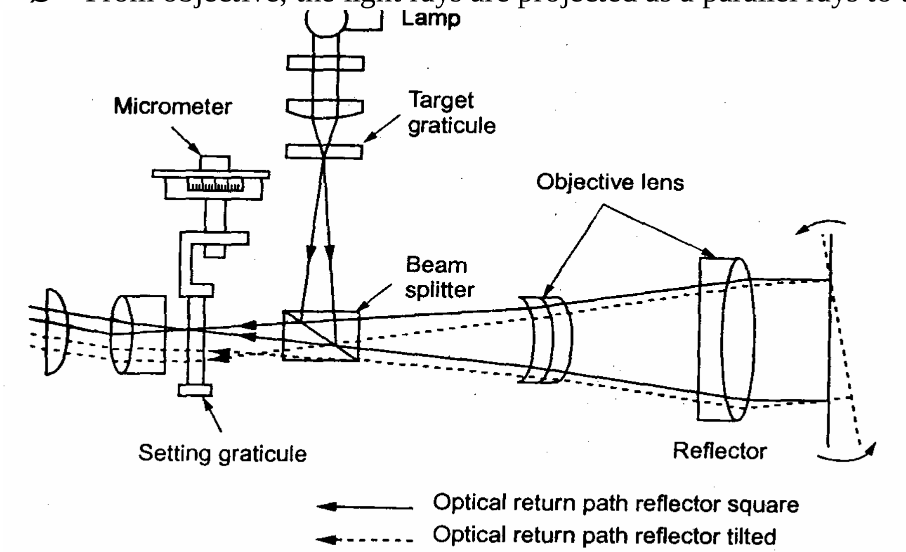
- The position of the final image does not depend upon the distance of reflector from the lens. i.e. distance x is independent of the position of reflection from the lens.
- But if the reflector is moved too much back then reflected rays would completely miss the lens and no image will be formed.
- Thus for full range of reading of instrument to be used, the maximum remoteness of the reflector is limited.
- For high sensitivity, i.e. for large range of reading of x for a small angular deviation 0, a long focal length is required.

WORKING OF AUTO-COLLIMATOR:

There are three main parts in auto-collimator.

1. Micrometer microscope.
2. Lighting unit and
3. Collimating lens.

- Fig. Shows a line diagram of a modern auto-collimator. A target graticule is positioned perpendicular to the optical axis.
- When the target graticule is illuminated by a lamp, rays of light diverging from the intersection point reach the objective lens via beam splitter.
- From objective, the light rays are projected as a parallel rays to the reflector.



Line diagram of an injected graticule auto-collimator

- A flat reflector placed in front of the objective and exactly normal to the optical axis reflects the parallel rays of light back along their original paths.
- They are then brought to the target graticule and exactly coincide with its intersection.
- A portion of the returned light passes through the beam splitter and is visible through the eyepiece.
- If the reflector is tilted through a small angle (θ), the reflected beam will be changed its path at twice the angle.
- It can also be brought to target graticule but linearly displaced from the actual target by the amount 2θ x f.
- Linear displacement of the graticule image in the plane tilted angle of eyepiece is directly proportional to the reflector. This can be measured by optical micrometer.
- The photoelectric auto- collimator is particularly suitable for calibrating polygons, for checking angular indexing and for checking small linear displacements.

. **APPLICATIONS OF AUTO-COLLIMATOR**

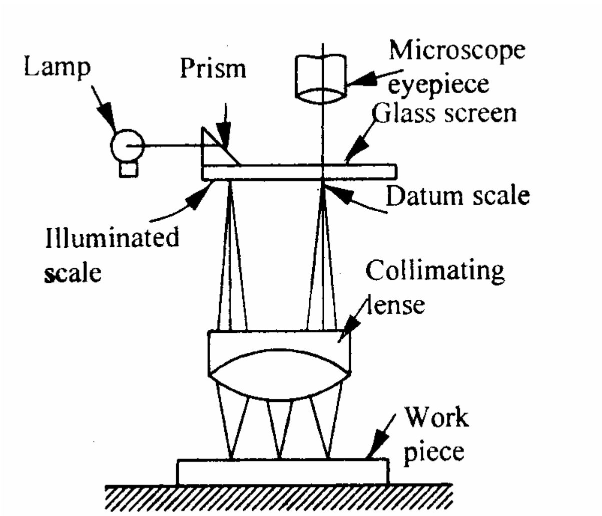
Auto-collimators are used for

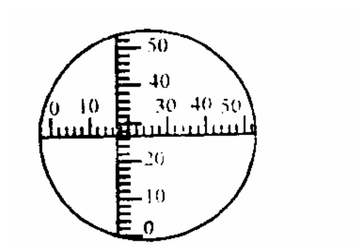
- Measuring the difference in height of length standards.
- Checking the flatness and straightness of surfaces.
- Checking squareness of two surfaces.
- Precise angular indexing in conjunction with polygons.
- Checking alignment or parallelism.
- Comparative measurement using master angles.

- Measurement of small linear dimensions.
- For machine tool adjustment testing.

ANGLE DEKKOR

- This is also a type of auto-collimator.
- There is an illuminated scale in the focal plane of the collimating lens.
- This illuminated scale is projected as a parallel beam by the collimating lens which after striking a reflector below the instrument is refocused by the lens in the filed of view of the eyepiece.
- In the field of view of microscope, there is another datum scale fixed across the center of screen.
- The reflected image of the illuminated scale is received at right angle to the fixed scale as shown in fig.
- Thus the changes in angular position of the reflector in two planes are indicated by changes in the point of intersection of the two scales.
- One division on the scale is calibrated to read 1 minute.





- The whole optical system is enclosed in a tube which is mounted on an adjustable bracket.
- The adjustable bracket is attached to a flat lapped reflective base as shown in fig.

USES OF ANGLE DEKKOR:

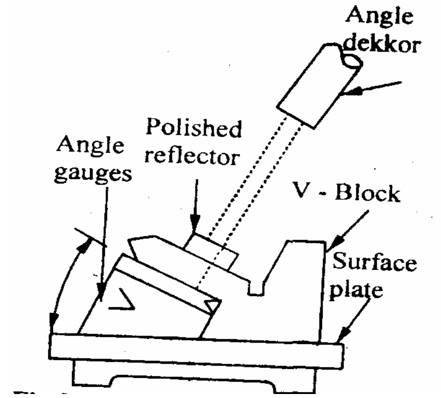
(i) Measuring angle of a component:

- Angle dekkor is capable of measuring small variations in angular setting i.e. determining angular tilt.
- Angle dekkor is used in combination with angle gauge. First the angle gauge combination is set up to the nearest known angle of the component.
- Now the angle dekkor is set to zero reading on the illuminated scale. The angle gauge build up is then removed and replaced by the component under test.
- Usually a straight edge being used to ensure that there is no change in lateral positions. The new position of the reflected scale with respect to the fixed scale gives the angular tilt of the component from the set angle.

(ii) Checking the slope angle of a V-block:

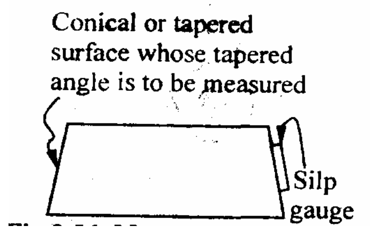
- Fig. shows the set up for checking the sloping angle of V block.
- Initially, a polished reflector or slip gauge is attached in close contact with the work surface. By using angle gauge zero reading is obtained in the angle dekkor.

- Then the angle may be calculated by comparing the reading obtained from the angle dekkor and angle gauge.



(iii) To measure the angle of cone or Taper gauge:

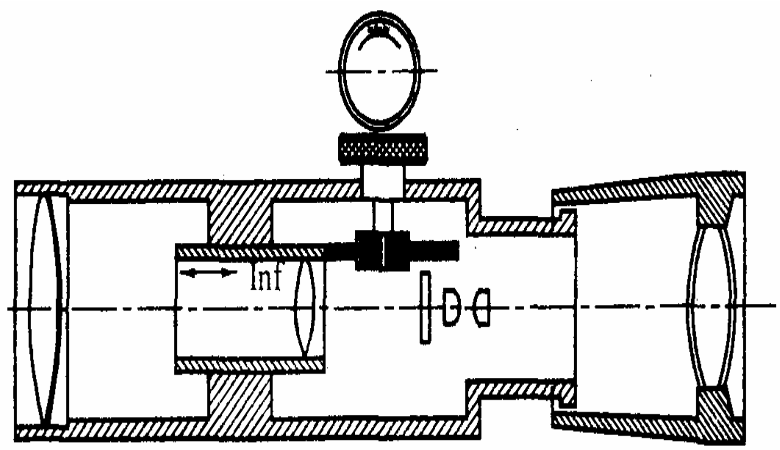
- Fig. shows the set up for this purpose. Initially, the angle dekkor is set for the nominal angle of cone by using angle gauge or sine bar.
- The cone is then placed in position with its base resting on the surface plate.



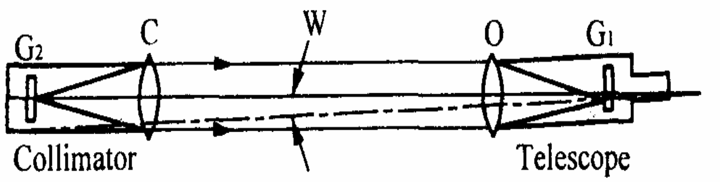
- A slip gauge or reflector is attached on the cone since no reflection can be obtained from the curved surface.
- Any deviation from the set angle will be noted by the angle dekkor in the eyepiece and indicated by the shifting of the image of illuminated scale.

ALIGNMENT TELESCOPE

- Alignment telescope is used for aligning of bores, surfaces and check squareness, straightness, flatness, parallelism, vertically and level.
- One of the important type of alignment telescope is **Taylor-Hobson alignment telescope**.
- This instrument can be used to measure angular alignment as well as lateral displacement and for this purpose the sighting target is mounted in a collimating unit.
- The telescope has an internal-focusing optical system, similar in principle to that of the surveyor' s level built into a robust unit having a precisely ground external diameter.
- The focusing knob can be clearly seen in the optical system is shown in fig.
- The collimating unit consists of another steel tube, ground to the same diameter as the telescope and containing an illuminating system, a graticule G a collimating lens and another graticule G.
- The graticule G is graduated with central cross lines, surrounded with scales and concentric circles and lies exactly at the principal focus of the collimating lenses.
- The graticule G contains a central pattern of converging V and several graduated scales lying in two directions at right angles.



- The use of telescope with the collimator is given in fig.
- If the telescope is aligned with the collimator and sighted on it with its focus adjusted to infinity target graticule G will appear in the field of view, since rays from this target will emerge parallel beams from the collimating lens.
- Purely lateral displacements of telescope and target will therefore not register, but any angular misalignment will show as a displacement of the image of the target.
- If the telescope is now refocused until the target G appears in the field, only lateral displacements of the collimator will be indicated, the parallel beams from the target G being out of focus.

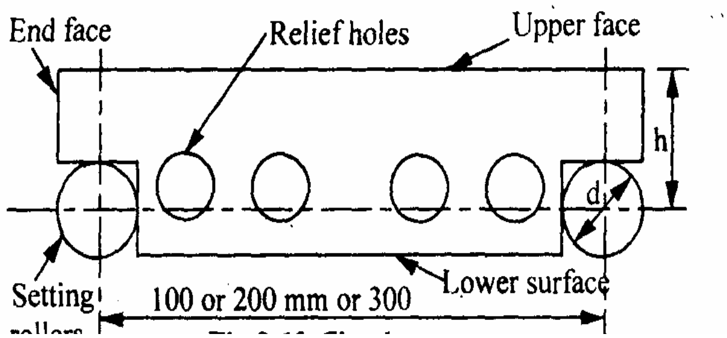


Use of Collimator

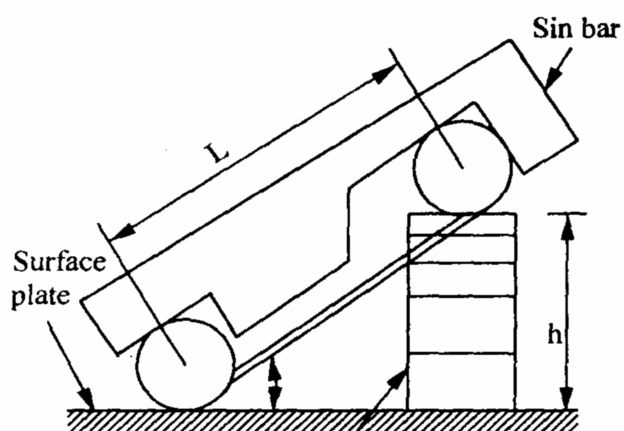
- Lateral displacements of the collimator unit will therefore be measured in the telescope by means of the scales on graticule G
- The ground bores of the telescope and collimator make the instrument particularly suitable for the alignment of two or more bores, such as bearings of a large engines.
- The two units can be located centrally in each bore, using ground bushes where necessary. and both lateral and angular alignment can be measured.
- Accurate optical alignment of the telescope with its ground diameter is ensured by careful centering of the lenses and accuracy of the draw table of the focusing lens.
- The use of the optical micrometer and the accuracy obtainable by rotation of the telescope are only available for the measurement of lateral displacement of the target.
- The instrument is not equipped for a similar accuracy or angular measurement without any reason; a micrometer eyepiece would provide the means of doing this.

SINE BAR

- Sine bars are always used along with slip gauges as a device for the measurement of angles very precisely.
- They are used to
  1) Measure angles very accurately.
  2) Locate the work piece to a given angle with very high precision.
- Generally, sine bars are made from high carbon, high chromium, and corrosion resistant steel. These materials are highly hardened, ground and stablished.
- In sine bars, two cylinders of equal diameter are attached at lie ends with its axes are mutually parallel to each other.
- They are also at equal distance from the upper surface of the sine bar mostly the distance between the axes of two cylinders is 100mm, 200mm or 300mm.
- The working surfaces of the rollers are finished to 0.2μm R value.
- The cylindrical holes are provided to reduce the weight of the sine bar.



Working principle of sine bar:



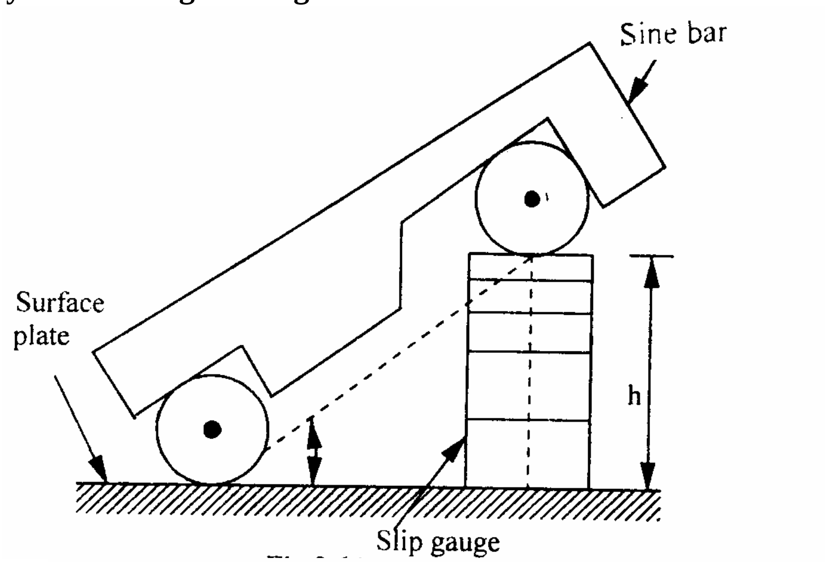
- The working of sine bar is based on **trigonometry principle**.
- To measure the angle of a given specimen, one roller of the sine bar is placed on the surface plate and another one roller is placed over the surface of slip gauges.
- Now, ' h be the height of the slip gauges and ' L' be the distance between roller centers, then the angle is calculated as

$$\sin\theta = \frac{h}{L}$$

$$\therefore \theta = \sin^{-1}(h/L)$$

USE OF SINE BAR:

(1,) Locating any' work to a given angle:

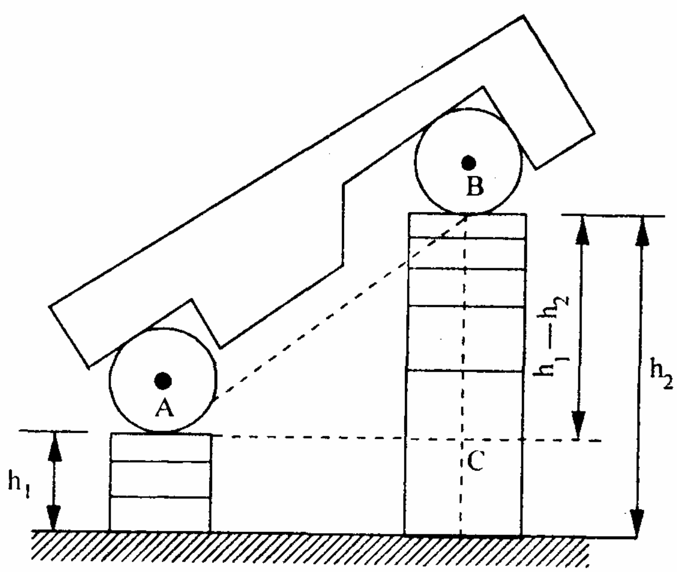


i. To set at a given angle θ, first '*h*' of slip gauge is calculated by the formula $Sin\theta = h/L$

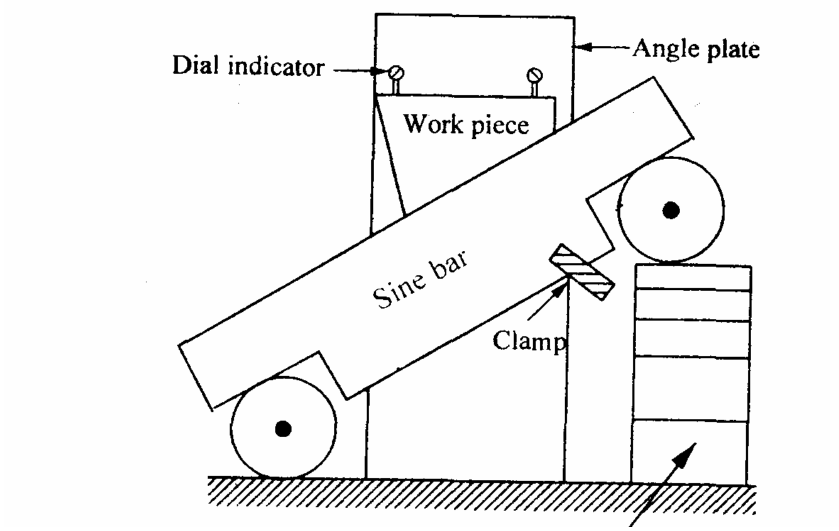
ii. After calculating the height '*h*', the required height '*h*' is made by using suitable slip gauge combinations.

iii. After this, one of the rollers is placed on the top of the sine bar and the other one is placed on the top of the slip gauge combination.

For getting more accurate results, both the rollers can be placed slip gauges as shown in fig. 2.65.



(ii) To check unknown angles:



1) Before checking the unknown angle of the specimen, first the angle (0) of given specimen is found approximately by bevel protractor.
2) Then the sine bar is set at angle of 0 and clamped on the angle plate.
3) Now, the work is placed on the sine bar and the dial indicator set at one end of the work is moved across the work piece and deviation is noted.
4) Slip gauges are adjusted so that the dial indicator reads zero throughout the work surface.

Limitations of sine bars:

1) Sine bars are fairly reliable for angles than 15°.
2) It is physically difficult to hold in position.
3) Slight errors in sine bar cause larger angular errors.
4) A difference of deformation occurs at the point of roller contact with the surface plate and to the gauge blocks.
5) The size of parts to be inspected by sine bar is limited.

Sources of error in sine bars:

The different sources of errors are listed below:

1) Error in distance between roller centers.
2) Error in slip gauge combination.
3) Error in checking of parallelism.
4) Error in equality of size of rollers and cylindricity.
5) Error in parallelism of roller axes with each other.
6) Error in flatness of the upper surface of sine bar.

BEVEL PROTRACTORS

Bevel protractors are nothing but angular measuring instruments.

