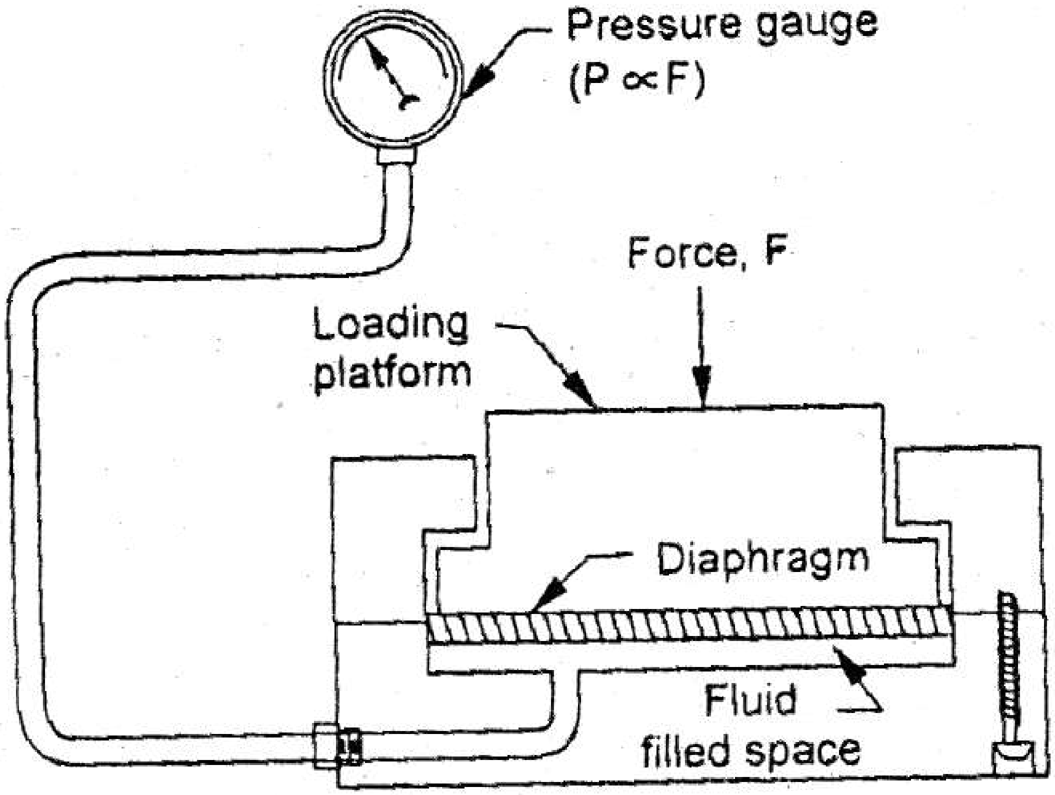
Force Measurement

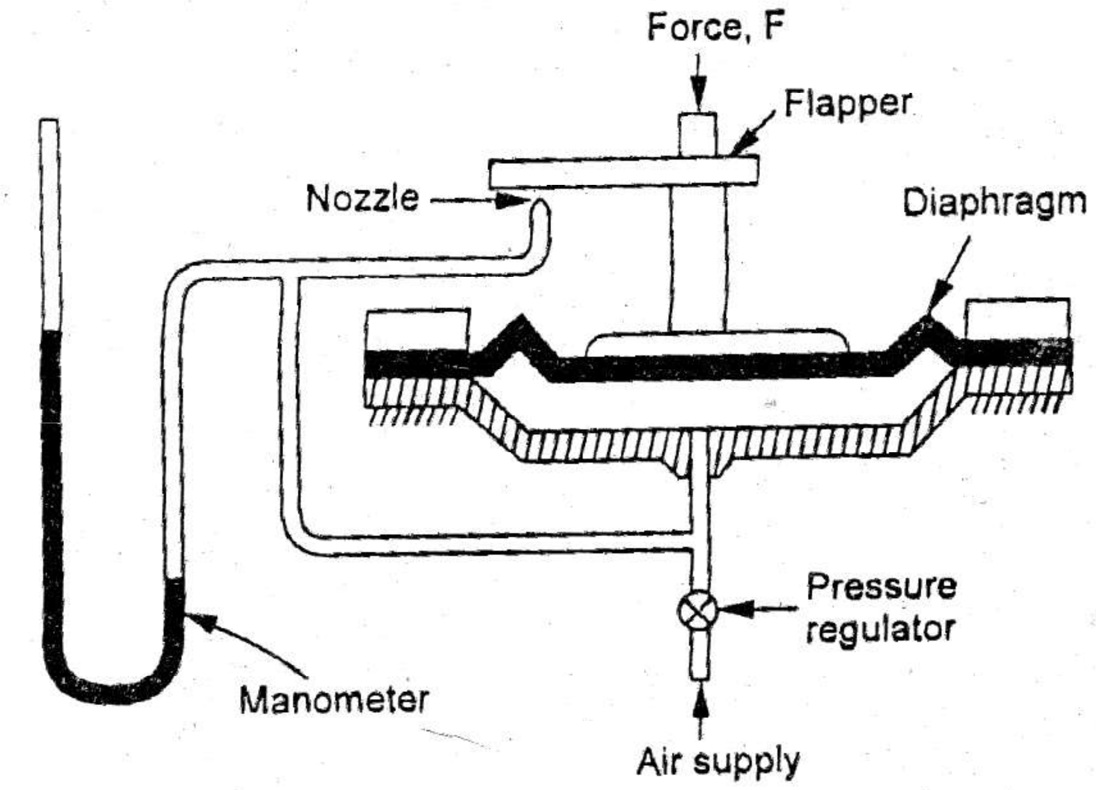
Hydraulic Load Cell



Hydraulic Load Cell

- **Force** is impressed upon diaphragm which deflects & transmit it to liquid
- The liquid in a space has preload pressure of the order of 2 bar.
- Application of force increases the liquid pressure. It equals force magnitude divided by effective area of diaphragm.
- The pressure is transmitted to pressure gauge calibrated in force units.
- This system has good dynamic response.
- **Used to measure loads up to 2.5 MN with accuracy of the order of 0.1 % of full scale ; resolution is about 0.02%.**