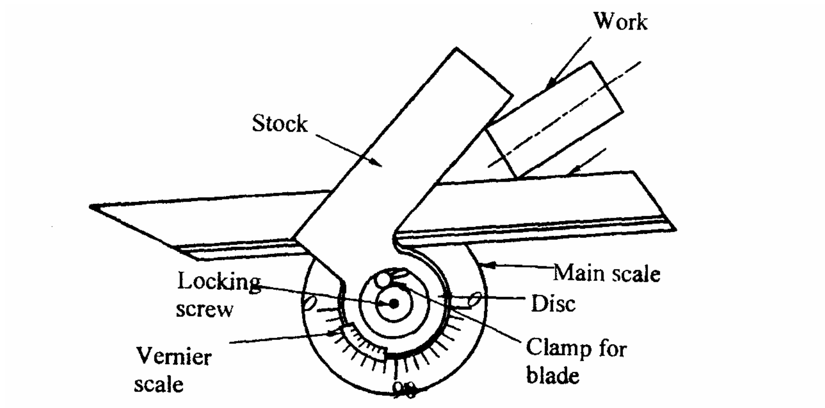
Types of bevel protractors:

The different types of bevel protractors used are:

1) Vernier bevel protractor
2) Universal protractor
3) Optical protractor

1. VERNIER BEVEL PROTRACTOR:

Working principle:



- A vernier bevel protractor is attached with acute angle attachment.
- The body is designed its back is flat and no projections beyond its back. The base plate is attached to the main body and an adjustable blade is attached to the circular plate containing vernierscale.
- The main scale is graduated in degrees from 0° to 90° in both the directions. The adjustable can be made to rotate freely about the center of the main scale and it can be locked at any position.
- For measuring acute angle, a special attachment is provided. The base plate is made fiat for measuring angles and can be moved throughout its length. The ends of the blade are beveled at angles of 45° and 60°.
- The main scale is graduated as one main scale division is 1° and vernier is graduated into 12 divisions on each side of zero. Therefore the least count is calculated as

$$Least\ count = \frac{One\ main\ scale\ division}{No.\ of\ divisions\ on\ vernier\ scale}$$

$$= \frac{1^\circ}{12}(\deg rees)$$

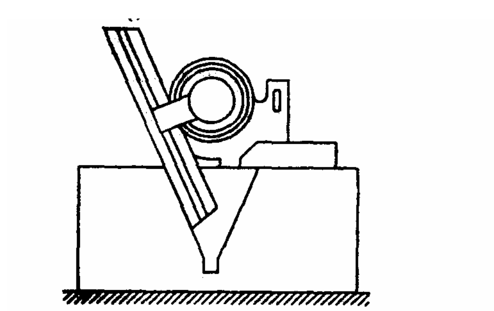
$$= \frac{1}{12} \times 60 = 5\ \min utes$$

Thus, the bevel protractor can be used to measure to an accuracy of 5 minutes.

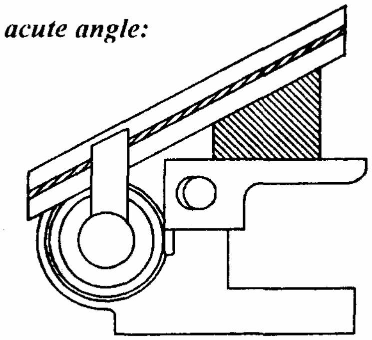
Applications of bevel protractor

The bevel protractor can be used in the following applications.

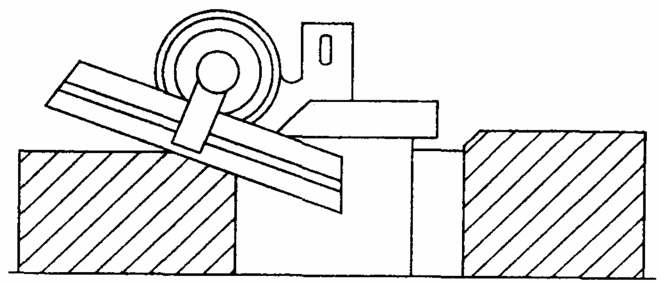
1. **For checking a 'V' block:**



2. For measuring acute angle:



3. For checking in inside beveled face of a ground surface.



PART-A

1. What is comparator?
2. Give the uses of comparators.
3. How are comparators classified?
4. Name important mechanical comparators.
5. State the advantages and disadvantages of mechanical comparators.
6. What are the various linear measuring devices?
7. What are the various angular measuring devices?
8. How levels are calibrated?
9. State the advantages of vernier caliper and micrometer?
10.How slip gauges are manufactured?
11.What is the other name for slip gauges?
12.Define-Rollers and its types?
13. Define-Limit gauges and its types?
14.State the applications of limit gauges?
15. Define-Feeler gauges?
16. Define-Auto collimator?
17. Define-Angle Dekkor?
18. Define-Alignment telescope ?
19. Define-Sine Bar?
20. Define-Bevel protractor ?

PART-B

1. Describe a ‘dial indicator’ with a neat sketch.
2. Explain about Comparators and its types in detail with neat sketch?
3. Explain about Mechanical Comparators and its types in detail with neat sketch?
4. Explain about Pneumatic Comparators in detail with neat sketch?
5. Explain about Optical Comparators and its types in detail with neat sketch?
6. Explain about Electrical Comparators and its types in detail with neat sketch?
7. Explain about Slip gauges and its classification in detail with neat sketch?
8. Explain about Rollers and its types in detail with neat sketch?
9. Explain about Limit gauges and its types in detail with neat sketch?
10. Explain about Auto collimator in detail with neat sketch?
11. Explain about Angle Dekkor in detail with neat sketch?
12. Explain about Alignment telescope in detail with neat sketch?
13. Explain about Sine Bar in detail with neat sketch and its applications?
14. Explain about Bevel protractor in detail with neat sketch and its applications?

Principles and Methods of Temperature Measurement

Course No: E02-012

Credit: 2 PDH

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PRINCIPLES & METHODS OF TEMPERATURE MEASUREMENT

Abstract

Temperature measurement is a vital part of most industrial operations and is typically accomplished by a temperature sensor--a thermocouple or a resistance temperature detector (RTD)--in contact with a solid surface or immersed in a fluid. Although these sensors have overlapping temperature ranges, each has certain application-dependent advantages.

Several factors must be considered when selecting the type of sensor to be used in a specific application: temperature range, accuracy, response time, stability, linearity, and sensitivity. An RTD is the sensor of choice when sensitivity and application flexibility are the most important criteria. When it comes to component cost, an RTD is more expensive than a thermocouple. Choosing the perfect sensor for a particular application therefore requires an understanding of the basics of temperature sensors.

There are four basic types of temperature measuring devices, each of which uses a different principle:

1. Mechanical devices (liquid-in-glass thermometers, bimetallic strips, bulb & capillary, pressure type etc.)
2. Thermojunctive (thermocouples)
3. Thermoresistive (RTDs and thermistors)
4. Radiative (infrared and optical pyrometers)

Each of these is defined and the discussed in this course.

PART -1: MECHANICAL DEVICES

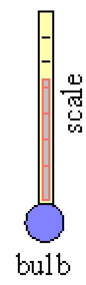
Principle of Operation

A change in temperature causes some kind of mechanical motion, typically due to the fact that most materials expand with a rise in temperature. Mechanical thermometers can be constructed to use liquids, solids, or even gases as the temperature-sensitive material.

The mechanical motion is read on a physical scale to infer the temperature. The examples include:

1) ***Liquid-in-glass thermometer***

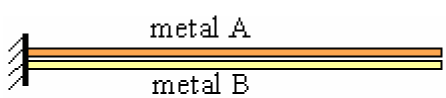
The most common and well-known thermometer is the liquid-in-glass thermometer.



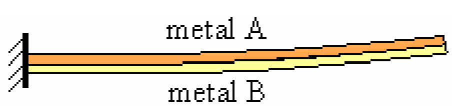
As the temperature rises, the liquid expands, moving up the tube. The scale is calibrated to read temperature directly. Usually, mercury or some kind of alcohol is used for the liquid.

2) ***Bimetallic strip thermometer***

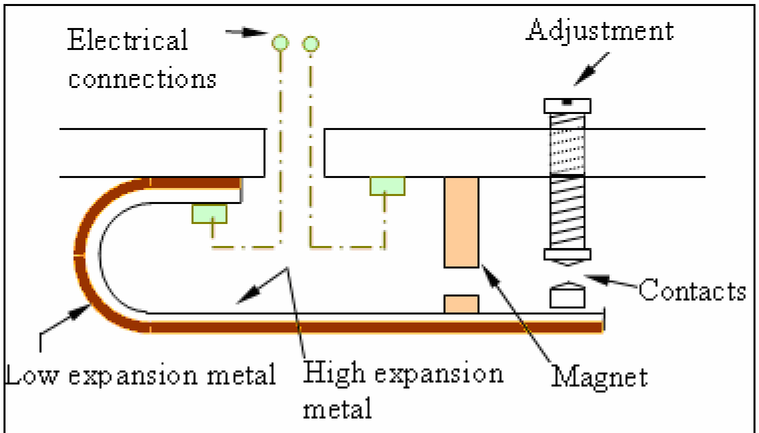
Two dissimilar metals are bonded together into what is called a bimetallic strip as shown below.



Suppose metal A has a smaller coefficient of thermal expansion than does metal B. As temperature increases, metal B expands more than does metal A, causing the bimetallic strip to curl upwards as shown below.



One common application of bimetallic strips is in air-conditioning thermostats, where a bimetallic strip is used as the arm of a switch between electrical contacts. As the room temperature changes, the bimetallic strip bends as discussed above. When the bimetalic strip bends far enough, it makes contact with electrical leads which turn the heat or air conditioning on or off.

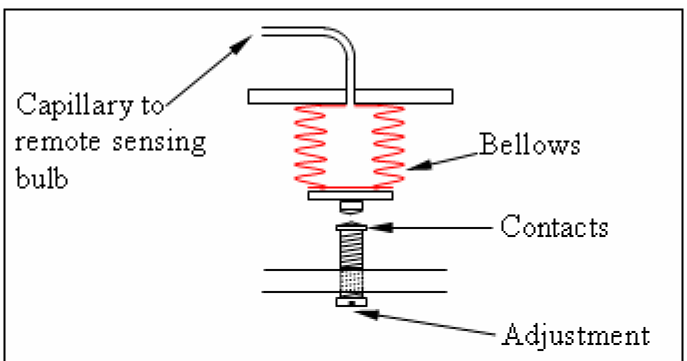


Bi-Metallic Thermostat

Another common application is for use as oven thermometers or wood burner thermometers. These thermometers consist of a bimetallic strip wound up in a spiral, attached to a dial which is calibrated into a temperature scale.

3) **Sealed Bellows**

The sealed bellows type is filled with a gas, vapor or liquid, which responds to change in temperature by variation in volume and pressure causing expansion or contraction.

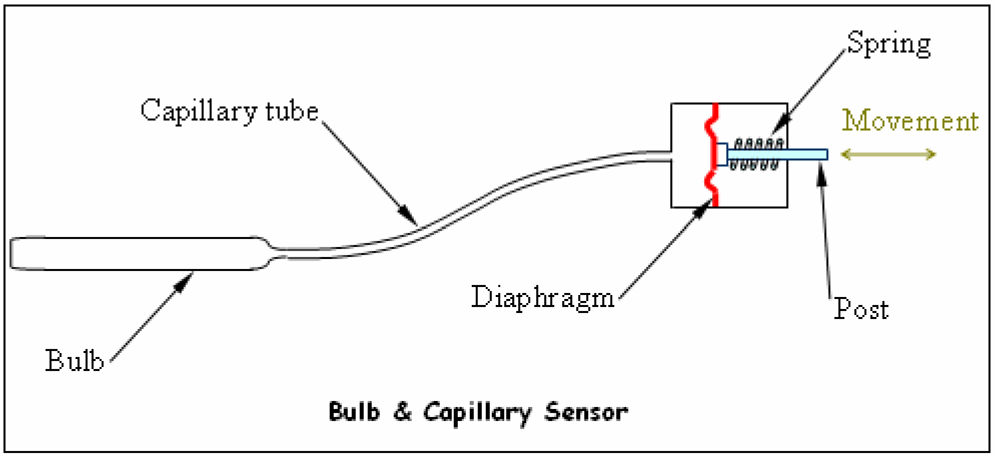


Sealed Bellows Temperature Sensor

4) **Bulb and Capillary Sensor**

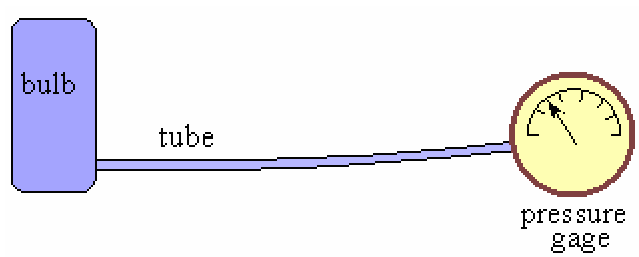
Bulb and capillary elements are used where temperatures are to be measured in ducts, pipes, tanks or similar locations remote from the controller.

The bulb is filled with liquid, gas or refrigerant depending on the temperature range required. Expansion of the fluid in the heated bulb exerts a pressure which is transmitted by the capillary to the diaphragm and there translated into movement.



5) **Pressure thermometer**

A pressure thermometer, while still considered mechanical, operates by the expansion of a gas instead of a liquid or solid. (Note: There are also pressure thermometers which use a liquid instead of a gas.)



Suppose the gas inside the bulb and tube can be considered an ideal gas. The ideal gas law is:

$PV = m R T$

Where:

- P is the pressure,
- V is the volume of the gas,
- m is the mass of the gas,
- R is the gas constant for the specific gas (not the universal gas constant), and
- T is the absolute temperature of the gas.

The bulb and tube are of constant volume, so V is a constant. Also, the mass, m, of gas in the sealed bulb and tube must be constant. Hence, the above equation reduces to $P = kT$, where k is constant.

A pressure thermometer therefore measures temperature *indirectly* by measuring pressure. The gage is a pressure gage, but is typically calibrated in units of temperature instead.

A common application of this type of thermometer is measurement of outside temperature from the inside of a building. The bulb is placed outside, with the tube running through the wall into the inside. The gage is on the inside. As T increases outside, the bulb temperature causes a corresponding increase in pressure, which is read as a temperature increase on the gage.

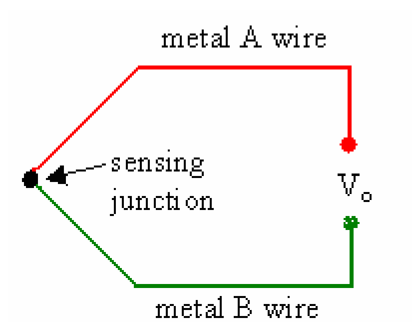
PART -2: THERMOCOUPLES

A thermocouple is made up of two dissimilar metals, joined together at one end, that produce a voltage (expressed in millivolts) with a change in temperature. The junction of the two metals, called the sensing junction, is connected to extension wires. Any two dissimilar metals may be used to make a thermocouple.

Principle of Operation

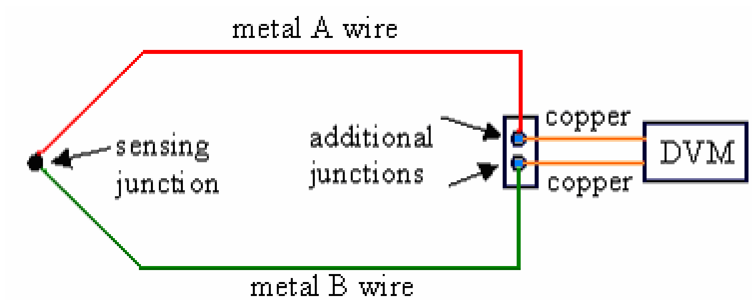
1. When two dissimilar metals are connected together, a small voltage called a *thermo-junction voltage* is generated at the junction. This is called the *Peltier effect*.
2. If the temperature of the junction changes, it causes voltage to change too, which can be measured by the input circuits of an electronic controller. The output is a voltage proportional to the temperature difference between the junction and the free ends. This is called the *Thompson effect*.
3. Both of these effects can be combined to measure temperature. By holding one junction at a known temperature (reference junction) and measuring the voltage, the temperature at the sensing junction can be deduced. The voltage generated is directly proportional to the temperature difference. The combined effect is known as the *thermo-junction effect* or the *Seebeck effect*.

The figure below illustrates a simple thermocouple circuit.



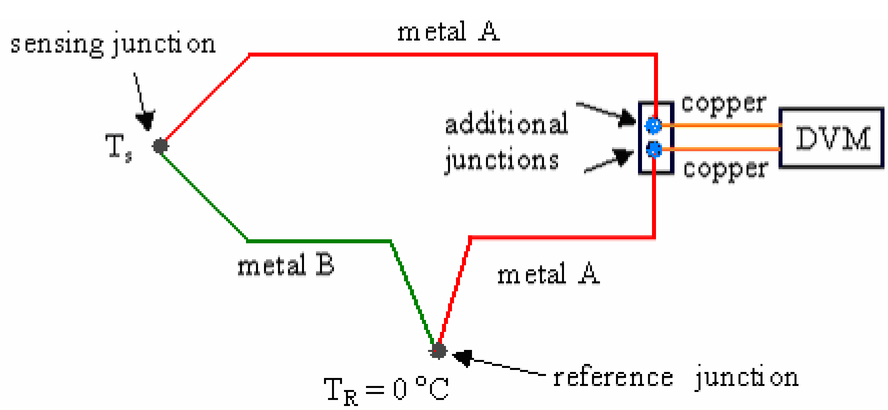
The voltage is measured to infer the temperature. In practical operation, wires A and B are connected to a digital voltmeter (DVM), digital multimeter (DMM), digital data acquisition system, or some other voltage measuring device. If the measuring device has very high input impedance, the voltage produced by the thermo-junction can be measured accurately.

However, the main problem with thermocouple temperature measurement is that wires A and B must connect to the leads of the voltmeter, which are generally made of copper. If neither wire A nor wire B is itself copper, connecting to the DVM creates *two more thermo-junctions*! (Thermocouple metals are typically not the same as those of the DVM leads.) These additional thermo-junctions also produce a thermo-junctive voltage, which can create an error when trying to measure the voltage from the sensing junction.



How can this problem be resolved?

One simple solution is to add a fourth thermo-junction, called a *reference junction*, by inserting an additional length of metal A wire into the circuit as sketched below. The reference junction consists of metals A and B as indicated on the sketch.



This modified circuit is analyzed as follows:

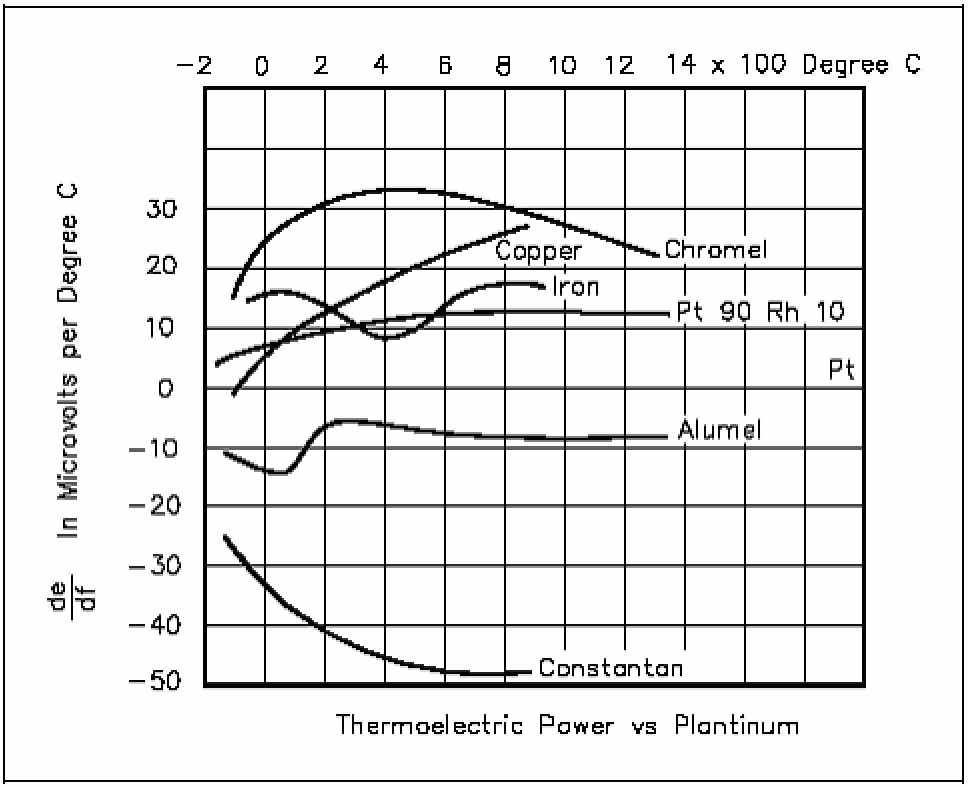
With this arrangement, there are still two additional thermocouple junctions formed where the compensated thermocouple is connected to the voltmeter (DVM). The two junctions to the DVM are now both between metal A and copper. These two junctions are placed *close together*, and at the *same temperature*, so that their thermo-junction voltages are identical, and cancel each other out. Meanwhile, the new reference junction is placed in a location where the *reference temperature* T_R is known accurately, typically in an ice-water bath with a fixed temperature of T_R = 0°C. If the sensing junction is also at 0°C (T_s = 0 ^oC), the voltage generated by the sensing junction will be equal and opposite of that generated by the reference junction. Hence, V_o = 0 when T_s = 0°C. However, if the sensing junction temperature is not equal to T_R, V_o will be non-zero.

In summary, *V_o is a unique function of the sensor temperature T_s and the two metals used for the thermocouple*. Thus, for known reference temperature and known thermocouple wire materials, output voltage V_o can be used to measure temperature. This is the fundamental concept of thermocouple usage.

Thermocouple Materials

Thermocouples may be constructed of several different combinations of materials. The performance of a thermocouple material is generally determined by using that material with platinum. The most important factor to be considered when selecting a pair of materials is the "thermoelectric difference" between the two materials. A significant difference between the two materials will result in better thermocouple performance. The figure below illustrates the characteristics of the more commonly used materials when used with platinum. For example: Chromel-Constantan is excellent for temperatures up to 2000°F; Nickel/Nickel-Molybdenum sometimes replaces Chromel-Alumel; and Tungsten-Rhenium is used for temperatures up to 5000°F. Some combinations used for specialized applications are Chromel-White Gold, Molybdenum-Tungsten, Tungsten-Iridium, and Iridium/Iridium-Rhodium.

The figure below illustrates the thermocouple material characteristics when used with Platinum.



Characteristics of Thermocouple Types

Of the infinite number of thermocouple combinations, the Instrument Society of America (ISA) recognizes 12 of them. Most of these thermocouple types are known by a single-letter designation; the most common are J, K, T, and E. The compositions of thermocouples are international standards, but the color codes of their wires are different. For example, in the U.S. the negative lead is always red, while the rest of the world uses red to designate the positive lead. Often, the standard thermocouple types are referred to by their trade names. For example,

1. A *type K* thermocouple has the color *yellow*, and uses *chromel – alumel,* which are the trade names of the Ni-Cr and Ni-Al wire alloys.
2. A *type J* thermocouple has the color *black*, and uses *iron* and *constantan* as its component metals. (Constantan is an alloy of nickel and copper.)
3. A *type T* thermocouple has the color *blue*, and uses *copper* and *constantan* as its component metals.
4. A type S thermocouple uses Pt/Rh-Pt
5. A type E thermocouple uses Ni/Cr-Con

6. *A type N thermocouple uses Ni/Cr/Si-Ni/Si*

Each calibration has a different temperature range and environment, although the maximum temperature varies with the diameter of the wire used in the thermocouple. Variations in the alloy composition and the condition of the junction between the wires are sources of error in temperature measurements. The standard error of thermocouple wire varies from ±0.8 °C to ±4.4 °C, depending on the type of thermocouple used. The K type thermocouple is recommended for most general purpose applications. It offers a wide temperature range, low standard error, and has good corrosion resistance. In fact, many digital multi-meters (DMMs) can measure temperature by plugging in a type K thermocouple with standard connections.

The voltage produced by a thermocouple varies *almost*, but not exactly, linearly with temperature. Therefore, there are no simple equations to relate thermocouple voltage to temperature. Rather, voltage is tabulated as a function of temperature for the various standard thermocouples. In order to convert the millivolt reading to its corresponding temperature, you must refer to tables like the one shown below. These tables can be obtained from the thermocouple manufacturer, and they list the specific temperature corresponding to a series of millivolt readings. *By convention, the reference temperature for thermocouple tables is 0ºC.*

Temperature V/s Voltage Reference Table for Type J

Temperature (^{o}C)	**voltage (mV)**
0.0	0.000
10.0	0.507
20.0	1.019
30.0	1.537
40.0	2.059
50.0	2.585
60.0	3.116

Temperature (^oC)	**voltage (mV)**
70.0	3.650
80.0	4.187
90.0	4.726
100.0	5.269

Choosing a thermocouple type

Because thermocouples measure in wide temperature ranges and can be relatively rugged, they are very often used in industry. The following criteria are used in selecting a thermocouple:

1. Temperature range
2. Chemical resistance of the thermocouple or sheath material
3. Abrasion and vibration resistance
4. Installation requirements (may need to be compatible with existing equipment; existing holes may determine probe diameter).

Standard Specifications

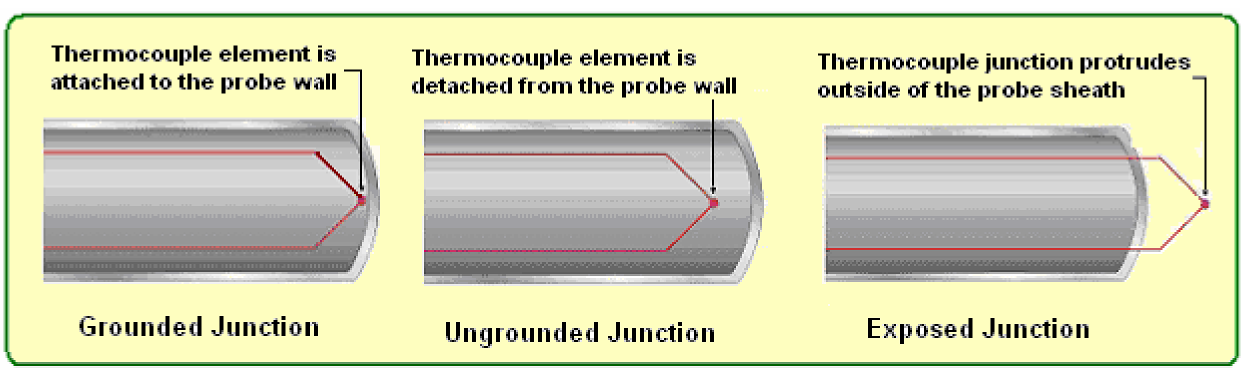
- Diameters: Standard diameters: 0.010", 0.020", 0.032", 0.040", 1/16", 1/8", 3/16", and 1/4" with two wires.
- Length: Standard thermocouples have 12 inch immersion lengths. Other lengths are custom made.
- Sheaths: 304 stainless steel and Inconel are standard.
- Insulation: Magnesium Oxide is standard. Minimum insulation resistance wire to wire or wire to sheath is 1.5megohms at 500 volts dc in all diameters.
- Calibration: Iron-Constantan (J), *chromel – alumel* (K), Copper-Constantan (T), and Chromel-Constantan (E) are standard calibrations.

- Bending: Easily bent and formed. Bend radius should be not less than twice the diameter of the sheath.
- Polarity: In the thermocouple industry, standard practice is to color the negative lead red.
- Thermocouple Junctions: Sheathed thermocouple probes are available with one of three junction types: grounded, ungrounded or exposed.

Grounded Junction- In this type, the thermocouple wires are physically attached to the inside of the probe wall. This results in good heat transfer from the outside, through the probe wall to the thermocouple junction. The grounded junction is recommended for the measurement of static or flowing corrosive gas and liquid temperatures and for high pressure applications. The junction of a grounded thermocouple is welded to the protective sheath giving faster response than the ungrounded junction type.

Ungrounded Junction- In an underground probe, the thermocouple junction is detached from the probe wall. Response time is slowed down from the grounded style, but the ungrounded offers electrical isolation of 1.5 M1/2 at 500 Vdc in all diameters. An ungrounded junction is recommended for measurements in corrosive environments where it is desirable to have the thermocouple electronically isolated from and shielded by the sheath. The welded wire thermocouple is physically insulated from the thermocouple sheath by MgO powder (soft).

Exposed Junction- In the exposed junction style, the thermocouple protrudes out of the tip of the sheath and is exposed to the surrounding environment. This type offers the best response time, but is limited in use to non-corrosive and non-pressurized applications. The junction extends beyond the protective metallic sheath to give accurate fast response. The sheath insulation is sealed where the junction extends to prevent penetration of moisture or gas which could cause errors.



In summary, the exposed junction provides the quickest response time followed by grounded junction. Temperature measurement decisions can make or break the expected results of the process. Choosing the correct sensor for the application might be a difficult task, but processing that measured signal is also very critical.

Thermocouple Laws

First some *notation*:

Let T_1 be the temperature of bath 1, and T_2 be the temperature of bath 2.

Let $V_{1\text{-}R}$ be defined as the voltage produced by a thermocouple at temperature T_1 when a proper reference junction at temperature T_R is used (T_R = reference temperature = 0 ^oC). $V_{1\text{-}R}$ *is the voltage listed in the thermocouple tables at temperature* T_1.

Let $V_{1\text{-}2}$ be defined as the difference in voltage between $V_{1\text{-}R}$ and $V_{2\text{-}R}$,

$V_{1\text{-}2} = V_{1\text{-}R} - V_{2\text{-}R}$

Sign convention:

Negative sign errors can be problematic when working with these equations, if one is not consistent.

By convention, the thermocouple tables are constructed such that *higher* temperature yields *higher* thermo-junctive voltage.

In other words, it is always be assumed that the two thermocouple wires (let's call them wire A and wire B) are connected to the voltmeter in such a way that the voltage is *positive* when the temperature being measured is *greater* than the reference temperature. Likewise, the voltage is *negative* when the temperature being measured is *less* than the reference temperature.

Since the standard reference temperature for thermocouple tables is 0ºC, positive temperatures in units of ºC yield positive thermo-junctive voltages, and negative temperatures in units of ^oC yield negative thermo-junctive voltages.

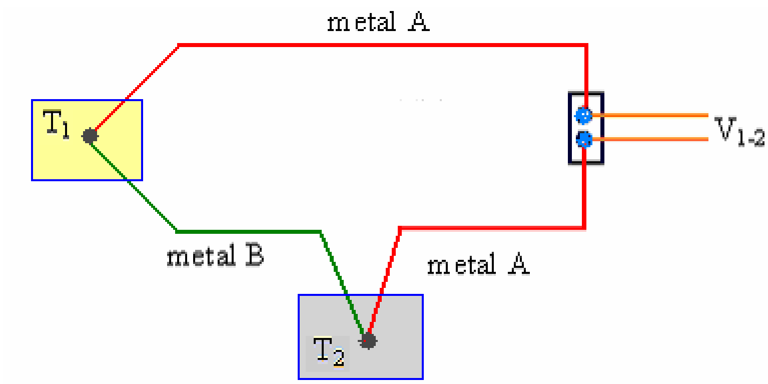
Note that if the wires are connected the *opposite* way to the voltmeter, the voltages will, of course, be of opposite signs.

There are three laws or rules that apply to thermocouples:

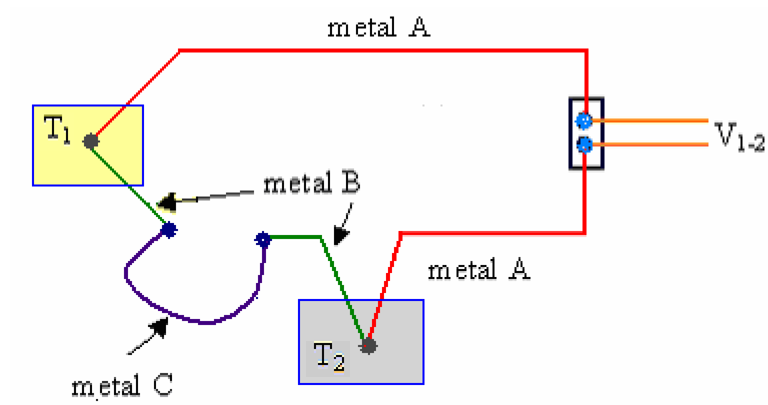
1) ***Law of intermediate metals***

"A third (intermediate) metal wire can be inserted in series with one of the wires without changing the voltage reading (provided that the two new junctions are at the same temperature)".

Consider the setup below, where a rectangle around a thermo-junction indicates a constant temperature bath (e.g. a pot of boiling water or an ice-water bath).



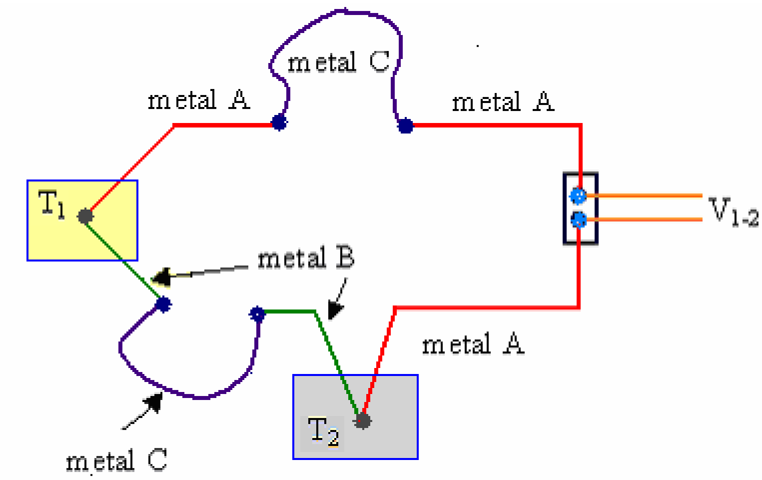
The law of intermediate metals states that the voltage reading, $V_{1\text{-}2}$ does not change if one adds a third (intermediate) wire in line with any of the wires in the circuit, as sketched below:



In the above diagram, it is assumed that both of the new junctions (between metal B and metal C) are at the same temperature, i.e. ambient temperature, T_a.

One can easily see that the law of intermediate metals must hold here, since whatever voltage is generated at one of the new junctions is canceled exactly by an equal and opposite voltage generated at the other new junction.

Likewise, metal C can be inserted anywhere else in the circuit without any effect on the output voltage, provided that the two new junctions are at the same temperature. For example, consider the following modified circuit:



Again, if the two new junctions (this time between metals A and C) are at the same temperature, there is no net effect on the output voltage.

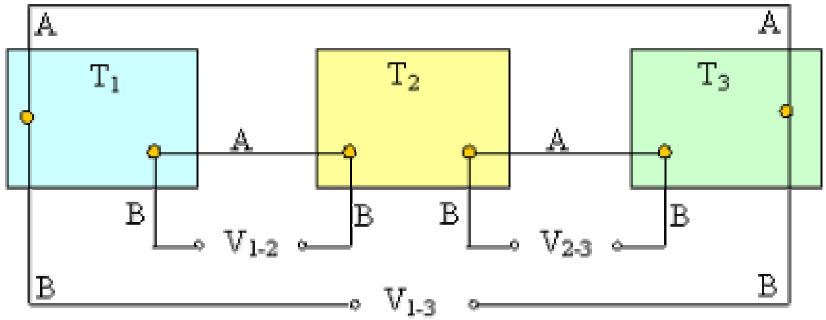
2) ***Law of intermediate temperatures***

"If identical thermocouples measure the temperature difference between T_1 and T_2, and the temperature difference between T_2 and T_3, then the sum of the corresponding voltages V_{1-2} + V_{2-3} must equal the voltage V_{1-3} generated by an identical thermocouple measuring the temperature difference between T_1 and T_3".

<u>Mathematical statement of the law of intermediate temperatures:</u>

$V_{1-3} = V_{1-2} + V_{2-3}$ for any three temperatures, T_1, T_2, and T_3.

Consider the setup below, where six thermo-junctions are shown, two in each constant temperature bath. Note: To avoid clutter in the diagram, the copper leads of the DVM are no longer shown. Also, for brevity, letters A and B indicate metal A and metal B; two different types of thermocouple wires.



By the notation convention adopted here:

$V_{1\text{-}3} = V_{1\text{-}R} - V_{3\text{-}R}$,

which can be written as:

$V_{1\text{-}3} = (V_{1\text{-}R} - V_{2\text{-}R}) + (V_{2\text{-}R} - V_{3\text{-}R})$

But since (also by definition):

$V_{1\text{-}2} = V_{1\text{-}R} - V_{2\text{-}R}$, and

$V_{2\text{-}3} = V_{2\text{-}R} - V_{3\text{-}R}$,

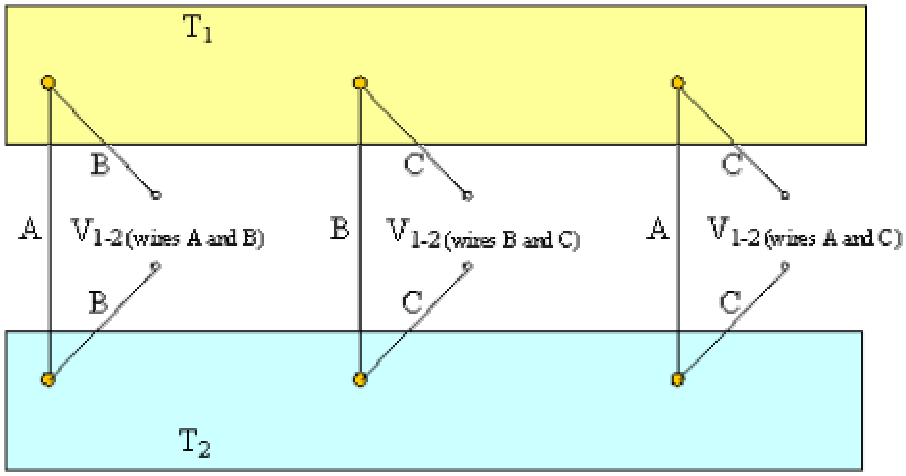
it follows directly that:

$V_{1\text{-}3} = V_{1\text{-}2} + V_{2\text{-}3}$.

3) ***Law of additive voltages***

"For a given set of 3 thermocouple wires, A, B, and C, all measuring the same temperature difference T_1 - T_2, the voltage measured by wires A and C must equal the sum of the voltage measured by wires A and B and the voltage measured by wires B and C".

Consider the setup below, where six thermo-junctions are shown, three in constant temperature bath T_1, and three in constant temperature bath T_2. As above, letters A, B, and C indicate different types of thermocouple wires.



The law of additive voltages can be stated mathematically as:

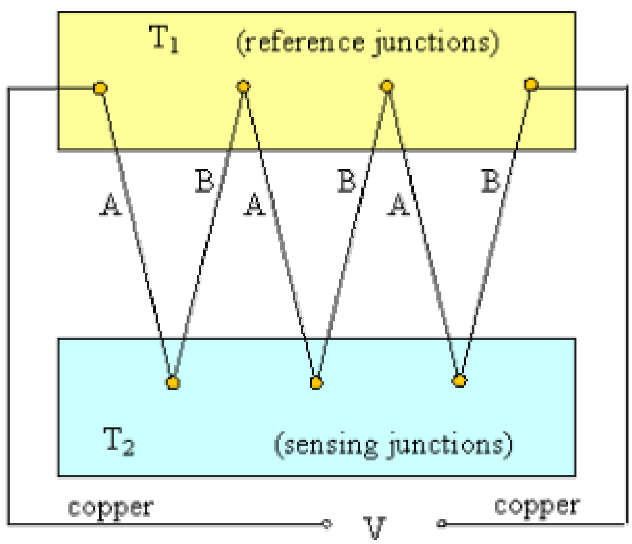
$V_{1\text{-}2\text{ (wires A and C)}} = V_{1\text{-}2\text{ (wires A and B)}} + V_{1\text{-}2\text{ (wires B and C)}}$

Or, rearranging in terms of voltage *differences*,

$V_{1\text{-}2\text{ (wires A and B)}} = V_{1\text{-}2\text{ (wires A and C)}} - V_{1\text{-}2\text{ (wires B and C)}}$.

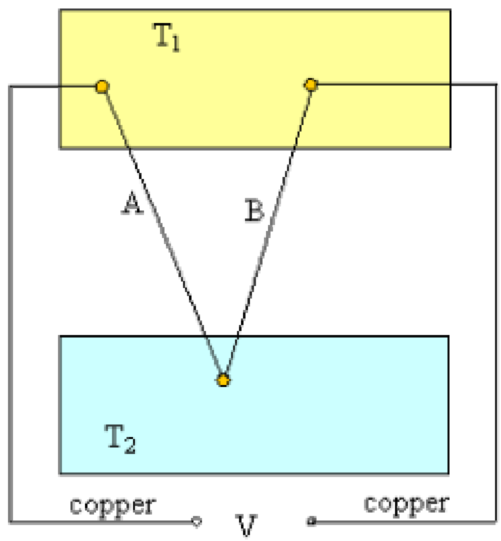
Thermopile

A *thermopile* is defined as several thermocouples connected in series. For example, a thermopile with three sensing junctions is shown below:



As T_2 is increased, the output voltage increases significantly. The advantage of a thermopile (as compared to just one sensing junction) is *increased sensitivity*.

Here, the voltage output is three times that which is generated by just one thermocouple under otherwise identical conditions, as sketched below:



With enough sensing junctions, a thermopile can actually generate a useful voltage. For example, *thermopiles are often used to control shut-off valves in furnaces*.

PART -3: THERMO-RESISTIVE TEMPERAURE MEASURING DEVICES

A change in temperature causes the electrical resistance of a material to change. The resistance change is measured to infer the temperature change.

There are two types of thermo-resistive measuring devices:

1) Resistance temperature detectors (RTD) and

2) Thermistors

Resistance Temperature Detectors

A resistance temperature detector (abbreviated RTD) is basically either a long, small diameter metal wire wound in a coil or an etched grid on a substrate, much like a strain gage. Platinum is the most common metal used for RTDs.