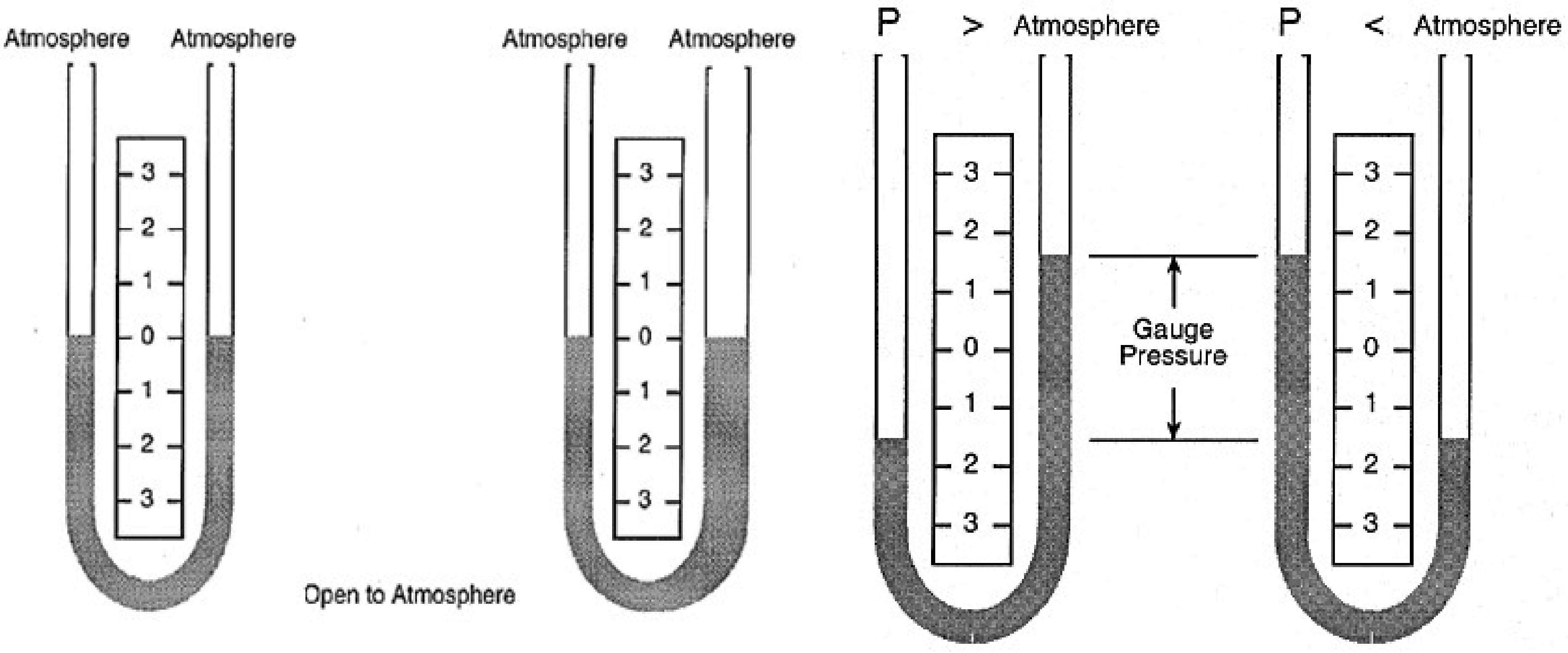
Pneumatic Load Cell



Pneumatic Load Cell

- A downward force is balanced by an upward force of air pressure against the effective area of a diaphragm.
- Application of force causes flapper to come closer to nozzle, and the diaphragm to deflect downwards.
- Nozzle opening is nearly shut-off and this results into an increased back pressure in the system.
- For constant applied force system attains equilibrium at a specific nozzle opening and a corresponding pressure is indicated by height of mercury column .
- Can measure loads upto 250 kN with an accuracy of 0.5 % of full scale