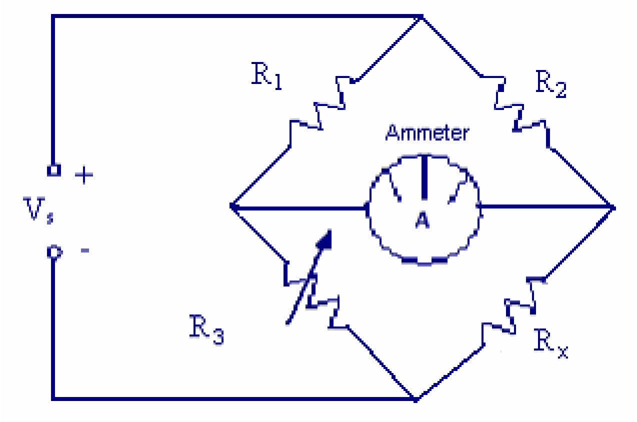
Principle of Operation

Resistance Temperature Detectors (RTD) operates on the principle that the electrical resistance of a metal changes predictably in an essentially linear and repeatable manner with changes in temperature. RTD have a positive temperature coefficient (resistance increases with temperature). The resistance of the element at a base temperature is proportional to the length of the element and the inverse of the cross sectional area.

A typical electrical circuit designed to measure temperature with RTDs actually measures a change in *resistance* of the RTD, which is then used to calculate a change in temperature. The resistance of an RTD increases with increasing temperature, just as the resistance of a strain gage increases with increasing strain.

Bridge Circuit Construction

The figure below shows a basic bridge circuit which consists of three known resistances, R1, R2, and R3 (variable), an unknown variable resistor RX (RTD), a source of voltage, and a sensitive ammeter.



Bridge Circuit

Resistors R1 and R2 are the ratio arms of the bridge. They ratio the two variable resistances for current flow through the ammeter. R3 is a variable resistor known as the standard arm that is adjusted to match the unknown resistor. The sensing ammeter visually displays the current that is flowing through the bridge circuit. Analysis of the circuit shows that when R3 is adjusted so that the ammeter reads zero current, the resistance of both arms of the bridge circuit is the same. The relationship of the resistance between the two arms of the bridge can be expressed as:

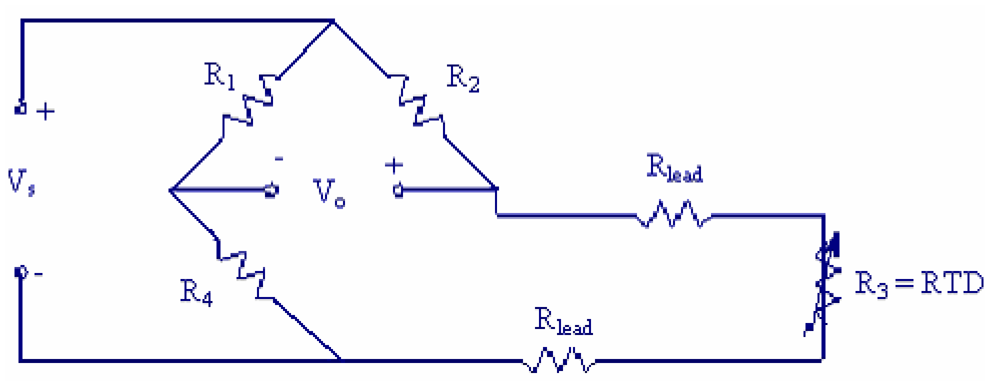
$$\frac{R_1}{R_3} = \frac{R_2}{R_x}$$

Since the values of R1, R2, and R3 are known values, the only unknown is Rx. The value of Rx can be calculated for the bridge during an ammeter zero current condition. Knowing this, resistance value provides a baseline point for calibration of the instrument attached to the bridge circuit. The unknown resistance, Rx, is given by:

$$R_x = \frac{R_2 R_3}{R_1}$$

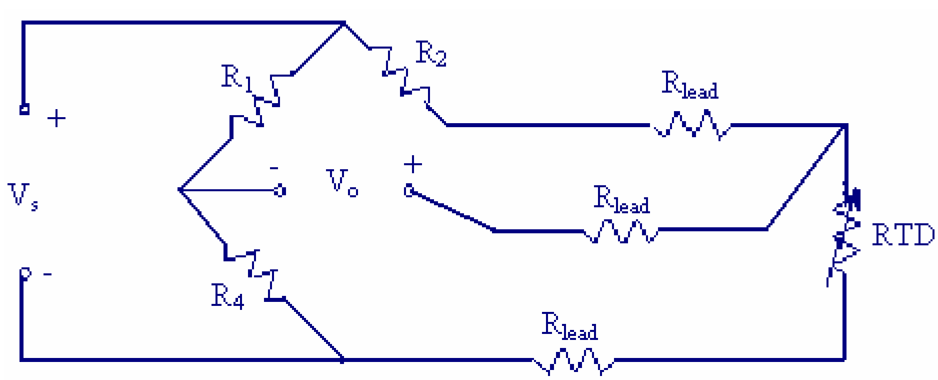
RTD Bridge Circuit Operation

One simple circuit is the quarter bridge Wheatstone bridge circuit, here called a ***two-wire RTD bridge circuit***.



R_{lead} represents the resistance of one of the wires (called *lead wires*) that run from the bridge to the RTD itself. Lead resistance was of no concern in strain gage circuits because R_{lead} remained constant at all times.

For RTD circuits, however, some portions of the lead wires are exposed to changing temperatures. Since the resistance of metal wire changes with temperature, R_{lead} changes with T, which can cause errors in the measurement. This error can be non-trivial - *changes in lead resistance may be misinterpreted as changes in RTD resistance*. Furthermore, there are two lead wires in the two-wire RTD bridge circuit shown above, which doubles the error. A clever circuit designed to eliminate the lead wire resistance error is called a *three-wire RTD bridge circuit*. The three-wire RTD bridge circuit is shown below.



It is still a quarter bridge circuit, since only one of the four bridge resistors has been replaced by the RTD. However, one of the lead wires has been placed on the R_2 leg of the bridge instead of the R_3 leg.

To analyze this circuit, assume that $R_1 = R_4$, and $R_2 = R_3$ initially, when the bridge is balanced.

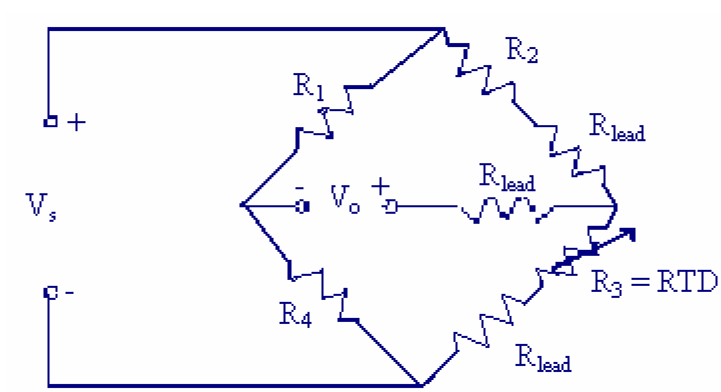
Recall the general formula for a Wheatstone bridge:

$$V_o = V_s \frac{R_3 R_1 - R_4 R_2}{(R_2 + R_3)(R_1 + R_4)}.$$

Notice that R_3 and R_2 have opposite signs in the above equation. So, if the lead wire resistance in leg 2 (top) and that in leg 3 (bottom) are the *same*, *the lead resistances cancel each other out*, with no net effect on the output voltage, thus eliminating the error.

What about the third lead resistance, R_{lead} of the middle wire? Well, since V_o is measured with a nearly infinite impedance device, *no current flows in the middle lead wire*, so its resistance does not affect anything!

The following re-drawn equivalent circuit may help explain why the lead resistances cancel out:



In the above diagram, it is clear that if R_{lead} changes equally in leg 2 and leg 3 of the bridge, its effect cancels out.

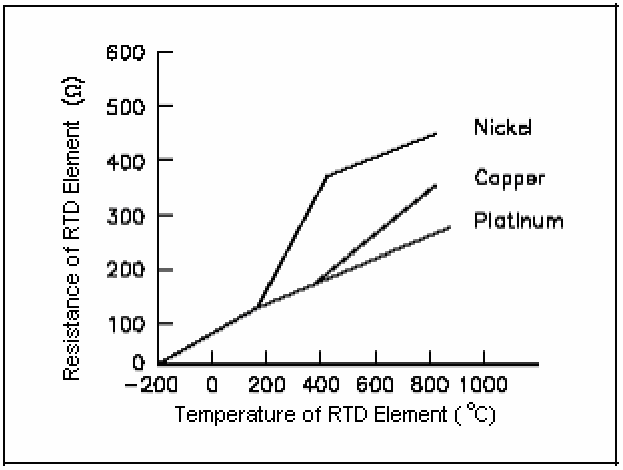
RTD Materials & Construction

RTD acts somewhat like an electrical transducer, converting changes in temperature to voltage signals by the measurement of resistance. The metals that are best suited for use as RTD sensors are pure metals or certain alloys of uniform quality that increase in resistance as temperature increases and conversely decrease in resistance as temperature decreases. Only a few metals have the properties necessary for use in RTD elements. Common materials used in RTD sensor are BALCO wire, Copper, Platinum.

1) ***BALCO* -** A sensor constructed using a BALCO wire is an annealed resistance alloy with a nominal composition of 70 percent nickel and 30 percent iron. A BALCO 500-ohm resistance element provides a relatively linear resistance variation from –40 to 250°F. The sensor is a low-mass device and responds quickly to changes in temperature. When 1000 ohms is measured across the BALCO element, the temperature is approximately 70°F. As the temperature increases, the resistance changes 2.2 ohms per 1°F. This is called a Temperature Coefficient of Resistance Curve (TCR Curve). In a BALCO, as the resistance has direct relationship with temperature; i.e. as temperature increases, the resistance increases proportionally. The usual range of temperature measurement with BALCO is -40° to 240°F.

2) ***Platinum -*** RTD sensors using platinum material exhibit linear response and stable over time. In some applications a short length of wire is used to provide a nominal resistance of 100 ohms. However, with a low resistance value, element self-heating and sensor lead wire resistance can effect the temperature indication. With a small amount of resistance change of the element, additional amplification must be used to increase the signal level. Platinum film sensor on an insulating base provides high resistance to the tune of 1000 ohms at 74°F. With this high resistance, the sensor is relatively immune to self-heating and responds quickly to changes in temperature. RTD elements of this type are common.

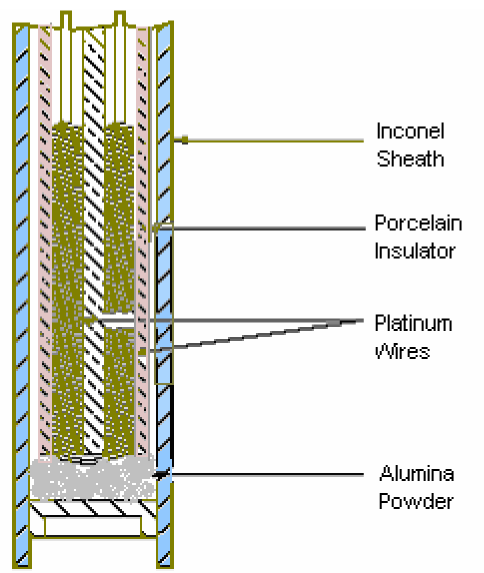
These metals are best suited for RTD applications because of their linear resistance-temperature characteristics (as shown in figure below), their high coefficient of resistance, and their ability to withstand repeated temperature cycles. The coefficient of resistance is the change in resistance per degree change in temperature, usually expressed as a percentage per degree of temperature. The material used must be capable of being drawn into fine wire so that the element can be easily constructed.



Electric Resistance-Temperature Curves

Copper and nickel versions operate at lower temperature ranges and are less expensive than platinum. Platinum is the most versatile material because of its wide temperature range (–200°C to 850°C), excellent repeatability, stability, and resistance to chemicals and corrosion.

RTD elements are usually long, spring-like wires surrounded by an insulator and enclosed in a sheath of metal. The figure below shows the internal construction of an RTD.



Internal Construction of Typical RTD

This particular design has a platinum element that is surrounded by a porcelain insulator. The insulator prevents a short circuit between the wire and the metal sheath. Inconel, a nickel-iron-chromium alloy, is normally used in manufacturing the RTD sheath because of its inherent corrosion resistance. When placed in a liquid or gas medium, the Inconel sheath quickly reaches the temperature of the medium. The change in temperature will cause the platinum wire to heat or cool, resulting in a proportional change in resistance.

Advantages: Linear resistance with temperature, good stability, wide range of operating temperature, interchangeable over wide temperature range.

Disadvantages: Small resistance change with temperature, responses may be slower, subject to self heating, transmitter or three to four wire leads required for lead resistance compensation, external circuit power required.

Additional facts

1. RTD's are commonly used in sensing air and liquid temperatures in pipes and ducts, and as room temperature sensors. The resistance of RTD elements varies as a function of temperature. Some elements exhibit large resistance changes, linear changes, or both over wide temperature ranges.

2. Varying voltage across the sensor element determines the resistance of the sensor. The power supplied for this purpose can cause the element to heat slightly and can create an inaccuracy in the temperature measurement. Reducing supply current or by using elements with higher nominal resistance can minimize the self-heating effect.

3. Some RTD element resistances are as low as 100 ohms. In these cases, the resistance of the lead wires connecting the RTD to the controller may add significantly to the total resistance of the connected RTD, and can create an error in the measurement of the temperature. For instance, a sensor placed 25 feet from the controller has a copper control wire of 25 x 2 = 50 feet. If a control wire has a DC resistance of 6.39 ohms/ft, the 50 feet of wire shall have a total dc resistance of 0.319 ohms. If the sensor is a 100-ohm platinum sensor with a temperature coefficient of 0.69 ohms per degree F, the 50 feet of wire will introduce an error of 0.46 degrees F. If the sensor is a 3000-ohm platinum sensor with a temperature coefficient of 4.8 ohms per degree F, the 50 feet of wire will introduce an error of 0.066 degrees F.

4. Therefore the lesser is the resistance of sensor element, the higher shall be the likelihood of error. Significant errors can be removed by adjusting a calibration setting on the controller, or, if the controller is designed for it, a third wire can be run to the sensor and connected to a special compensating circuit designed to remove the lead length effect on the measurement.

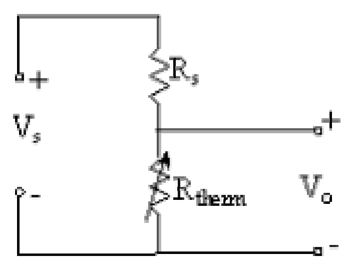
Thermistors

Thermistors are temperature sensitive semiconductors that exhibit a large change in resistance over a relatively small range of temperature. There are two main types of thermistors: positive temperature coefficient (PTC) and negative temperature coefficient (NTC). NTC thermistors exhibit the characteristic of resistance falling with increasing temperature. These are most commonly used for temperature measurement.

A *thermistor* is similar to an RTD, but a *semiconductor material* is used instead of a metal. A thermistor is a *solid state* device and has larger *sensitivity* than does an RTD. Unlike RTD's, the temperature-resistance characteristic of a thermistor is non-linear, and cannot be characterized by a single coefficient. Furthermore, unlike RTDs, the resistance of a thermistor *decreases* with increasing temperature.

Thermistors cannot be used to measure high temperatures compared to RTDs. In fact, the maximum temperature of operation is sometimes only 100 or 200°C.

Manufacturers commonly provide resistance-temperature data in curves, tables or polynomial expressions. Linearizing the resistance-temperature correlation may be accomplished with analog circuitry, or by the application of mathematics using digital computation. A typical thermistor circuit is shown below.



From the circuit diagram, it is clear that this is a simple voltage divider. R_s is some fixed (supply) resistor. R_s and the supply voltage, V_s, can be adjusted to obtain the desired range of output voltage V_o for a given range of temperature.

Advantages: Large resistance change with temperature, rapid response time, good stability, high resistance eliminates difficulties caused by lead resistance, low cost and interchangeable.

Disadvantages: Non-linear, limited operating temperature range, may be subjected to inaccuracy due to overheating, current source required.

PART -4: RADIATIVE TEMPERATURE MEASURING DEVICES

Two types of radiative measuring devices are:

1. Infrared pyrometers, and
2. Optical pyrometers.

Infrared Pyrometer

Infrared temperature sensors also known as pyrometers or non-contact temperature sensors are used to measure the temperature of an object without contact. This is different from most temperature measurement devices, which require direct contact with the measured media. Non-contact methods of temperature measurement are advantageous when contact methods are impossible or impractical, such as when the target is inaccessible or so hot that contact devices will not survive.

Principle of Operation

Infrared temperature sensors use the principle that any object emits an amount of energy that is a function of its temperature. This function dictates that as the temperature of an object rises, so does the amount of energy it emits.

"An infrared temperature sensor determines temperature by measuring the intensity of energy given off by an object."

Calculating the temperature of an object from the measured emitted energy seems straightforward. However, the quantity of energy emitted by an object is not a function of temperature only. The other variable besides temperature that affects emissions is emissivity. From a practical standpoint, emissivity is an inherent surface characteristic that can fluctuate with changes to surface oxidation, texture, composition, and microstructure. When it comes to non-contact temperature measurement, all that is really important is knowing that emissivity is a correction factor greater than 0 but less than 1 that enables infrared temperature sensors to output the correct surface temperature.

<u>Mathematical statement of Infrared Temperature Measurement:</u>

The amount of energy a surface emits is a function of temperature and emissivity, therefore to correctly determine surface temperature from a measurement of emitted energy, it is imperative to know something about fundamentals of radiation and surface's emissivity. The fundamental equation for radiation from a body is the ***Stefan-Boltzmann equation:***

$E = \varepsilon\sigma T^4$,

where:

- E is the emissive power radiated per unit area (units of W/m^2).
- ε is the emissivity, defined as the fraction of blackbody radiation emitted by an actual surface. The emissivity must lie between 0 and 1, and is dimensionless. Its value depends greatly on the type of surface. A blackbody has an emissivity of exactly 1.
- σ is the Stefan-Boltzmann constant:

  $$\sigma = 5.669 \times 10^{-8} \frac{W}{m^2 K^4}.$$

- T is the *absolute* temperature of the surface of the object (units of K). The following is a list of the emissivity of several common surfaces:

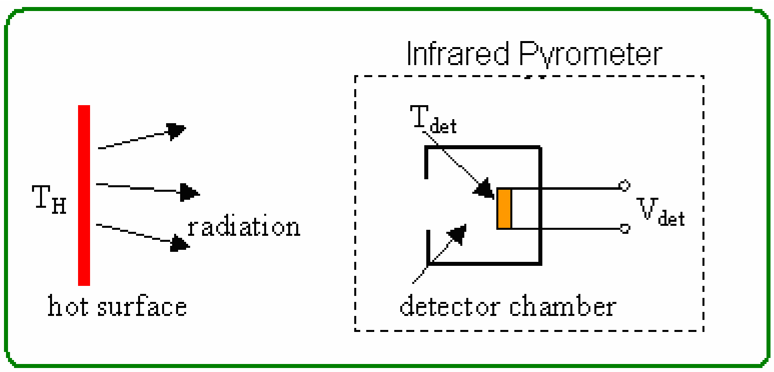
surface	**emissivity, ε**
aluminum (anodized)	0.84
aluminum (polished)	0.03
asphalt pavement	0.85 to 0.93
glass	0.62 to 0.95
human skin	approx. 0.95
water (deep)	0.95 to 0.96

The emissivity of other materials can be found in heat transfer textbooks. Once sufficient information about the surface's emissivity is obtained, the temperature sensor can be programmed to compensate for emissivity.

Calibration of Infrared Temperature Measurement

The challenge that perplexes manufacturers and users of infrared temperature sensors is definitively quantifying emissivity. Some surfaces have a predictable emissivity; others have an emissivity that will change significantly with no discernable pattern. Experience has sorted out which surfaces are easy to measure and which are difficult. With that, different types of non-contact temperature sensors have been developed that eliminate, or at least reduce, errors caused by emissivity variations.

An infrared pyrometer infers the temperature of a hot surface by measuring the temperature of a detector inside a detector chamber as shown below:



The detector itself is usually a thermopile. It measures T_{det}, the temperature of the detector inside the chamber. T_{ind} is the *indicated* temperature, which is calculated from T_{det}, from the known geometry and the radiation equations. T_{ind} is calibrated as a function of T_H for a body of some assumed emissivity.

The instrument is set up such that T_{ind} is a function of the voltage output. The instrument typically displays a temperature, i.e. T_{ind}, rather than voltage V_{det}.

T_{ind} can be thought of as an *uncorrected* estimate of T_H, since the emissivity of the object may not be the same as that assumed by the infrared pyrometer. In other words, if the actual emissivity of the object is not the same as the assumed emissivity, T_{ind} will be incorrect.

To correct for the actual emissivity of the object:

$$T_H = \left(\frac{\varepsilon_{assumed}}{\varepsilon_{actual}}\right)^{1/4} T_{ind}$$

In the above equations, ***absolute temperatures*** must be used.

Type of Infrared Temperature Sensors

Infrared temperature sensors fall into one of three categories: single-wavelength, dual wavelength and multi-wavelength.

1. Single wavelength temperature sensors, also referred to as single-color temperature sensors, measure all of the energy emitted from a target at one wavelength and calculate the average temperature of the measured area. They require that the target emissivity be relatively constant, or else error is introduced. Single-wavelength temperature sensors are appropriate for measuring an unobstructed target of constant emissivity.

2. Dual-wavelength temperature sensors, also known as two-color or ratio pyrometers, measure the energy emitted from a target at two different wavelengths, take a ratio of the energies, and calculate the temperature. Different from single-wavelength sensors, dual wavelength sensors tend to measure the hottest point in the target area and are less sensitive to emissivity variations. However, severe emissivity variations still introduce error. Dual wavelength temperature sensors are recommended for applications with intervening media such as dirty optics, scale, steam, dust, or water spray. Also, they are appropriate for targets with low or varying emissivity and situations with a partially filled field of view caused by mechanical obstructions or a small target.

3. Multi-wavelength sensors use sophisticated electronics to combine signals measured from multiple wavelengths and then calculate the temperature of surfaces with dramatic, yet repeatable, variations in emissivity. Multi wavelength sensors provide the same benefits of a dual-wavelength sensor, but are recommended for non-grey body materials like aluminum, copper, zinc, and stainless steel.

Once the most appropriate type of sensor has been chosen considering the emissivity characteristics of the measured target, the rest of the challenge is selecting a sensor package appropriate for the sensor's operating environment and adjusting for other potential causes of error. Operating conditions to consider when selecting a sensor package include ambient temperature, cleanliness, humidity, electromagnetic radiation, atmosphere, and accessibility. Other causes of error are those conditions that artificially either add to or subtract from the amount of energy transmitted from the target to the sensor. Such sources include background energy that is reflected off of a surface into the sensor, mechanical obstructions that block emitted energy, and windows, thin films, or intervening media that interfere with specific wavelengths.

Optical Pyrometer

An optical pyrometer is useful for measuring very high temperatures (even flames). The optical pyrometer uses an infrared radiation-sensitive sensor, e.g. a photodiode or a photoresistor, to compare the radiation from the unknown with that of the radiation from an internal incandescent source. The accuracy of the optical pyrometer is very much a function of the emissivity of the device that is radiating the heat. The obvious advantage in using an optical pyrometer at very high temperatures is that the measurement is non-contacting.

This approach is very expensive, and due to the variability in emissivity of many physical bodies, it is not very accurate. However, for making non-contact measurements on very high temperature bodies such as molten glass and molten steel, the optical pyrometer excels.

Basic Characteristics are as follows:

- Infrared radiation sensitive
- Accuracy= f (emissivity)
- Useful at very high temperatures
- Non-contacting
- Very expensive
- Not very accurate

Summarizing

The two most common type of temperature sensors are Thermocouples and RTD's. Although these sensors have overlapping temperature ranges, each has certain application-dependent advantages. These are summarized below.

Temperature Sensor Selection Guide		
	RTD	**Thermocouple**
Temperature Range	–200°C to 850°C –328°F to 1562°F	–190°C to 1821°C –310°F to 3308°F
Accuracy	±0.001°F to 0.1°F	±1°F to 10°F
Response Time	Moderate	Fast
Stability	Stable over long periods <0.1% error/5 yr.	Not as stable 1°F error/yr.
Linearity	Best	Moderate
Sensitivity	High sensitivity	Low sensitivity

An RTD is the sensor of choice when sensitivity and application flexibility are the most important criteria. When it comes to component cost, an RTD is more expensive than a thermocouple.

*****

MEASUREMENT OF PRESSURE

Aims of the measurement:

- To get familiar with the pressure gauges.
- Pressure measurement with U-tube (liquid column gauge) and Bourdon gauge. Measurement of the pressure difference between two locations of a fluid flow system.
- Flow rate measurement with metering orifice and metering tank.
- Calibration of a Bourdon gauge.

1. Measuring pressure

1.1. Liquid column gauge (U tube)

Liquid column gauges consist of a vertical column of liquid in a tube whose ends are exposed to different pressures. The column will rise or fall until its weight is in equilibrium with the pressure differential between the two ends of the tube. A very simple version is a U-shaped tube half-full of liquid, one side of which is connected to the region of interest while the reference pressure (which might be the atmospheric pressure or a vacuum) is applied to the other. The difference in liquid level represents the applied pressure.

Although any fluid can be used, mercury is preferred for its high density (13.534 g/cm^3) and low vapour pressure. For low pressure differences well above the vapour pressure of water, water is commonly used (and "meters of water" is a common pressure unit).

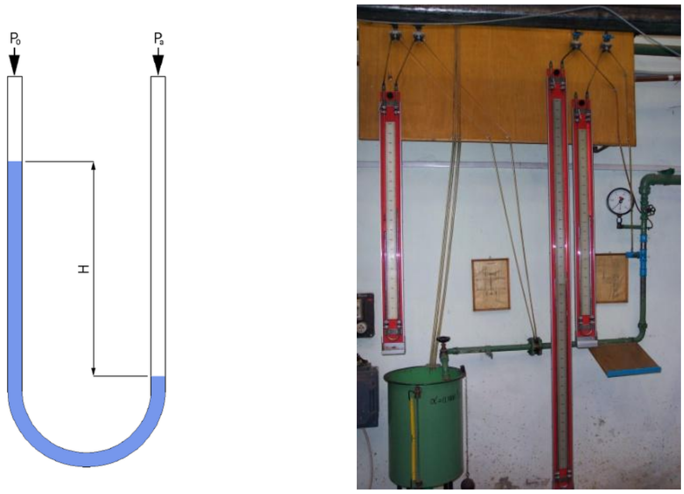


Figure 1 (left) Schematic draw of a liquid column gauge (right) Liquid column gauges

1.2. Bourdon gauge

The Bourdon pressure gauge uses the principle that a flattened tube tends to change to a more circular cross-section when pressurized. Although this change in cross-section may be hardly noticeable, the displacement of the material of the tube is magnified by forming the tube into a C shape or even a helix, such that the entire tube tends to straighten out or uncoil, elastically, as it is pressurized.

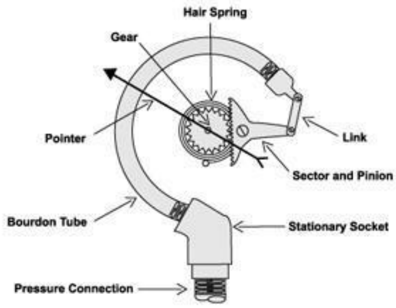



Figure 2 (left) Bourdon gauge (right) Mechanism of the Bourdon gauge

In practice, a flattened thin-wall, closed-end tube is connected at the hollow end to a fixed pipe containing the fluid pressure to be measured. As the pressure increases, the closed end moves in an arc, and this motion is converted into the rotation of a (segment of a) gear by a connecting link which is usually adjustable. A small diameter pinion gear is on the pointer shaft, so the motion is magnified further by the gear ratio. The positioning of the indicator card behind the pointer, the initial pointer shaft position, the linkage length and initial position, all provide means to calibrate the pointer to indicate the desired range of pressure for variations in the behaviour of the Bourdon tube itself.

Bourdon tubes measure gage pressure, relative to ambient atmospheric pressure, as opposed to absolute pressure; vacuum is sensed as a reverse motion. When the measured pressure is rapidly pulsing, such as when the gauge is near a reciprocating pump, an orifice restriction in the connecting pipe is frequently used to avoid unnecessary wear on the gears and provide an average reading; when the whole gauge is subject to mechanical vibration, the entire case including the pointer and indicator card can be filled with an oil or glycerin. Typical high-quality modern gauges provide an accuracy of ±2% of span, and a special high-precision gauge can be as accurate as 0.1% of full scale.

1.3. Electronic pressure sensors

A **pressure sensor** measures pressure, typically of gases or liquids. A pressure sensor usually acts as a transducer; it generates an electronic signal as a function of the pressure imposed. Although there are various types of pressure transducers, one of the most common is the strain-gage base transducer. The conversion of pressure into an electrical signal is achieved by the physical deformation of strain gages which are bonded into the diaphragm of the pressure transducer. Pressure applied to the pressure transducer produces a deflection of the diaphragm which introduces strain to the gages. The strain will produce an electrical resistance change proportional to the pressure.

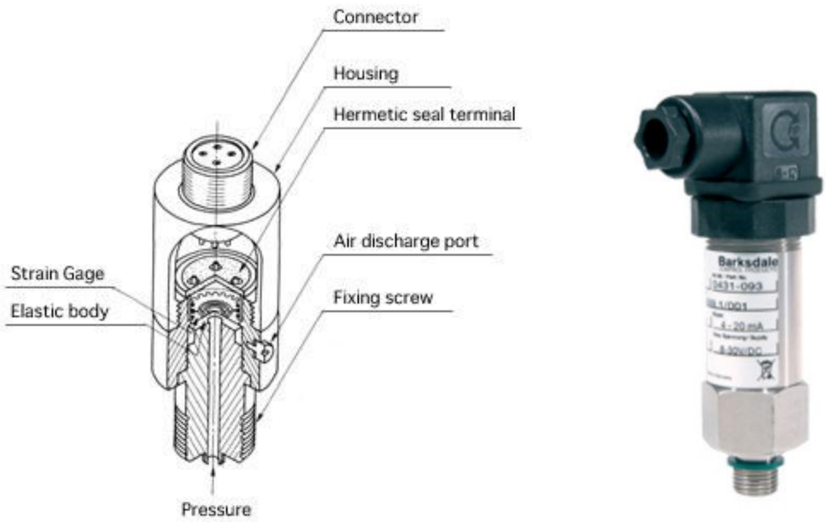


Figure 3 (left) Cut-away of an electronic pressure sensor (right) pressure sensor

1.4. Calibration

Calibration is a comparison between measurements - one of known magnitude or correctness made or set with one device and another measurement made in as similar a way as possible with a second device. The device with the known or assigned correctness is called the standard.

The calibration process begins with the design of the measuring instrument that needs to be calibrated. The design has to be able to "hold a calibration" through its calibration interval. In other words, the design has to be capable of measurements that are "within engineering tolerance" when used within the stated environmental conditions over some reasonable period of time.

Suppose that one owns an old Bourdon gauge, whose scale is inaccurate – yet the device itself is working. After a calibration process the gauge can be used again with high accuracy as the calibration results in a relationship between the “read” and “real” value as $p_{real}=f(p_{read})$, e.g. in the form of a “calibration diagram”.

2. Measuring flow rate

2.1. Metering tank (bucket-and-stopwatch)

Perhaps the simplest way to measure volumetric flow is to measure how long it takes to fill a known volume container. A simple example is using a bucket of known volume, filled by a fluid. The stopwatch is started when the flow starts, and stopped when the bucket overflows. The volume divided by the time gives the flow:

$$Q = \alpha \frac{\Delta m}{\Delta t} \left[\frac{dm^3}{s} \right]$$

where

α [dm3/mm] is the constant of the tank being the volume of a 1 mm high quantity of liquid in the tank,

Δm [mm] is the rising of the level

Δt [s] is the time taken for rising.

2.2. Orifice plate

An orifice plate (metering orifice) is a plate with a hole through it, placed in the flow; it constricts the flow, and measuring the pressure differential across the constriction gives the flow rate.

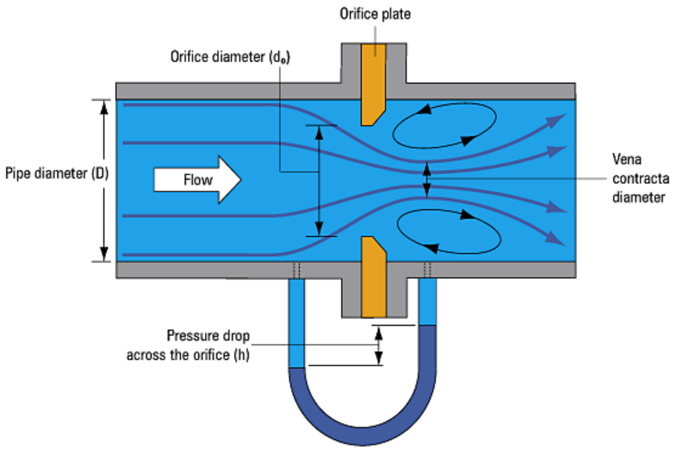


Figure 4 Cut-away of a metering orifice

The square root of measured pressure difference is proportional to the flow rate:

$$Q = K \sqrt{\Delta p}$$

where K is constant (its computation is described by standards).

3. The measurement exercise

3.1. Measurement of flow rate

On the rig presented in Fig. 5 there are two possibilities to measure the flow-rate (i.e. the quantity of liquid delivered per unit time):

- in the horizontal pipe-section there is a metering orifice (OR) and
- a volume meter tank (VMT) is also available at the end of the system.

You will measure the same flow rate with devices and compare the (possibly same) results.

In Fig. 6 there is shown the diagram of the orifice. On the abscissa we have not drawn the pressure-drop but the square root of the level-difference read on the U-tube manometer U1 (see Figure 5) and so the flow-rate is given directly after the reading of the manometer.

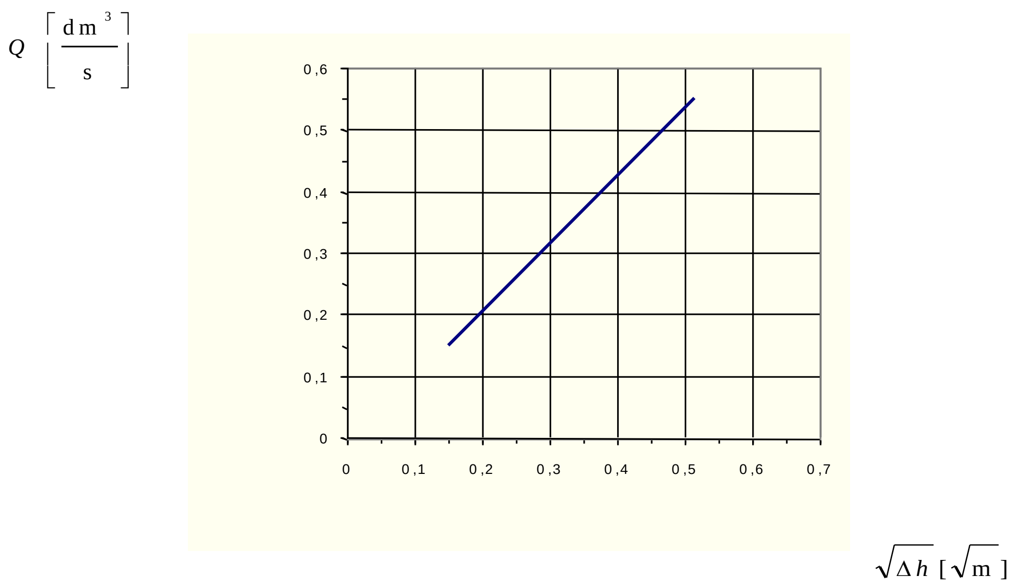


Figure 6. The pressure difference – flow rate relationship of the metering orifice.

3.2. Measurement of pressure

The next task is to determine pn and ps pressures, i.e. the pressure before and after a nozzle.

Note that in the nozzle, as the velocity increases (area decreases), thus, based on Bernoulli's equation, we expect a $p_n > p_s$:

$$Q = const = A_n v_n = A_s v_s, \qquad A_n \gg A_s \rightarrow v_n \ll v_s \searrow$$

$$p_n + \frac{\rho}{2} v_n^2 + \rho g h_n = p_s + \frac{\rho}{2} v_s^2 + \rho g \underbrace{h_s}_{\approx h_n} \qquad \rightarrow \qquad p_n \gg p_s$$

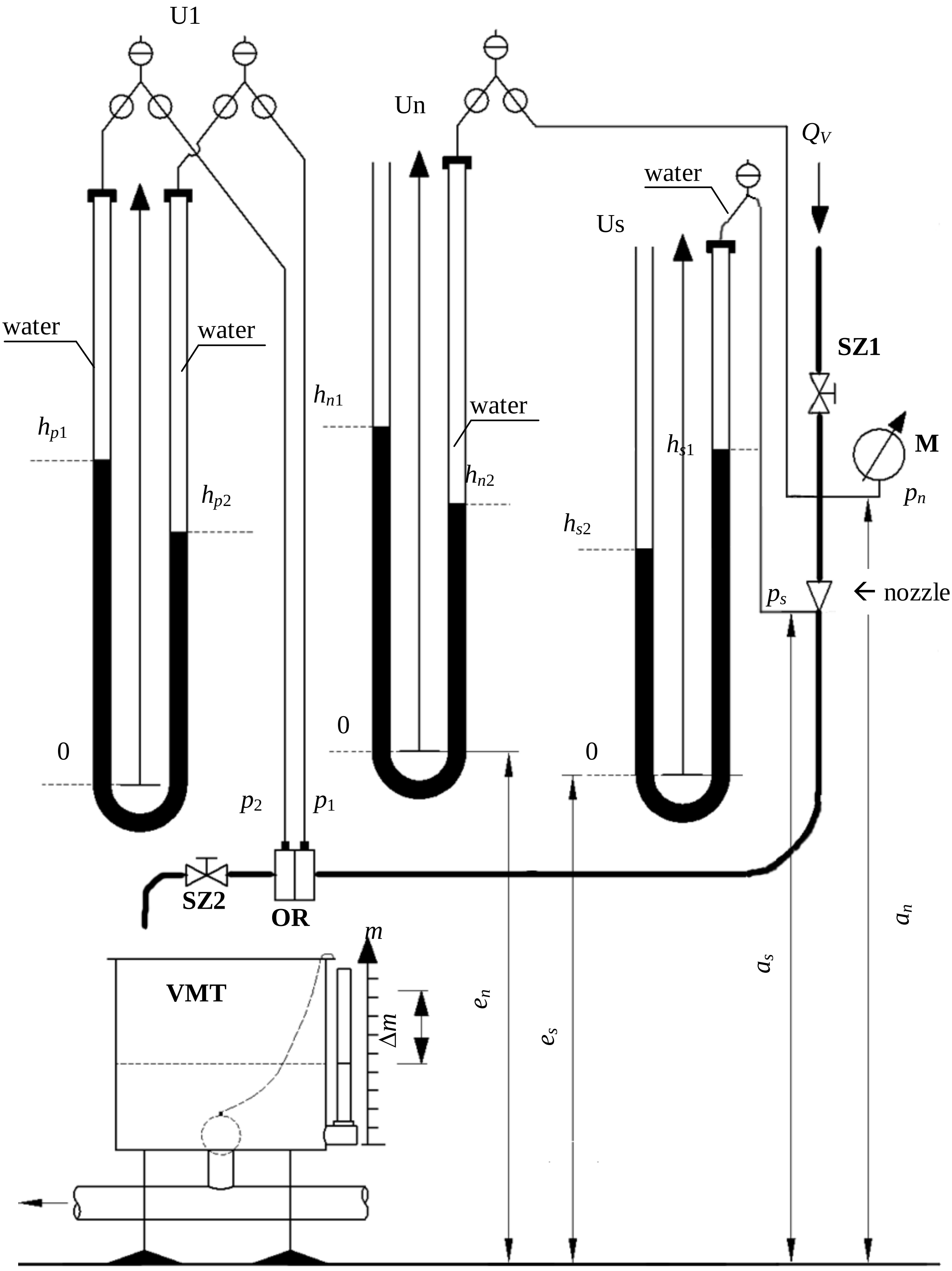


Figure 5 The measuring rig

The actual value of p_n and p_s is calculated as follows. The balance equation for U tube Un is (note that this is again Bernoulli's equation, with zero velocity, as the fluid in the U-tube is at rest):

$$p_0 + (h_1 - h_2)\rho_m g = p_n + (a - (e + h_2))\rho_w g$$

The balance equation for U tube Us is:

$$p_0 = p_s - (e_s + h_{s1} - a_s)\rho_w g + (h_{s1} - h_{s2})\rho_m g$$

The data needed for evaluation are:

- ρ_w = 1000 kg/m^3, ρ_{Hg} = 136000 kg/m^3
- p0 will be measured on site and
- geometry (a, a_s, e, e_s) will also be measured on site.

3.3. *Calibration of a Bourdon gauge*

The third task is to measure the calibration chart of a Bourdon gauge.