Variations on the U-Tube Manometer



A. Positive Pressure

B. Negative Pressure

U – Tube Manometer

- Filled with Manometric fluid whose specific gravity is known

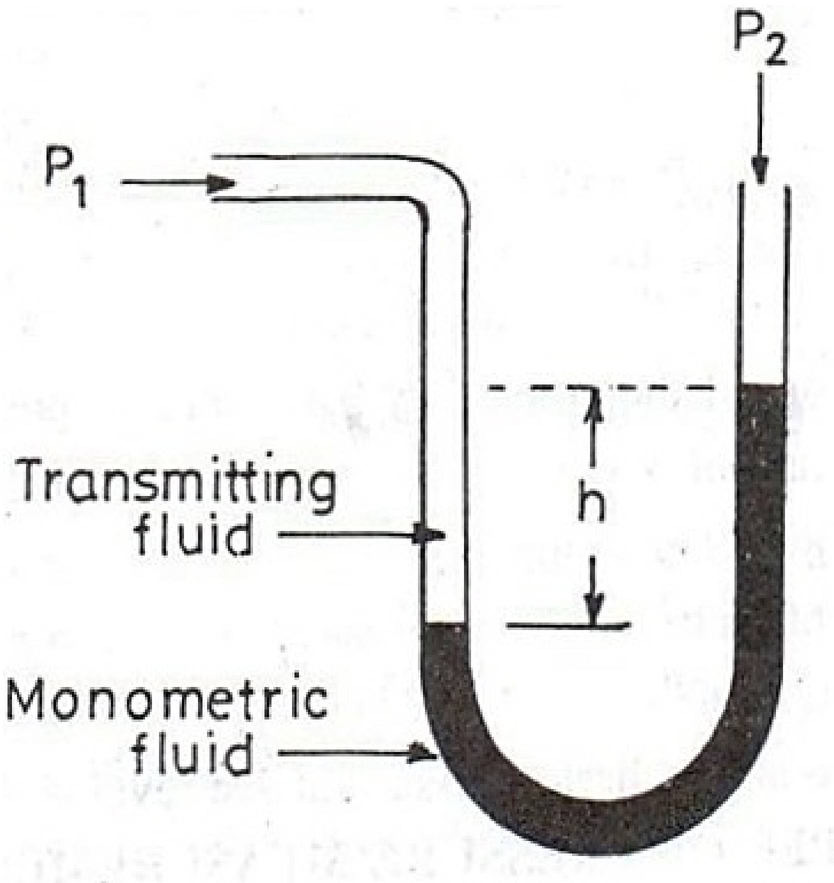
- Pressure balance equation is,

$$P_1 + gh\rho_f = P_2 + gh\rho_m$$

$$\Delta P = gh\,(\rho_m - \rho_f)$$

Where,

g is gravitational force (9.81 m/s^2), ρ_m and ρ_f are densities of manometric fluid and transmitting fluid in kg/m^3



- If pressure due to transmitting fluid can be neglected, difference in pressure,

$$\Delta P = P_1 - P_2 = gh\,\rho_m$$

- Pressure sensitivity is: $S = \frac{\Delta h}{\Delta P} = \frac{1}{g\rho_m}$

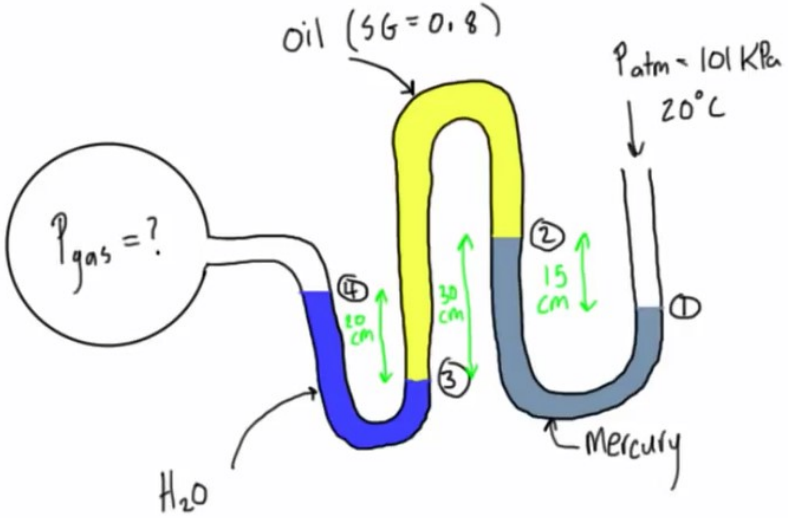
- If P_1 is pressure being measured, U-tube manometer can be used for measurement of:

✓ Absolute pressure, if $P_2 = 0$,

✓ Gauge pressure if $P_2 =$ atmospheric pressure,

✓ Differential pressure, if P_2 is the second pressure to be compared with P_1

U Tube Manometer



$$P_2 = P_1 - \rho g h$$
$$= 101{,}000\ Pa - (13{,}580\ \tfrac{Kg}{m^3})(9.81\ \tfrac{m}{s^2})(0.15m)$$
$$= 101{,}000\ Pa - 19.9\ Pa$$
$$P_2 = 81{,}100\ Pa$$

$0.8(\rho_{H_2O})$ ρ_{oil} =

$0.8(998\ \tfrac{Kg}{m^3}) = 798.4\ \tfrac{Kg}{m^3}$

$$P_3 = P_2 + \rho g h$$
$$= 81{,}000\ Pa + (798.4\ \tfrac{Kg}{m^3})(9.81\ \tfrac{m}{s^2})(0.3m)$$
$$= 81{,}000 + 2{,}300\ Pa$$
$$= 83.4\ KPa$$

$$P_4 = P_{gas} = P_3 - \rho g h$$
$$= 83{,}400\ Pa - (998)(9.81)(0.2)$$
$$= 83{,}400 - 1{,}958 \longrightarrow P_{gas} = 81{,}442\ Pa$$

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s1 saurabh_bhardwaj, 01-02-2016

Strain Gauge Load Cell

- Uses change in resistance to sense strain produced by a force
- If a metal conductor is stretched/compressed its resistance changes as both length and diameter of conductor changes.
- Gauge of circular wire with length(l), area(A), diameter(D) before strain. Let tensile stress ‘s’ be applied causing length to increase and area to decrease.
- When strained there are changes in its dimensions. Let ΔL is change in length, ΔA is change in area, ΔD is change in diameter and ΔR is change in resistance