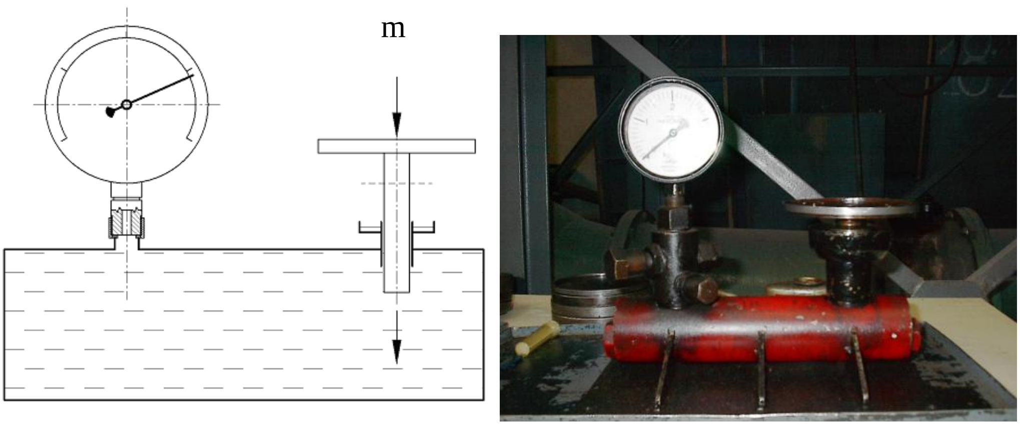


Figure 6 Calibrating a Bourdon gauge.

Figure 6 depicts the simple system used for calibration. By adding weights to the plunger, we create a *known pressure* in the tank, which is compared to the *dial pressure* of the Bourdon gauge. The pressure of the fluid is:

$$p = \frac{(m + m_0)g}{a} \quad ,$$

Where m_0 is the mass of the plunger, m_0 = 1 kg, "a" stands for the cross section of the plunger, a=2x10^{-4}m^2. To increase the pressure, several steal disks of 1 and 2 kg mass will be used. You should measure at least 8 points.

3.4. The report

You report shall include the following items.

1. Numerical calculations of the flow rate measurement: result of the metering tank and orifice measurement (two flow rates) and an evaluation whether you think if the results are reasonably close to each other (as you measured the same flow rate in two different ways).
2. Numerical calculations and results of the pressure measurement, with an explanation (why does the pressure drop after the nozzle?).
3. Calibration diagram of the Bourdon gauge: the dial (read) pressure as a function of the computed (real) pressure on a **mm paper**.

The calculations have to be well-documented, i.e. every quantity (time, length, pressure) should be included in the report.

4. Preparation questions

1. Explain two ways of measuring flow rate (sketch + equations).
2. Explain three techniques to measure pressure (sketches).
3. Make a sketch of the device used for the Bourdon gauge calibration and explain how it works.
4. We measure the pressure before and after a nozzle. Make a sketch and explain with equations, why the pressure after the nozzle is lower than that one before the nozzle.
5. Give Bernoulli's equation and the continuity equation and explain the terms.

UNIT 5 LINEAR MEASURING DEVICES AND COMPARATORS

Structure

5.1 INTRODUCTION

Linear measurement includes the measurement of lengths, diameters, heights and thickness. The basic principle of linear measurement (mechanical type) is that of comparison with standard dimensions on a suitably engraved instrument or device. Linear measuring instruments are categorized depending upon their accuracy. The two categories are non-precision instruments and precision instruments. Non-precision instruments include steel rule, caliper divider, and telescopic gauge that are used to measure to the line graduations of a rule. Precision instruments include micrometers, vernier calipers, height gauges and slip gauges. A wide variety of electrical measuring devices is also available. Electric measuring devices are mainly transducers, i.e. they transform the displacement into suitable measurable parameter like voltage and current. Some of the displacement transducers are strain gauges, linear variable differential transformers (LVDT) and potentiometers. This unit will discuss different type of linear measuring devices and comparators.

Objectives

After studying this unit, you should be able to

- familiarise yourself with various type of linear measuring devices, and
- choose a suitable measuring device according to the precision required.

5.2 NON-PRECISION MEASURING INSTRUMENTS

Non-precision instruments are limited to the measurement of parts to a visible line graduation on the instrument used. There are several non-precision measuring devices. They are used where high measurement accuracy is not required. This section describes some of the non-precision measuring devices.

5.2.1 Steel Rule

It is the simplest and most common measuring instruments in inspection. The principle behind steel rule is of comparing an unknown length to the one previously calibrated. The rule must be graduated uniformly throughout its length. Rules are made in 150, 300, 500 and 1000 mm length. There are rules that have got some attachment and special features with them to make their use more versatile. They may be made in folded form so that they can be kept in pockets. The degree of accuracy when measurements are made by a steel rule depends upon the quality of the rule, and the skill of the user in estimating part of a millimeter.

5.2.2 Calipers

Calipers are used for measurement of the parts, which cannot be measured directly with the scale. Thus, they are accessories to scales. The calipers consist of two legs hinged at top, and the ends of legs span part to be inspected. This span is maintained and transferred to the scale. Calipers are of two types : **spring type** and firm **joint type**.

Spring Type

As the name explains, the two legs are attached with spring in this type of calipers. The working ends of each leg of a spring calipers should be identical in shape and have contact points equally distant from the fulcrum. The cross-section of the legs is either rectangular or circular in shape. The calipers are adjusted to set dimensions by means of either a knurled solid nut or a knurled quick action release nut operating in a finely threaded adjusting screw. The top portion of the legs are located in a flanged fulcrum roller and held in position by a spring in order to maintain the alignment of the working ends. The spring provides sufficient tension to hold the legs rigid at all points of the adjustment. A separate washer under the nut minimizes the friction between the adjusting nut and the leg.

Spring type calipers are of following types :

Outside Spring Calipers

These are designed to measure outside dimensions. The accuracy in caliper measurement depends upon the inspectors' sense of feel. The legs are held firmly against the end of the proper dimensions by adjusting nut with the thumb and forefinger. For accurate settings, the distance between the outside calipers may be set by slip gauges or by micrometer anvils. Figure 5.1 shows the diagrams of Outside spring calipers. A steel rule must be used in conjunction with them if a direct reading is desired.

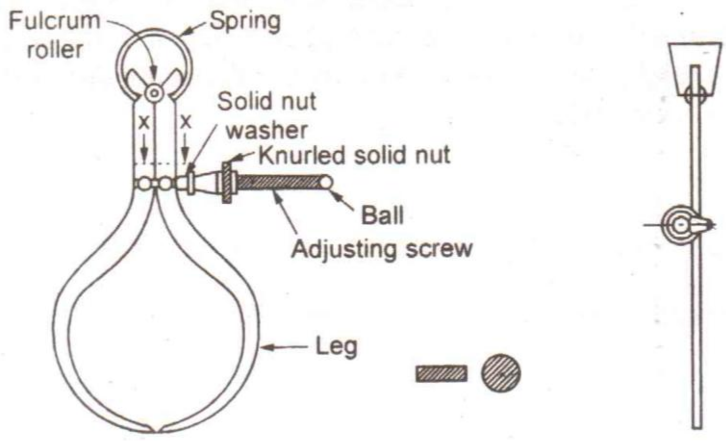


Figure 5.1 : Outside Spring Caliper

Inside Spring Calipers

They are designed to measure the inside dimensions. An inside spring caliper is exactly similar to an outside caliper with its legs bent outward as shown in Figure 5.2. Adjustment in them is generally made by knurled solid nut. They are used for comparing or measuring hole diameters, distances between shoulders, or other parallel surfaces of any inside dimensions. To obtain a specific reading, steel scale must be used as with the outside calipers.

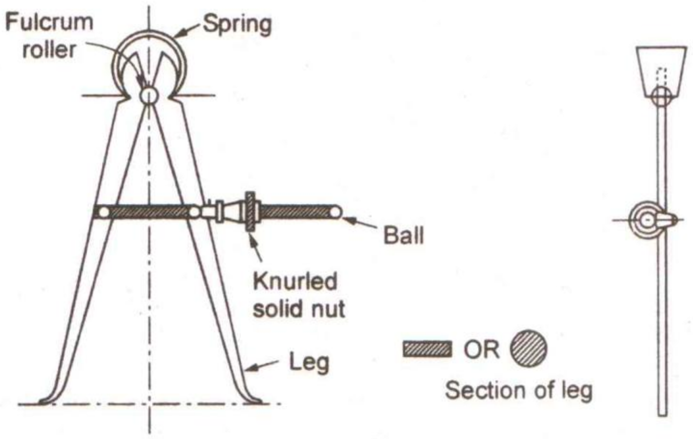


Figure 5.2 : Inside Spring Caliper

Firm Joint Type

They work on the friction created at the junction of the legs. The two legs are identical in shape with the contact points equally distant from the fulcrum and are joined together by a rivet. The component parts of the calipers should be free from seams, cracks and must have smooth bright finish. The distance between the rivet centre and the extreme working ends of the legs is known as *nominal size* and these calipers are available in the nominal size of 100, 150, 200 and 300 mm.

Firm joint calipers are of following types :

(i) Outside caliper

(ii) Inside caliper

(iii) Transfer caliper

(iv) Hermaphrodite caliper

Outside Firm Joint Caliper

Figure 5.3 shows the diagram of an outside firm joint caliper. Unlike spring type outside calipers, it does not have any spring. The construction is quite simple with two identical legs held firmly by the fulcrum. If direct reading is desired, a steel rule must be used in conjunction with them.

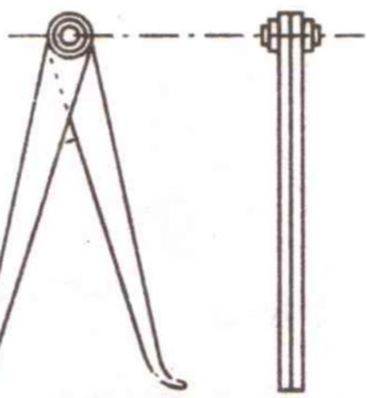


Figure 5.3 : Outside Firm Joint Caliper

Inside Firm Joint Caliper

Inside firm joint calipers are almost similar to inside firm joint caliper with the exception that it does not have any spring to hold the legs as shown in

Figure 5.4. Micrometers generally make adjustment in them. Like spring type inside calipers, they are also used for comparing or measuring hole diameters, distances between shoulders, or other parallel surfaces of any inside dimensions.

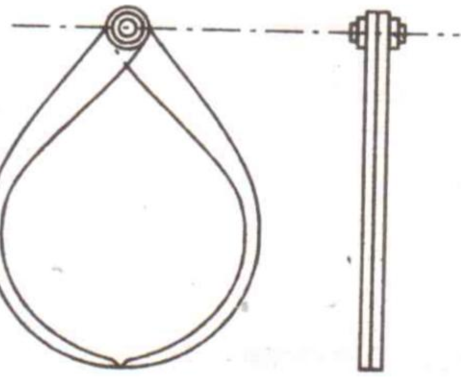


Figure 5.4 : Inside Firm Joint Caliper

Transfer Caliper

These are used for measuring recessed areas from which the legs of calipers can not be removed directly but must be collapsed after the dimension has been measured. Therefore, an auxiliary arm is provided with two legs so that it can preserve the original setting after the legs are collapsed. The nut *N* in Figure 5.5 is first locked and the caliper opened or closed against the work. The nut is then loosened and the leg is swung to clear the obstruction leaving the auxiliary arm in position. The leg can be moved back to the auxiliary leg, where it will show the size previously measured.

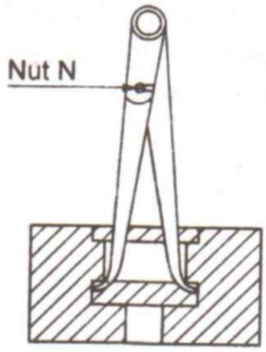


Figure 5.5 : Transfer Caliper

Hermaphrodite Caliper

It is also known as odd leg caliper consisting of one divider and one caliper leg. It is used for layout work like scribing lines parallel to the edge of the work and for finding the centre of a cylindrical work. It can be with two types of legs, viz. notched leg or curved legs.

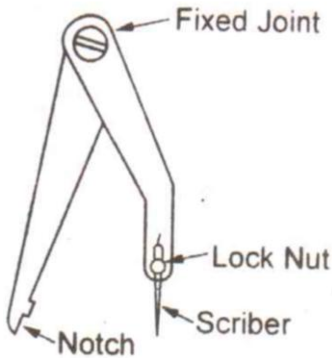


Figure 5.6 : Hermaphrodite Caliper

5.2.3 Divider

A divider is similar in construction to a caliper except that both legs are straight with sharp hardened points at the end as shown in Figure 5.8. These are used for scribing arcs and circles and general layout work. The distance between the fulcrum roller centre and the extreme working end of one of legs is known as the *nominal size* Dividers are available in the sizes of 100, 200, 300 mm. In practice, one point is placed in the centre position and the circle or arc may then be scribed on the job with the other point. A steel scale must be used with this instrument. Figure 5.7 shows a divider.

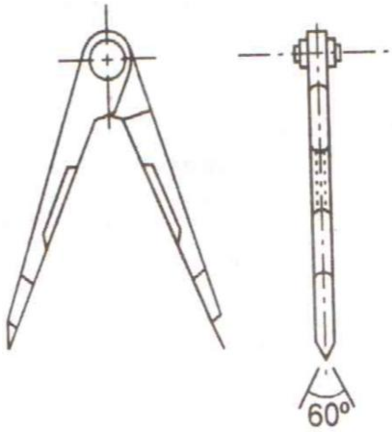


Figure 5.7 : Divider

5.2.4 Telescopic Gauge

The telescopic gauge shown in Figure 5.8 is used for the measurement of internal diameter of a hole during machining operation. It consists of a handle and two plungers, one telescopic into the other and both under spring tension. Ends of the plungers have spherical contacts. The plunger can be locked in position by turning a knurled screw at the end of the handle. To measure the diameter of a hole, the plungers are first compressed and locked in position. Next, the plunger end is inserted in the hole and allowed to expand the opposite edges. Finally, they are locked in place, taken out of the hole, and measured by an outside micrometer.

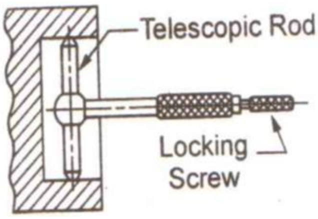


Figure 5.8 : Telescopic Gauge

5.2.5 Depth Gauge

This tool is used to measure the depth of blind holes, grooves, slots, the heights of shoulders in holes and dimensions of similar character. This is essentially a narrow steel rule to which a sliding head is clamped at the right angles to the rule as shown in Figure 5.9. The head forms a convenient marker in places where the rule must be held in a distance from the point being measured.

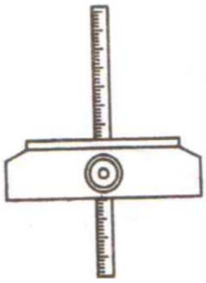


Figure 5.9 : Depth Gauge

5.3 PRECISION MEASURING INSTRUMENTS

Since modern production processes is concerned with interchangeable products, precise dimensional control is required in industry. Precision measurement instruments use different techniques and phenomena to measure distance with accuracy. We will discuss some of the precision measuring instruments in this section.

5.3.1 Vernier Calipers

Vernier calipers are precision measuring instruments that give an accuracy of 0.1 mm to 0.01 mm. The main scale carries the fixed graduations, one of two measuring jaws, a vernier head having a vernier scale engraved on. The vernier head carries the other jaw and slides on main scale. The vernier head can be locked to the main scale by the knurled screw attached to its head. Enlarged diagram of the metric vernier scale is shown in Figure 5.10.

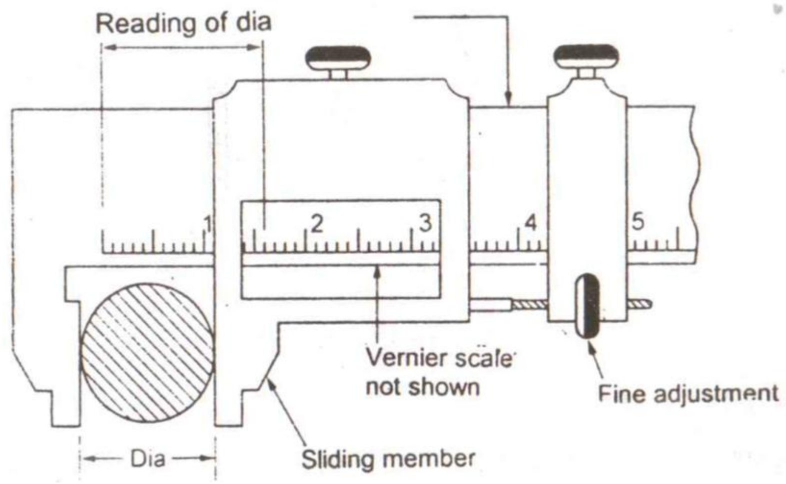


Figure 5.10 : Vernier Caliper

To understand the working principle of a vernier caliper, let us consider that the vernier scale has got 20 divisions which equals to 19 divisions of the main scale. Thus, one smallest division of the vernier scale is slightly smaller than the smallest division of the main scale. This difference is called vernier constant for that particular vernier caliper and when it is multiplied with the smallest unit of the main scale gives the least count of that vernier.

Now, 20 vernier scale divisions (VSD) = 19 main scale division (MSD)

$$\therefore \quad 1 \text{ VSD} = \frac{19}{20} \text{ MSD}$$

$$\therefore \quad \text{Vernier constant (VC)} = 1 \text{ MSD} - 1 \text{ VSD}$$

$$= 1 \text{ MSD} - \frac{19}{20} \text{ MSD}$$

$$= \frac{1}{20} \text{ MSD}$$

Now, if the smallest unit of the main scale be 1 mm, the least count of the vernier scale

= VC × one smallest unit of the main scale

$$= \frac{1}{20} \times 1 \text{ mm}$$

$$= 0.05 \text{ mm}$$

If the smallest unit in the main scale be 0.5 mm, the least count of the vernier scale is,

$$= \frac{1}{20} \times 0.5 \text{ mm}$$

$$= 0.025 \text{ mm}$$

To read a measurement from a vernier caliper, first the main scale reading up to the zero of the vernier scale is noted down. It will give accuracy up to the smallest division of the main scale. Now, vernier number of vernier scale division from its zero, which coincides exactly with the main scale is noted. This number when multiplied with the vernier constant gives the vernier scale reading. The actual length is obtained when the vernier scale reading is added to the main scale reading.

The caliper is placed on the object to be measured and the fine adjustment screw is adjusted until the jaws tightly fit against the Workpiece. There are vernier calipers that incorporate arrangements for measurement of internal dimensions and depth. The vernier calipers are designed to measure both internal and external dimensions. The lower jaws of a vernier scale are used for external measurement and the upper jaws for the measurement of internal dimensions. The rectangular rod carried by the movable jaw is used for the measurement of depth.

SAQ 1

(a) Describe different types of caliper for measuring the linear dimensions.

(b) A vernier scale consists of 25 divisions on 12 mm spacing and the main scale has 24 divisions on 12 mm. What is the least count?

5.3.2 Micrometers

Micrometer is one of the most widely used precision instruments. It is primarily used to measure external dimensions like diameters of shafts, thickness of parts etc. to an accuracy of 0.01 mm. The essential parts of the instruments shown in Figure 5.11, consist of

(a) Frame

(b) Anvil and spindle

(c) Screwed spindle

(d) Graduated sleeve or barrel

(e) Thimble

(f) Ratchet or friction stop

(g) Spindle clamp

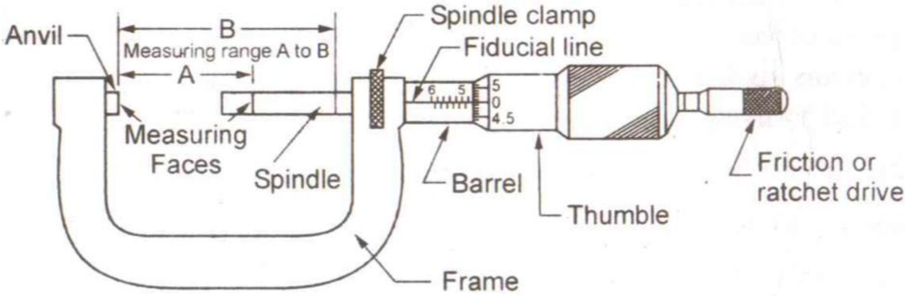


Figure 5.11 : Micrometer

The *frame* is made of steel, malleable cast iron or light alloy. The anvil shall protrude from the frame for a distance of at least 3-mm in order to permit the attachment of measuring wire support. The *spindle* does the actual measuring and possesses the threads of 0.5 mm pitch. The *barrel* has datum and fixed graduations *Thimble* is tubular cover fastened with the spindle. The beveled edge of the spindle is divided into 50 equal parts, every fifth being numbered. *The ratchet* is a small extension to the thimble. It slips when the pressure on the screw exceeds a certain amount. It produces uniform reading and prevents damage or distortion of the instruments. The *spindle clamp* is used to lock the instrument at any desired setting.

Procedure for Reading in a Micrometer

The graduation on the barrel is in two parts divided by a line along the axis of the barrel called the reference line. The graduation above the reference is graduated in 1 mm intervals. The first and every fifth are long and numbered 0, 5, 10, 15, etc. The lower graduations are marked in 1 mm intervals but each graduation shall be placed at the middle of the two successive upper graduations to be read 0.5 mm.

The thimble advances a distance of 0.5 mm in one complete rotation. It is called the pitch of the micrometer. The thimble has a scale of 50 divisions around its circumference. Thus, one smallest division of the circular scale is equivalent to longitudinal movement of $0.5 \times 1/50$ mm = 0.01mm. It is the least count of the micrometer.

The job is measured between the end of the spindle and the anvil that is fitted to the frame. When the micrometer is closed, the line marked zero on the thimble coincides with the line marked zero on the barrel. If the zero graduation does not coincide, the micrometer requires adjustment.

To take a reading from the micrometer, (1) the number of main divisions in millimeters above the reference line, (2) the number of sub-divisions below the reference line exceeding only the upper graduation, and (3) the number of divisions in the thimble have to be noted down. For example if a micrometer shows a reading of 8.78 mm when

8 divisions above the reference line	= 8.00 mm
1 division below the reference line	= 0.50 mm
28 thimble divisions	= 0.28 mm
	8.78 mm

The various important terms used in connection with micrometers are given below.

Backlash

It is the lack of motion or lost motion of the spindle when the rotation of thimble is changed in direction.

Measuring Range

It is the total travel of the measuring spindle for a given micrometer.

Cumulative Error

It is the deviation of measurement from the nominal dimension determined at any optional point of the measuring range. It includes the effect of all possible individual errors such as errors of the thread, errors of measuring faces etc. It can be determined by using slip gauges.

The following are the various types of micrometers.

Inside Micrometer Caliper

The measuring tips of inside micrometer are constituted by jaws with contact surface, which are hardened and ground to a radius. Unlike the conventional micrometer, an inside micrometer does not have any U-shape frame and spindle. One of the jaws is held stationary at the end and second one moves by the movement of the thimble. A locknut is provided to check the movement of the movable jaw. This facilitates the inspection of small internal dimension.

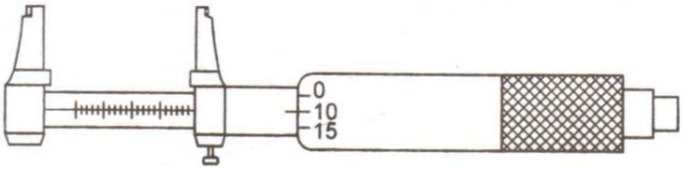


Figure 5.12 : Inside Micrometer Caliper

Inside Micrometer

The inside micrometer is intended for internal measurement to an accuracy of 0.001 mm. In principle, it is similar to an external micrometer and is used for measuring holes with a diameter over 50 cm. It consists of :

(a) measuring unit

(b) extension rod with or without spacing collar, and

(c) handle.

When the micrometer screw is turned in the barrel, the distance between the measuring faces of the micrometer can vary from 50 to 63 mm. To measure the holes with a diameter over 63 mm, the micrometer is fitted with extension rods. The extension rods of the sizes 13, 25, 50, 100, 150, 200 and 600 mm are in common use.

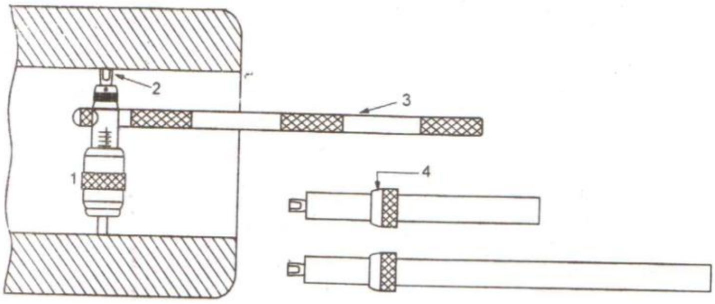


Figure 5.13 : Measuring the Inside Diameter of a Hole by an Inside Micrometer (1) Micrometer, (2) Anvil, (3) Handle and (4) Extension Rod

The measuring screw has a pitch of 0.5 mm. The barrel or sleeve is provided with a scale of 13 mm long and graduated into half-millimeter and millimeter divisions as in the external micrometer. A second scale is engraved on the beveled edge of the thimble. The beveled edge of the thimble is divided into 50 scale divisions round the circumference. Thus, on going through one complete turn, the thimble moves forward or backward by a thread pitch of 0.5 mm, and one division of its scale is, therefore, equivalent to a movement of $0.5 \times 1/50 = 0.01$ mm.

Stick Micrometers

Stick micrometers are used for measurement of longer internals length. A series of extension rods will permit continuous range of measurement up to the required length. It is connected with a 150 mm or 300 mm micrometer unit fitted with a micrometer of 25 mm range and having rounded terminal faces. Screw joints are used for joining the end-piece, extension rod and the measuring unit. The extension rod is generally hollow and has minimum external diameter of 14 mm. The accuracy of this instruments is in order of ± 0.005 mm. Figure 5.14 shows the parts of a stick micrometer.

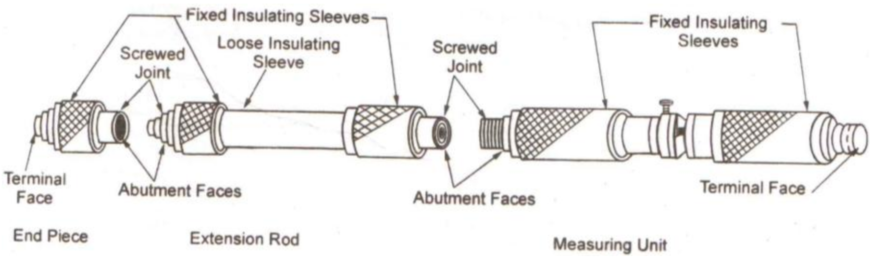


Figure 5.14 : Stick Micrometer

Screw Thread Micrometer Caliper

The shape of a Screw thread Micrometer is more or less like an ordinary micrometer with the difference that it is equipped with a pointed spindle and a double *V*-anvil, both correctly shaped to contact the screw thread of the work to be gauged. The angle of the *V*-anvil and the conical point at the end of the spindle correspond to the included angle of the profile of the thread. The extreme point of the cone is rounded so that it will not bear on the root diameter at the bottom of the thread, and similarly clearance is provided at the bottom of the groove in the *V*-anvil so that it will not bear on the thread crest. The spindle point of such a micrometer can be applied to the thread of any pitch provided the form or included angle is always same.

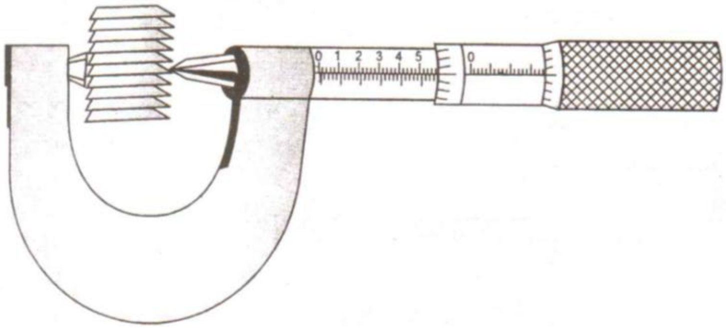


Figure 5.15 : Screw Thread Micrometer Caliper

V-anvil Micrometer Caliper

This is a special purpose micrometer used for checking out-of-roundness condition in centreless grinding and machining operations, odd-fluted taps, milling cutters, reamers etc. Use of special fixtures is eliminated in this type of micrometer. The *V* equals 60 degrees and the tip of the *Vee* coincides with axis of spindle. The zero reading of micrometer starts from a point where the two sides of the *V* meet. Figure 5.16 shows a *V*-anvil micrometer caliper.

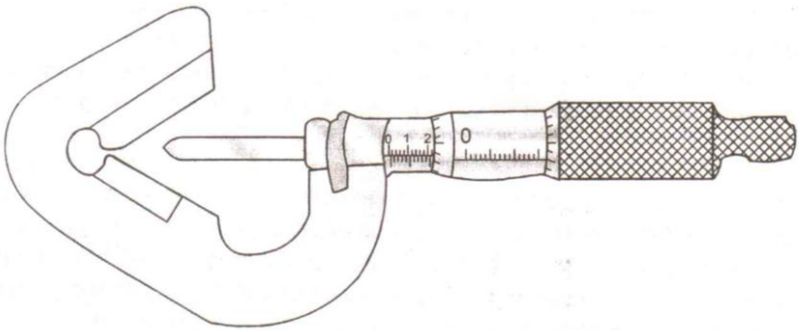


Figure 5.16 : *V*-anvil Micrometer Caliper

Blade Type Micrometer

It is ideally suited for fast and accurate measurement of circular formed tools, diameters and depth of all types of narrow grooves, slots, keyways, recesses etc. It has non-rotating spindle which advances to contact the work without rotation.

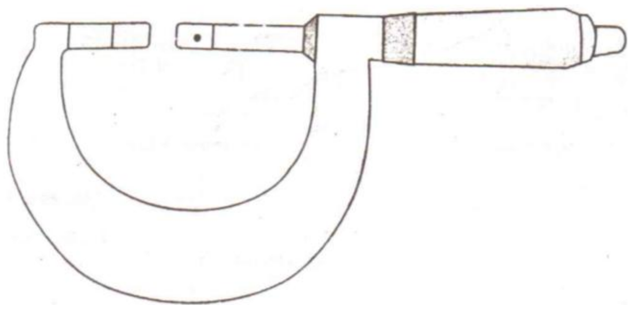


Figure 5.17 : Blade Type Micrometer

Bench Micrometer

A bench micrometer is a high precision micrometer with an anvil retractor device for repeated measurement. The worktable is adjustable and the indicator can measure up to 1 μm. The Anvil pressure is adjustable and linear friction transfer mechanism is used between anvil and indicator for high accuracy.

Groove Micrometer

It is used for measuring grooves, recesses and shoulders located inside a bore. Standard discs with diameter 12.7 mm and 6.35 mm are used to measure the locations inside a small bore. It is also capable of measuring an edge of a land and groove.

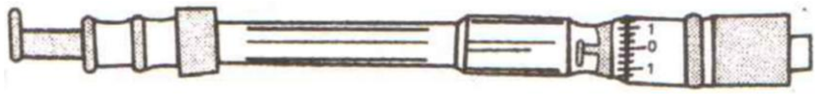


Figure 5.18 : Groove Micrometer

Digital Micrometer

Digital micrometer is capable of giving direct reading up to 0.001 mm. The spindle thread is hardened, ground and lapped in this type of micrometers. The positive locking clamp ensures locking of spindle at any desired setting. Operation is very simple with push button controls for "Zero" reset and indication "hold".

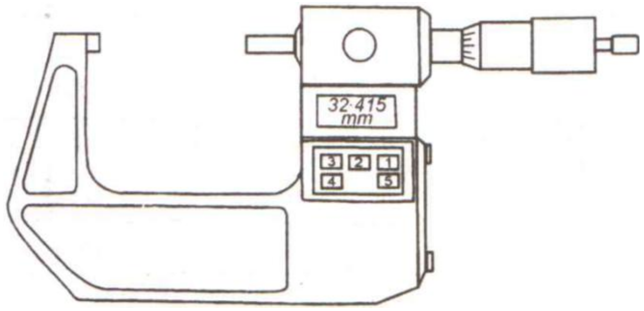


Figure 5.19 : Digital Micrometer

5.3.3 Height Gauge

This also uses the same principle of vernier caliper and is used especially for the measurement of height. It is equipped with a special base block, sliding jaw assembly and a removable clamp. The upper and lower surfaces of the measuring jaws are parallel to the base, which make possible to measure both over and under surfaces. A scribing attachment in place of measuring jaw can be used for scribing lines at certain distance above the surface. Specification of a vernier height gauge is made by specifying the range of measurement, type of scale required and any particular requirement in regard to the type of vernier desired.

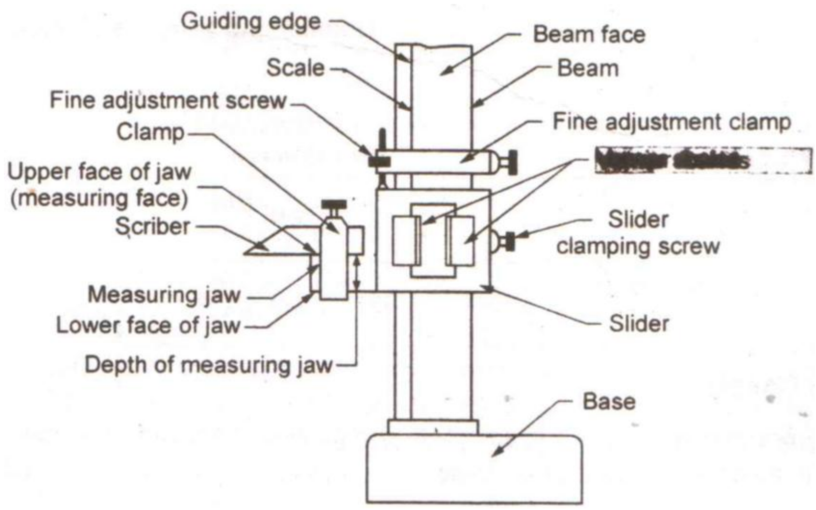


Figure 5.20 : Vernier Height Gauge

5.3.4 Slip Gauges

Slip gauges are rectangular blocks of steel having a cross-section of about 30 by 10 mm. The essential purpose of slip gauges is to make available end standards of specific lengths by temporarily combining several individual elements, each representing a standard dimension, into a single gauge bar. The combination is made by pressing the faces into contact and then imparting a small twisting motion while maintaining the contact pressure. This is called wringing. Wringing occurs due to molecular adhesion between a liquid film (thickness about 6 μm to 7 μm) and the mating surface. The combination made in that way can be used as reference for transferring the dimensions of the unit of length from the primary standard to gauge block of lower accuracy. It is also used for the verification and graduation of measuring apparatus and for direct measurement of linear dimensions of industrial components. For this purpose, control geometry of form such as flatness and parallelism of the surfaces and squareness of the gauging surfaces are essential. According to accuracy, the slip gauges can be graded into three categories, i.e. Grade 0, Grade I and Grade II. Generally, two sets of slip gauges are available.

Normal Set

Slip gauges of the following dimensions are available in this type of set.

Table 5.1 : Normal Set

Range	Step	Pieces
1.001 to 1.009	0.001	9
1.01 to 1.09	0.01	9
1.1 to 1.9	0.1	9
1 to 9	1	9
10 to 90	10	9
	Total	45

Special Set

Slip gauges of the following dimensions are available in this type of set.

Table 5.2 : Special Set

Range	Step	Pieces
1.001 to 1.009	0.001	9
1.01 to 1.49	0.01	49
0.5 to 9.5	0.5	19
10 to 90	10	9
	Total	86

The cross-section of most commonly used rectangular slip gauges are as shown below.

Normal Size	Cross-sectional Area ($w \times d$) in mm
Up to 10 mm	$30^{+0.0}_{-0.3} \times 9^{-0.05}_{-0.3}$
Above 10 mm	$35^{+0.0}_{-0.3} \times 9^{-0.05}_{-0.3}$

Selection of Slip Gauges

Standard procedure is followed in selecting slip gauges. It should be such that minimum number of slip gauges is chosen for combination of blocks depending on the type of set available. The procedure will be clear if we explain it with an example :

Let us consider the case where we have to arrange a dimension of 56.421 mm and normal sets of slip gauges are available.

Always the last decimal point is to be considered first, i.e. 0.001 mm. Since gauge of 0.001 mm is not available, 1.001 mm slip gauge is to be selected.

The dimension left now is 56.421 – 1.001 = 55.42 mm.

Now considering the second decimal place, slip gauge with 1.02 mm height is selected. The dimension left is 55.42 – 1.02 = 54.4 mm.

Next for 54.4 mm, slip gauge with 1.4 mm is to be chosen and then 3.0 mm gauge. Finally, 50 mm gauge is to be chosen.

Thus, we have 50.000 + 3.000 + 1.400 + 1.020 + 1.001 = 56.421 mm. All these five slip gauges are wrung properly to get the required dimension.

If special set of gauges be used, the combination in this case would have been 50.000 + 5.420 + 1.001 = 56.421 mm.

SAQ 2

(a) List various types of micrometers. Describe screw thread micrometer caliper.

(b) List the slip gauges to be wrung together to produce an over all dimension of 93.458 mm using both normal and special set of slip gauges without any protection slips.

5.4 ELECTRICAL MEASURING DEVICES

Electrical measuring devices give the most precise value of measurement among all the instruments discussed above. They use electrical transducers that transform a variety of physical quantities and phenomena into electrical signals. We will discuss some of the widely used electric devices in linear measurement in the following sections.

5.4.1 Strain Gauge

The most widely used pressure and force sensitive transducer is the strain gauge. The principle of the strain gauge is based on the resistive properties of electrical conductors. Electrical conductor possesses resistance based on the relationship

$$R = \rho \left(\frac{L}{A} \right)$$

where R is the resistance, ρ is the resistivity, L is the length and A is the area of cross-section.

When a metal conductor is stretched or compressed, its resistance changes because of the fact that both length and diameter of the conductor change. These effects, called piezoresistive effect, can be used for measurement of several variables like strain and associated stress in experimental stress analysis, and small dimensional changes. Figure 5.21 shows the influence of forces.

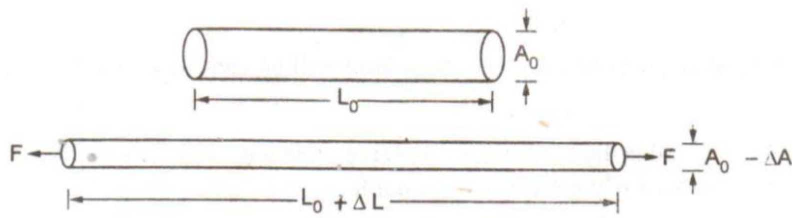


Figure 5.21

At the top of the figure, the conductor is unstressed. At the bottom of the figure, the conductor is in tension, increasing its length and reducing its area. The resistance of the strain gauge changes in proportion to its change in dimensions.

$$R_0 + \Delta R = \rho \frac{L_0 + \Delta L}{A_0 - \Delta A}$$

The gauge factor, *G*, of a strain gauge is the ratio of relative change in resistance to the relative change in length.

$$G = \frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}}$$

There are two primary constructions used in making strain gauges : bonded and unbonded. These are shown in Figure 5.22. In the unbonded strain gauge, the wire resistance element is stretched between two flexible supports. The wire stretches in accordance with the force applied to the diaphragm. The resistance of the wire changes due to these forces.

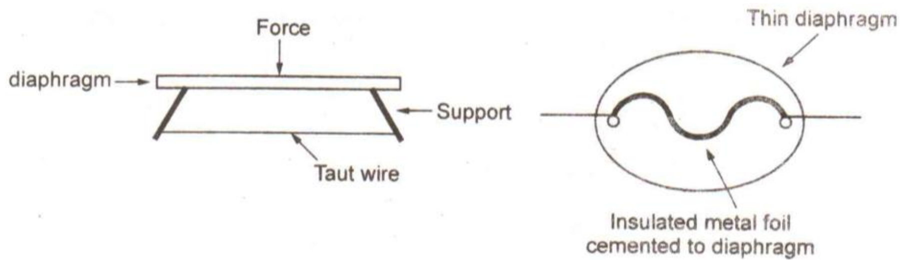


Figure 5.22 : (a) Unbonded; and (b) Bonded

In a bonded strain gauge, a wire metal foil is placed in a thin metal diaphragm. When the diaphragm is flexed, the element deforms and change in resistance occurs. Generally, bonded strain gauge is more durable than unbonded.

There are three types of strain gauges :

(a) Metallic resistance strain gauge made of metallic wires such as constantan (Cu-Ni alloy) Nichrome V or Platinum alloy.

(b) Foil strain gauge consists of a thin, 8-to 15 μm nitro-cellulose impregnated paper on which photo etched metal alloy filaments are attached as resistance material. For higher temperature, an epoxy backing is used instead of paper. The active length of the gauge is along the transverse axis. The gauge should be mounted with its transverse axis in the same direction as the direction of application of force or strain. Thus, the elongation of the gauge reduces the length and consequently the resistance.

(c) The third type is the semiconductor gauge. It depends on the piezoresistive properties of silicon and germanium. They have high sensitivities with gauge factor from 50 to 200. Their chief defects are fluctuations due to temperature and non-linear output. The p-type gauges increase resistance with applied tensile strain while n-type gauge resistance decreases. The gauge is generally bonded to the structure by epoxy adhesive or ceramic cement.

5.4.2 Potentiometer

A potentiometer consists of a resistive elements provided with a sliding contact. This sliding contact may move either in linear or rotational direction and accordingly the corresponding potentiometer is called a linear or rotary potentiometer respectively. Figure 5.23 shows the diagram for translational, single turn rotational, and multi-turn helix potentiometer.

Let e_i and e_0 = input and output voltage (V) respectively,

x_t = total length of translational potentiometer m,

x_i = displacement of wiper from its zero position, and

R_p = total resistance of the potentiometer.