Strain Gauge Load Cell

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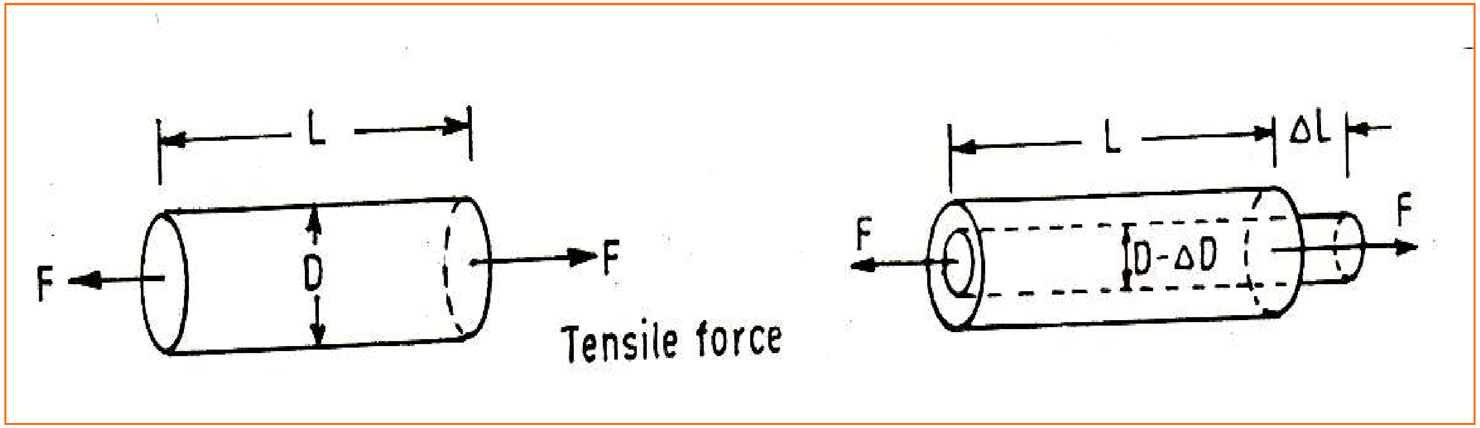


Strain Gauge Load Cell

- Resistance of unstrained gauge is

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

To find how ΔR depends upon the material physical quantities, the expression for R is differentiated with respect to stress s

$$\frac{dR}{ds} = \frac{\rho}{A}\frac{\partial L}{\partial s} - \frac{\rho L}{A^2}\frac{\partial A}{\partial s} + \frac{L}{A}\frac{\partial \rho}{\partial s}$$

- Dividing both side by resistance R = ρ L / A, we get

$$\frac{1}{R}\frac{dR}{ds} = \frac{1}{L}\frac{\partial L}{\partial S} - \frac{1}{A}\frac{\partial A}{\partial s} + \frac{1}{p}\frac{\partial \rho}{\partial s}$$

- Per unit change in resistance is due to the factors like per unit change in length= ΔL/L, area = Δ A/A and resistivity = $\Delta\rho/\rho$

Strain Gauge Load Cell

$$A = \frac{\pi}{4} D^2 \quad \therefore \quad \frac{\partial A}{\partial s} = 2 . \frac{\pi}{4} D . \frac{\partial D}{ds}$$

$$\frac{1}{A}\frac{dA}{ds} = \frac{(2\pi/4)D}{(\pi/4)D^2}\frac{\partial D}{\partial s} = \frac{2}{D}\frac{\partial D}{\partial s}$$

$$\frac{1}{R}\frac{dR}{ds} = \frac{1}{L}\frac{\partial L}{\partial s} - \frac{2}{D}\frac{\partial D}{\partial s} + \frac{1}{\rho}\frac{\partial \rho}{\partial s}$$

Also we know that Poission's ratio $v = \dfrac{lateralstrain}{longgitudinalstrain} = -\dfrac{\partial D/D}{\partial L/L}$

$$\partial D / D = -v \times \partial L / L$$

$$\frac{1}{R}\frac{dR}{ds} = \frac{1}{L}\frac{\partial L}{\partial s} + v\frac{2}{L}\frac{\partial L}{\partial s} + \frac{1}{\rho}\frac{\partial \rho}{\partial s}$$

Strain Gauge Load Cell

- For small variations, relationship can be written as

$$\frac{\Delta R}{R} = \frac{\Delta L}{L} + 2\nu\frac{\Delta L}{L} + \frac{\Delta\rho}{\rho}$$

- The gauges factor is defined as the ratio of per unit change in resistance to per unit change in length gauge factor

$$G_f = \frac{\Delta R / R}{\Delta L / L} \qquad G_f = \frac{\Delta R / R}{\Delta L / L} = 1 + 2\nu + \frac{\Delta\rho / \rho}{\Delta L / L}$$

$$G_f = 1 + 2\nu + \frac{\Delta\rho / \rho}{\in}$$

$$\varepsilon = strain = \frac{\Delta L}{L}$$

- If the change in the value of resistivity of a material when strained is neglected, the gauge factor is given by

$$G_f = 1 + 2\nu$$

Strain Gauge Load Cell

Quarter Bridge:

Only one strain gauge is used and other 3 elements are fixed resistors.

Half Bridge:

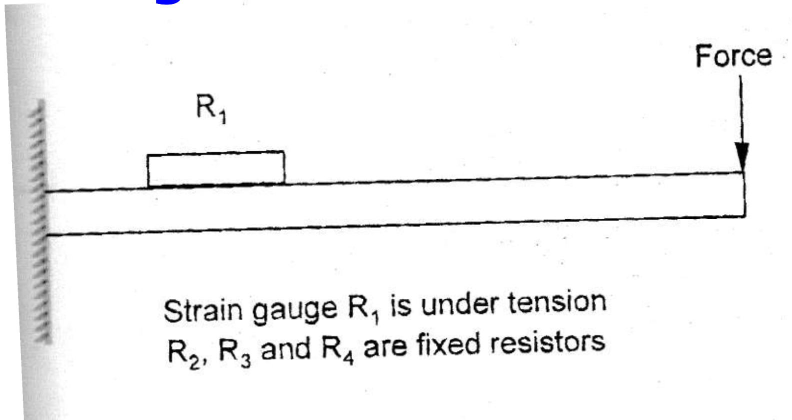
Two of the bridge elements are strain gauges and the other two are fixed resistors.

Full Bridge:

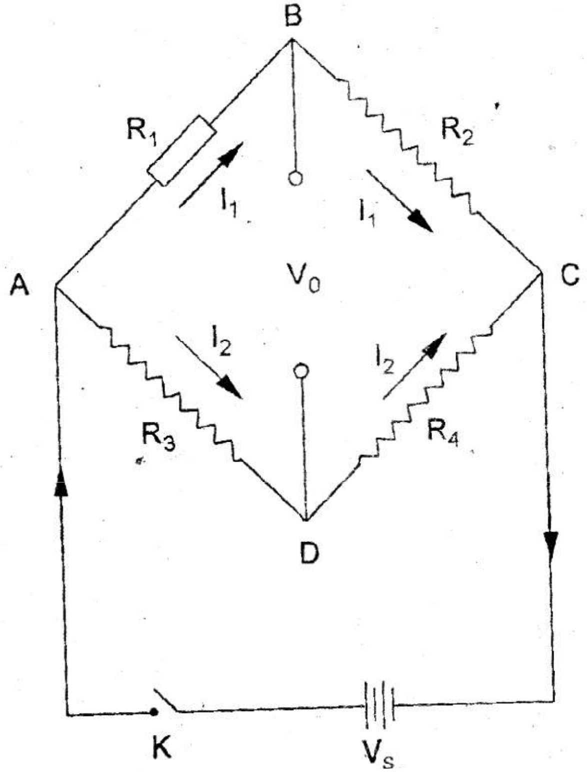
All the four elements are strain gauges.

Strain Gauge Load Cell

Quarter Bridge:

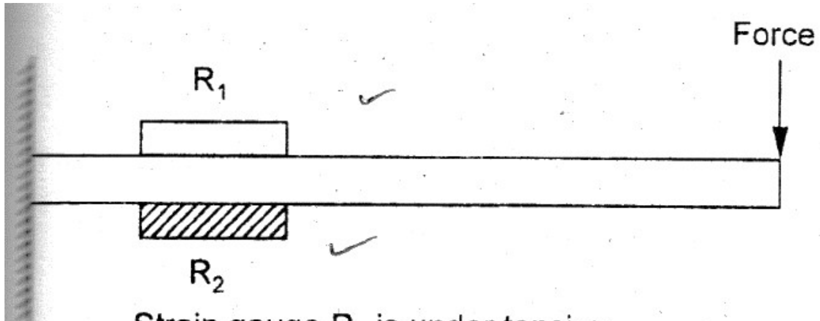


$$dV_o = \frac{V_s}{4}\frac{dR}{R}$$

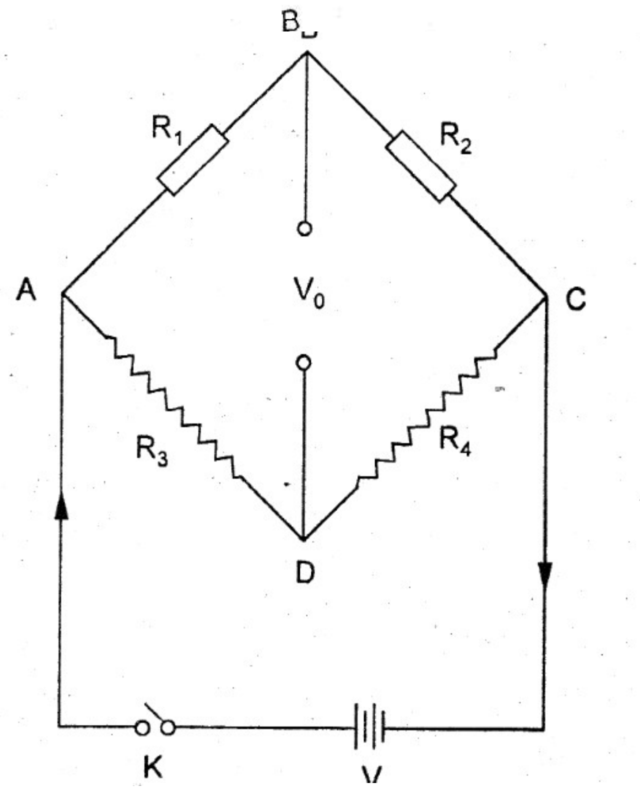


Strain Gauge Load Cell

Half Bridge:



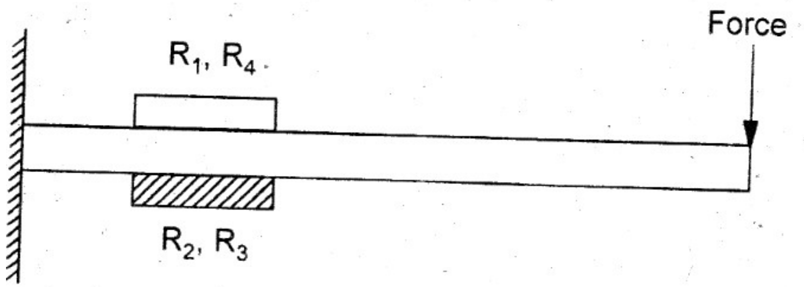
Strain gauge R_1 is under tension
Strain gauge R_2 is under compression
R_3 and R_4 are fixed resistors