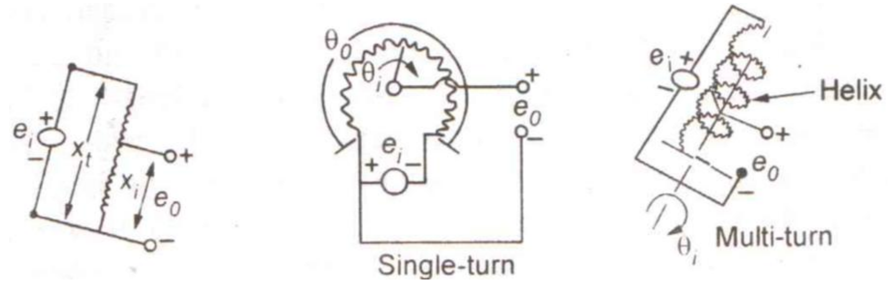


Figure 5.23

If the distribution of the resistance with respect to translational movement is linear, the resistance per unit length is R_p/x_p.

The output voltage under ideal condition is :

$$e_0 = \left(\frac{\text{Resistance at the Output Terminal}}{\text{Resistance at the Input Terminal}}\right) \times \text{Input Voltage}$$

$$= \left[\frac{R_p\,(x_i / x_t)}{R_p}\right] e_i = \frac{x_i}{x_t} \times e_i$$

Under ideal condition, the output voltage varies linearly with displacement.

5.4.3 Linear Variable Differential Transformer (LVDT)

LVDT is high-resolution contact transducer. As Figure 5.24 illustrates, it is connected with three coils, one primary and two secondary. A magnetic core sits within the coil.

If an alternating current is imposed on the primary coil, a voltage will be induced across the secondary coil. The magnitude of that voltage is a linear function of the position of the magnetic core. Deviation from the null position of the core can be translated into voltage reading by the equation

$$\Delta V_0 = K\,\Delta X$$

where, ΔV_0 is the change in output voltage, K is a proportionality constant, and ΔX is the change in position.

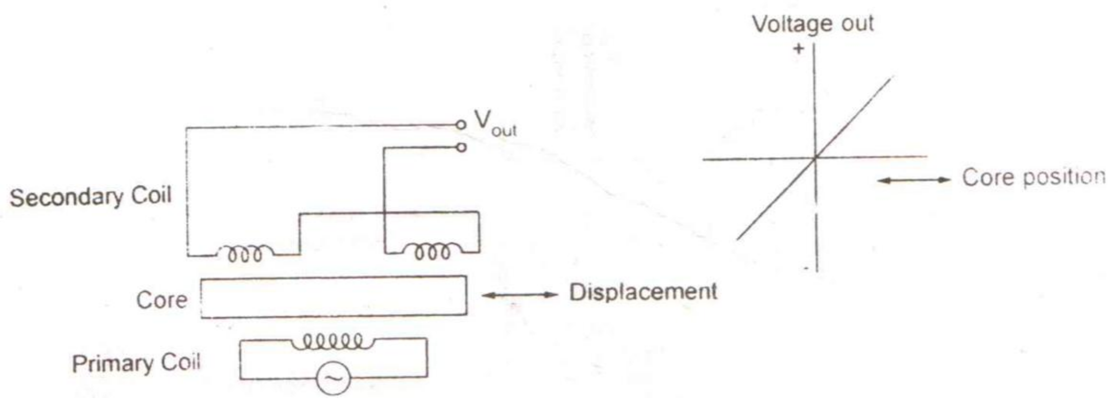


Figure 5.24 : LVDT

LVDTs come in various sizes. The resolution of an LVDT is excellent, easily able to measure displacement below 0.001 inch. Since this is an analog device, the limits of resolution are usually governed by the resolution of the A/D converters.

LVDT use alternating currents. Therefore, a requirement exists to transform the output voltage to DC before it is applied to the A/D converter. Manufacturers of LVDT serve this requirement with instrumentation packages that provide the required DC operation voltage.

It is apparent that the LVDT has an advantage over the potentiometer as a position measurement device. Since its core does not touch the coil, there is no mechanical wear that would result in deterioration of performance over time. On the other hand, it is a more expensive transducer. It is justifiable primarily where very high and repeatable accuracy is required.

5.5 COMPARATORS

Comparators are the instruments calibrated by means of end standards to measure unknown dimensions. The purpose of a comparator is to detect and display the small differences between the unknown linear dimensions and the length of the standard. The difference in lengths is detected as a displacement of a sensing probe. The important and essential function of the instruments is to magnify or amplify the small input displacement so that it is displayed on an analog scale. Comparators are classified on the basis of type of the amplification method used. Accordingly comparators are of following types or hybrid thereof.

(a) Mechanical comparators, (b) Optical Comparators.

(c) Pneumatic comparators, (d) Electrical comparators.

5.5.1 Mechanical Comparators

Conventional mechanical methods to obtain magnification are not suitable in construction of mechanical comparators as it causes backlash and friction. Also they require a large input force. Let us understand the mechanical comparators by studying a reed comparator which is strictly a mechanical comparator.

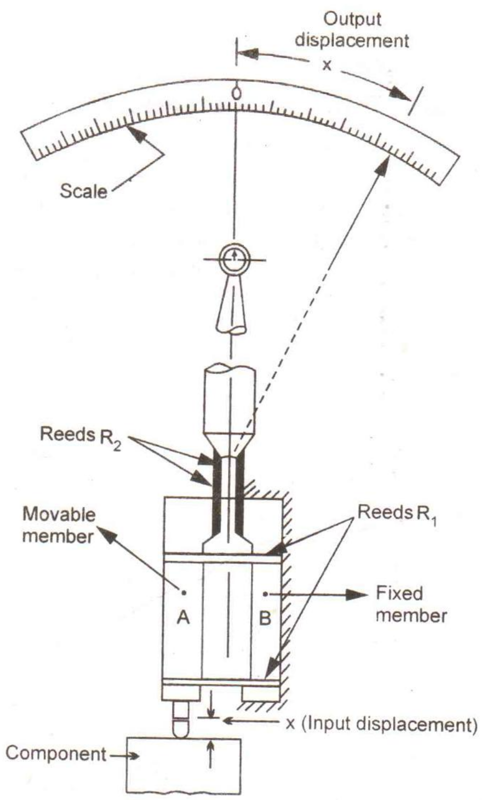


Figure 5.25 : Mechanical (Reed) Comparator

A spindle attached to the movable member is in contact with the component to be measured. Movable member moves through a distance *x*, in response to displacement with respect to fixed member. The movable member is constrained by flexture strips or reeds R_1, to move relative to the fixed member. The pointer is attached to reeds R_2. A small input displacement produces a large angular movement, *x*, of the pointer on account of their orientation relative to the motion. The scale is calibrated by means of gauge blocks and indicate the difference in displacement of the fixed and movable elements. There is no friction and the hysteresis effect is minimized by using suitable steel for the reeds. Comparators of this type have sensitivities of the order of 0.25×10^{-3} mm/scale division. There are many other systems which are used for mechanical comparators. However, there is a limit to magnification that can be achieved with purely a mechanical comparator.

5.5.2 Optical Comparators

Optical comparators are based on the principle of projection of image. A simple optical comparator for measurement of linear dimension is shown in Figure 5.26. The arrangement consists of mechanical system which causes a plane reflector to tilt about an axis so that the image of an index is projected on scale on the inner surface of a ground glass screen. The actual difference *x* between the two dimensions is amplified by a lever to give an angular displacement θ of a pivoted mirror. The reflected ray is deflected through an angle 2θ from the original line and gives a reading of *X* on the scale. The main advantage of an optical comparator is that it is capable of giving higher degree of magnification due to reduction of moving members and better wear resistance qualities.

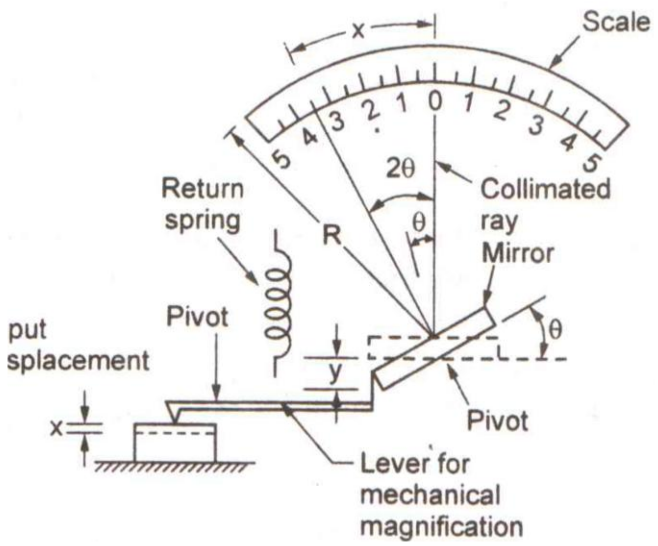


Figure 5.26 : Optical Comparator

5.5.3 Pneumatic Comparators

Pneumatic comparators are the widely used precision instruments which use the principle of obstructed nozzle. The schematic diagram of a pneumatic comparator is shown in Figure 5.27.

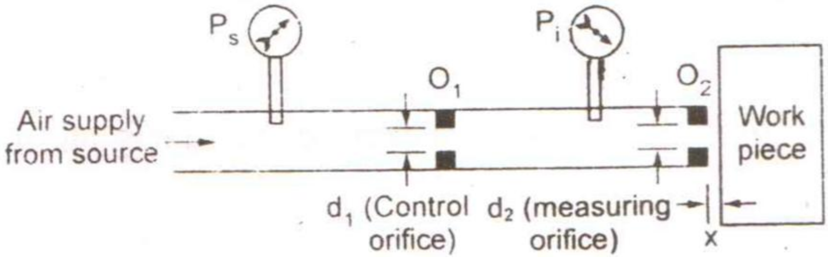


Figure 5.27 : Schematic Diagram of a Pneumatic Comparator

It has two orifices O_1 and O_2 with diameter d_1 and d_2 respectively. Through O_1, air is supplied at a constant pressure, P_s, which is the pressure of the source.

The area of orifice $O_1 = A_1 = (\pi / 4)\, d_1^2$. This area is fixed.

The area of the second orifice through which air can pass $O_2 = A_2 = \pi\, d_2\, x$.

Thus, the area of orifice O_2 is variable and depends upon the displacement of the workpiece x.

The intermediate pressure P_i between the fixed orifice and the outlet is dependent upon the source pressure P_s, and the pressure drops across the two orifices O_1 and O_2. Since area A_2 of the orifice O_2 varies with displacement x, the intermediate pressure, P_i, also changes with change in x. Thus, change of pressure is a function of displacement x and hence can be used as a measure of dimension x.

5.5.4 Electrical Comparators

Electrical comparators are used as a means of detecting and amplifying small movements of a work contacting elements. It may use any of the following transducers for magnification. They are

(a) strain gauges,

(b) variable inductance transducers, and

(c) variable capacitance transducers.

The transducer converts the displacement into a corresponding change in current and a meter recorder connected in the circuit to indicate the electrical change calibrated to show in terms of displacement. Generally, an amplifier is used to provide the requisite sensitivity and to match the characteristics of different parts of the circuit. There are different types of electrical comparators. One of them, called an electrolimit gauge, is used to check or measure the outside diameter of a roll. The object to be checked is placed on the anvil under overhanging gauging spindle. Movement of the spindle for its deviation from a standard dimension unbalances an electric circuit. The displacement is magnified electrically and shown on the dial meter.

There are a number of advantages of electrical comparators over the mechanical type. They have little or no moving parts and, therefore, they maintain their accuracy over long periods. In addition, the sensitivity of these comparators can be adjusted at will to suit the type of measurement being done. Electrical comparators can give magnification from 600 to 10,000 according to the meter. Figure 5.28 shows the basic parts of an electric comparator.

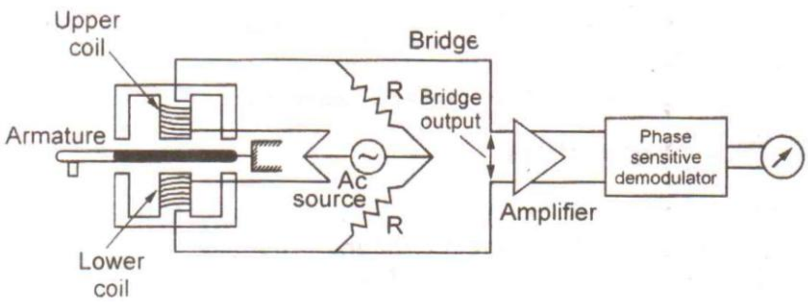


Figure 5.28 : Electric Comparator

SAQ 3

What are the advantages of electrical comparators over mechanical comparators?

5.6 SUMMARY

In this unit, linear measuring devices and comparators have been discussed. The unit begins with the description of non-precision measuring devices like scale (ruler), caliper, divider and telescopic gauge. Next, precision measuring devices, viz. vernier caliper, micrometer, height gauges and slip gauges are explained. The principles of electrical measuring devices like strain gauges, LVDTs, potentiometers have also been discussed. The four basic types of comparator viz. mechanical, optical, pneumatic and electrical are discussed.

5.7 KEY WORDS

Vernier Constant : It is defined as the difference between one small division of the vernier scale and one small division of the main scale.

Least Count : It is the minimum distance that can be measured by a vernier caliper or a micrometer accurately.

Wringing : It is the process of combining two slip gauges by application of pressure normal to the surface to be joined with sliding motion of one surface over the other.

Transducer : A transducer is a device which, when actuated, transform energy from one form to another.

Piezo-resistive Effect : It is defined as the phenomenon due to which resistivity of a conductor changes when it is subjected to strain.

Gauge Factor : The gauge factor of a strain gauge is the ratio of relative change in resistance to the relative change in length.

5.8 ANSWERS TO SAQs

SAQ 1

See preceding text for answer.

SAQ 2

(a) Least count of a vernier scale

= Main scale spacing – Vernier scale spacing

$$= \left(\frac{12}{24} - \frac{12}{25}\right) \text{ mm}$$

$$= \frac{1}{50} \text{ mm}$$

= 0.02 mm

(b) See preceding text for answer.

(c) By using the normal set

Original dimension	=	93.458
First Plate	=	1.008
		92.450
Second Plate	=	1.050

		91.000
Third Plate	=	1.400
		90.000
Fourth Plate	=	90.000

Therefore, combination = 1.008 + 1.05 + 1.40 + 90 mm

= 93.458 mm.

By Using the Special Set

Original dimension	=	93.458
First Plate	=	1.008
		92.450
Second Plate	=	1.45
		91.00
Third Plate	=	1.00
		90.00
Fourth Plate	=	90.00

Therefore, combination = 1.008 + 1.05 + 1.40 + 90 mm

= 93.458 mm.

Flow Measurement

7.1 Introduction

It is important to be able to measure and control the amount of material entering and leaving a chemical and other processing plants. Since many of the materials are in the form of fluids, they are flowing in pipes or conduits. Many different types of devices are used to measure the flow of fluids. The flow of fluids is most commonly measured using ***head flow meters***. The operation of these flow meters is based on the Bernoulli's equation.

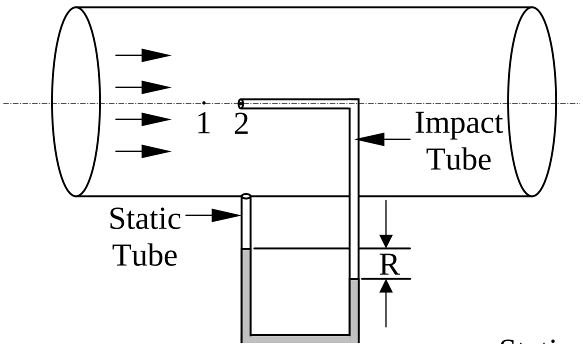
A construction in the flow path is used to increase in the lines flow velocity. This is accompanied by a decrease in pressure intensity or head and since *the resultant pressure drop is a function of the flow rate of fluid*, the latter can be evaluated.

7.2 Flow Measurement Apparatus

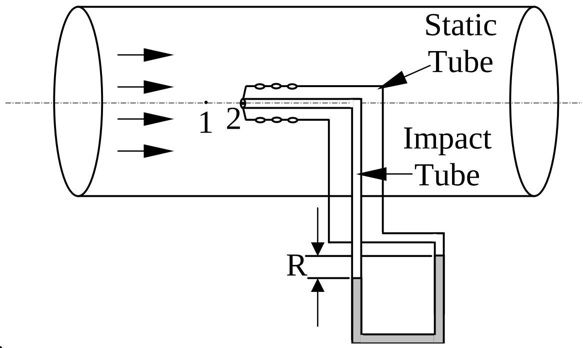
Head flow meters include **orifice, venture meter, flow nozzles, Pitot tubes, and wiers**. They consist of primary element, which causes the pressure or head loss and a secondary element, which measures it.

7.2.1 Pitot Tube

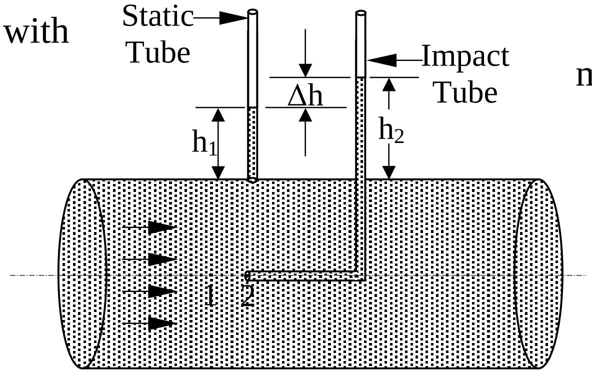
The Pitot tube is used to measure ***the local velocity*** at a given point in the flow stream and not the average velocity in the pipe or conduit. In the Figures below a sketch of this simple device is shown. One tube, ***the impact tube***, has its opening normal to the direction of flow and ***the static tube*** has its opening parallel to the direction of flow.



Simple Pitot tube with manometer



Simple Pitot tube with manometer provided with static pressure holes



Simple Pitot tube

Point 2 called ***stagnation point*** at which the impact pressure is be and $u_2 = 0$.

By applying Bernoulli's equation between points 1 and 2

$$\frac{P_1}{\rho g}+\frac{u_1^2}{2\alpha_1 g}+z_1=\frac{P_2}{\rho g}+\frac{u_2^2}{2\alpha_2 g}+z_2$$

$$\Rightarrow u_1=\sqrt{\frac{2(-\Delta P)}{\rho}}=\sqrt{2g\Delta h}=\sqrt{\frac{2R(\rho_m-\rho)g}{\rho}}$$ where, $\Delta P = R(\rho_m-\rho)g$

The fluid flows into the opening at point 2, pressure builds up, and then remains stationary at this point, called "***Stagnation Point***". The difference in the *stagnation pressure* (impact pressure) at this point (2) and the static pressure measured by the static tube represents the pressure rise associated with the direction of the fluid.

Impact pressure head = Static pressure head + kinetic energy head

Since Bernoulli's equation is used for ideal fluids, therefore for real fluids the last equations of local velocity become:

$$u_x=Cp\sqrt{\frac{2(-\Delta P)}{\rho}}=Cp\sqrt{2g\Delta h}=Cp\sqrt{\frac{2R(\rho_m-\rho)g}{\rho}}$$

where, Cp: dimensionless coefficient to take into account deviations from Bernoulli's equation and general varies between about 0.98 to 1.0.

Since the Pitot tube measures velocity at one point only in the flow, several methods can be used to obtain the average velocity in the pipe;

The first method, the velocity is measured at the exact center of the tube to obtain u_{max}. then by using the Figure, the average velocity can be obtained.

The second method, readings are taken at several known positions in the pipe cross section and then a graphical or numerical integration is performed to obtain the average velocity, from the following equation;

$$u=\frac{\iint_A u_x dA}{A}$$ (see Problem 5.16 Vol.I)

Example -7.1-

Find the local velocity of the flow of an oil of sp.gr. =0.8 through a pipe, when the difference of mercury level in differential U-tube manometer connected to the two tapping of the Pitot tube is 10 cm Hg. Take Cp = 0.98.

Solution:

$$u_x=Cp\sqrt{\frac{2R(\rho_m-\rho)g}{\rho}}=0.98\sqrt{\frac{2(0.1)(13600-1000)9.81}{800}}=5.49\,m/s$$

Example -7.2-

A Pitot tube is placed at a center of a 30 cm I.D. pipe line has one orifice pointing upstream and other perpendicular to it. The mean velocity in the pipe is 0.84 of the center velocity (i.e. u/u_x =0.94). Find the discharge through the pipe if: -

i- The fluid flow through the pipe is water and the pressure difference between orifice is 6 cm H_2O.

ii- The fluid flow through the pipe is oil of sp.gr. = 0.78 and the reading manometer is 6 cm H_2O. Take Cp = 0.98.

Solution:

i- $u_x=Cp\sqrt{2g\Delta h}=0.98\sqrt{2(9.81)(0.06)}=1.063\,m/s$

u = 0.84 (1.063) = 0.893 m/s, Q = A.u = $\pi/4(0.3)^2$ (0.893) = 0.063 m^3/s