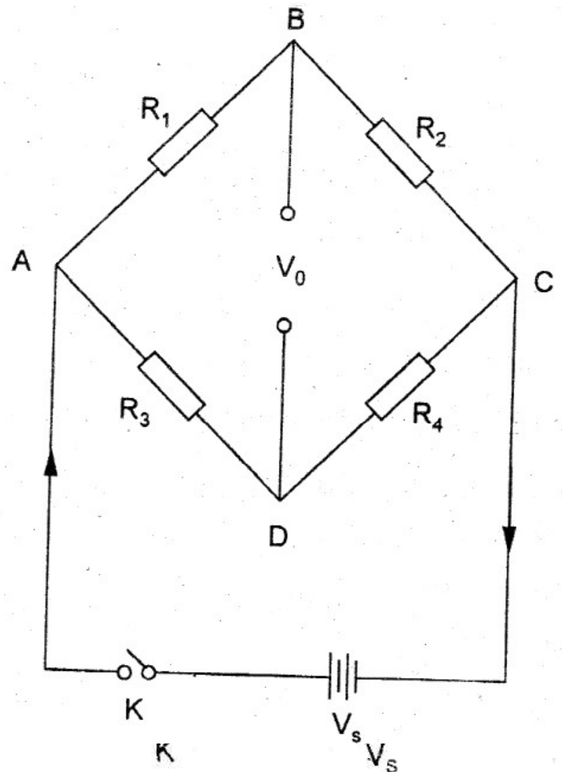
$$dV_o = \frac{V_s}{2}\frac{dR}{R}$$

Strain Gauge Load Cell

Full Bridge:



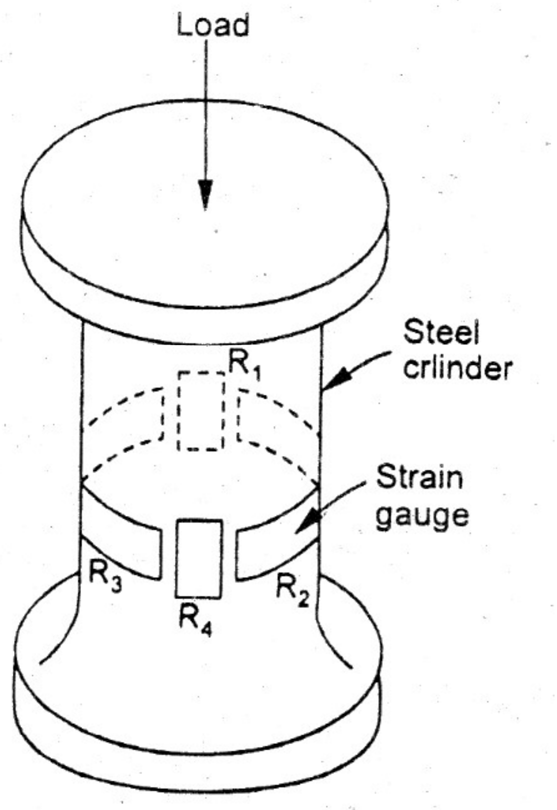
Gauge R_1 and R_4 is under tension
Gauge R_2 and R_3 is under compression



$$dV_o = V_s \frac{dR}{R}$$

Strain Gauge Load Cell

- The Gauges R1 and R4 are along the direction of applied load
- R2 and R3 are attached at right angles to gauges R1 and R4
- These 4 gauges are connected to the 4 limbs of wheat stone bridge

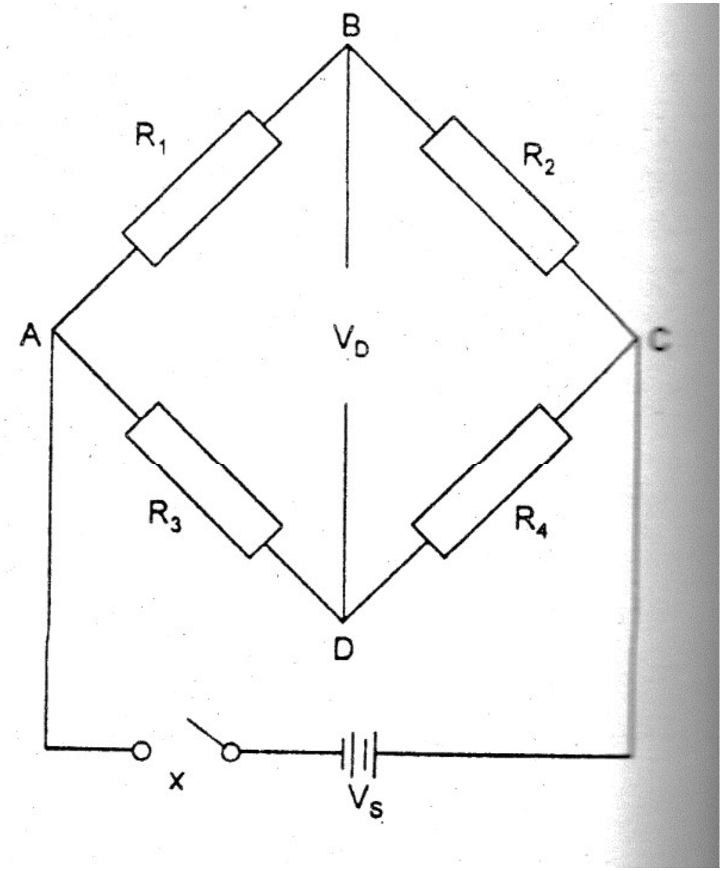


Strain Gauge Load Cell

- When a compressive load is applied the vertical gauges (R1 and R4) undergo compression and so decrease in resistance.

- Gauges R2 and R3 undergo tension and so increase in resistance.

- In Poisson’s arrangement changes in resistance are related to each other by poisson’s ratio



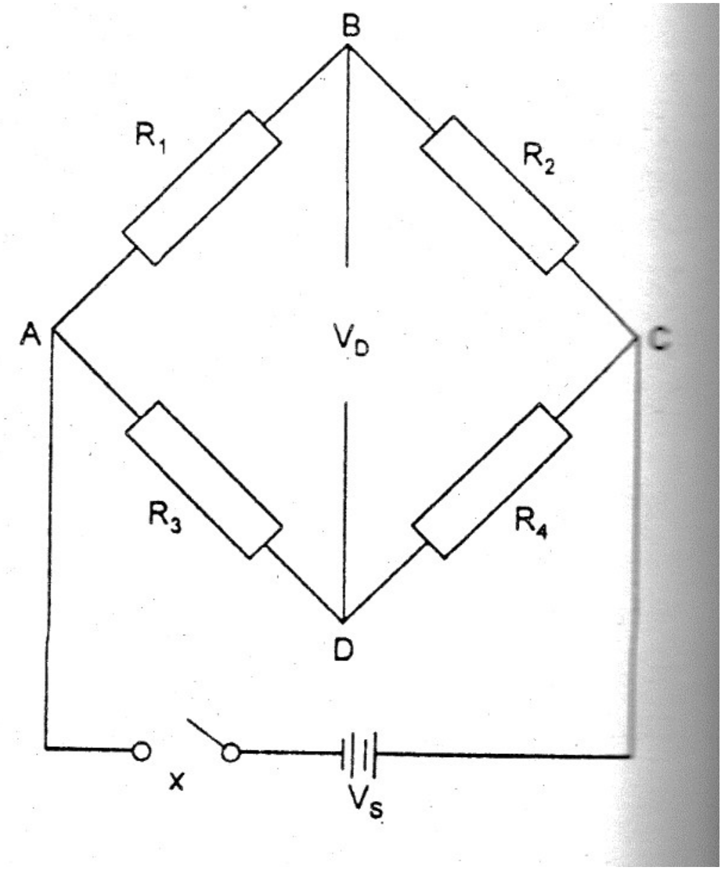
Strain Gauge Load Cell

- When strained ,

R1 and R4 = R – dR

R2 and R3 = R + μdR

Changed output voltage = $2(1+\mu)(\frac{V_s}{4}\frac{dR}{R})$



Speed Measurement

Things that Turn - Examples

Tire on a car or bike

Buckets on a waterwheel

Teeth on a gear

Horse on a Merry-Go-Round

Fins on a fan or a windmill

Earth on its axis

Linear & Angular Velocity - Examples

Film on a projector or tape on a videotape

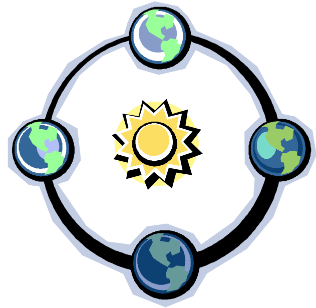
Turntable in a microwave oven

Blade on a lawnmower

Earth around the sun

Seat on a Ferris wheel

Rope around a pulley



A record on an old record player

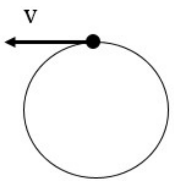
Drum/Barrel in a clothes dryer

Linear & Angular Velocity - Examples

- Linear Velocity is distance/time: $$v = \frac{s}{t}$$

- Angular Velocity is turn/time: $$\omega = \frac{\theta}{t}$$

Linear/Tangential Velocity



- Objects moving in a circle also have a rotational or angular velocity, which is the rate angular position changes.
- Rotational velocity is measured in degrees/sec, rotations/minute (rpm), *etc*.
- Common symbol, ω

Rotational/Angular Velocity

- Objects moving in a circle still have a linear velocity = distance/time.
- This is often called tangential velocity, since direction of the linear velocity is tangent to the circle

Measurement of Linear Velocity

- Velocity is first derivative of displacement

- Linear velocity utilize

  - ✓ Electromagnetic transducers
  - ✓ Seismic transducers
  - ✓ Digital transducers
  - ✓ Transducers utilizing Doppler effect

Electromagnetic Transducers

- Here, voltage produced in a coil on account of change in flux linkages resulting from change in reluctance
- O/P voltage from coil is $$e_o = \frac{d\Phi}{dt}$$
- Flux $$\Phi = \frac{Ni}{R}$$

$$e_o = \frac{d}{dt}\left(\frac{Ni}{R}\right) = N\frac{d}{dt}\left(\frac{i}{R}\right) = \frac{N}{R}\frac{di}{dt} - \frac{Ni}{R^2}\frac{dR}{dt}$$

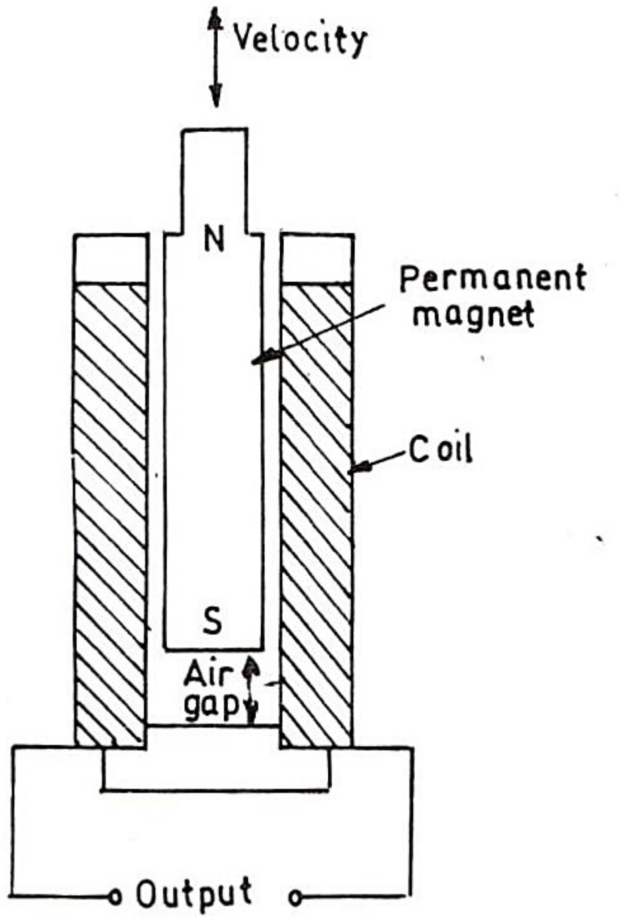
- Suppose current (i) is constant, O/P voltage $$e_o = \frac{Ni}{R^2}\frac{dR}{dt} = K\frac{dR}{dt}$$
- Electromagnetic transducers classification:

Reluctance varies directly as length of air gap & e_o is α to rate of change of length of air gap, hence v

- ➢ Moving magnet type
- ➢ Moving coil type

Moving Magnet Type

- Constant mmf Ni, can be provided by a solenoid of N turns and carrying a constant current
- Sensing element is rod i.e., rigidly coupled to the device whose velocity is being measured
- This rod is Permanent Magnet (PM)
- Motion of magnet induces a voltage in coil and amplitude of voltage is directly proportional to the velocity
- Reluctance varies directly as length of air gap and O/P voltage α rate of change of length of air gap, hence linear velocity



Moving Magnet Type

- For a coil placed in magnetic field, the voltage generated is

$$e_0 = BANv = Kv$$

where B = flux density, A = area of coil, N = number of turns of coil, v = relative velocity of magnet w.r.t coil

- Polarity of the O/P determines direction of motion
- **Advantages**

✓ Negligible maintenance (no mech. contact)

✓ O/P is linearly proportional to velocity

✓ Inexpensive

- **Disadvantages**

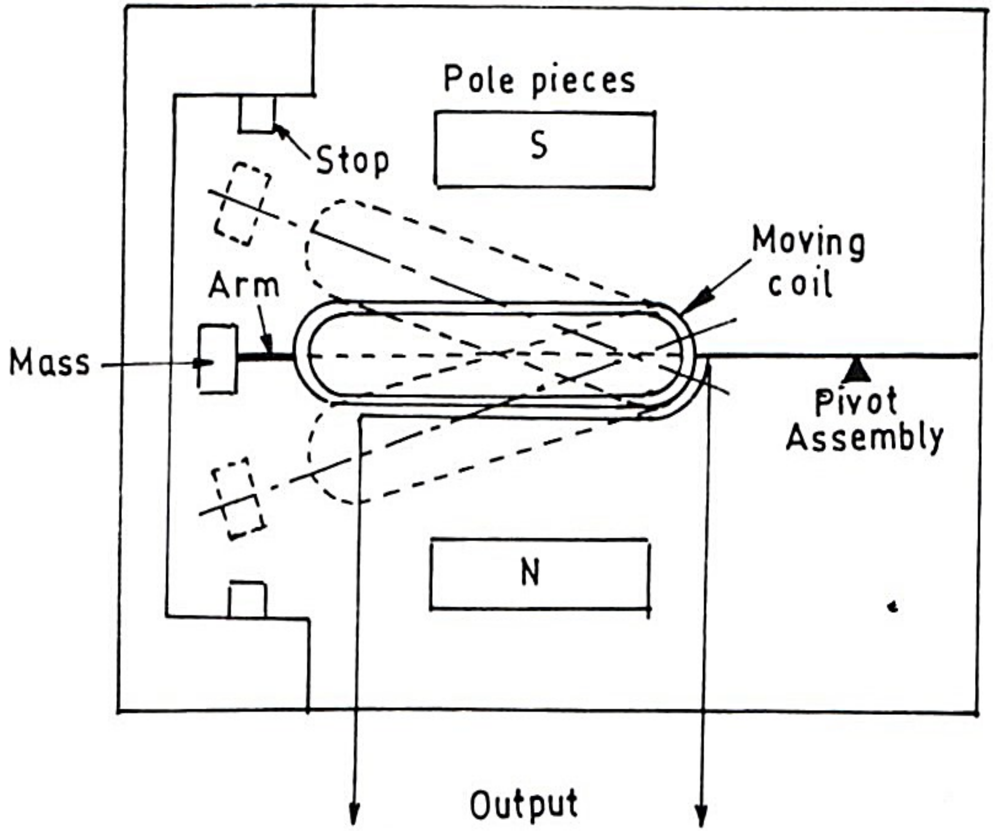
✓ Performance is adversely affected by stray magnetic fields, *resulting noise*

✓ Frequency response is limited

✓ Not very useful for measurement of vibrations

Moving Coil Type

- Operates through the action of a coil moving in a magnetic field
- Voltage is generated in the coil which is α to velocity of coil
- Velocity transducer uses a pivoted arm on which a coil is mounted
- Velocity to be measured is applied to the pivoted arm and the coil moves in the PM field



Moving Coil Type

- Voltage is generated on account of motion of the coil in the magnetic field
- O/P voltage is proportional to velocity
- Used for measurement of velocities developed in
  - linear
  - sinusoidal or random

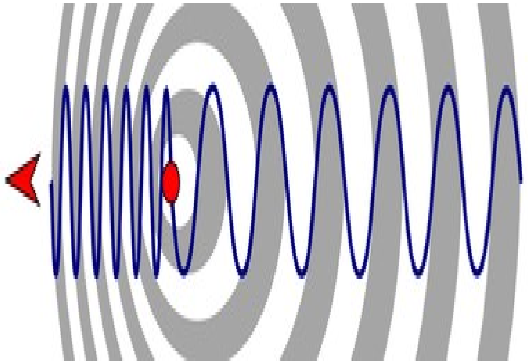
- **Advantages**

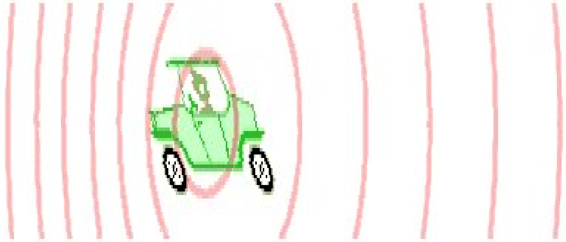
✓ More satisfactory arrangement as the system now forms a closed magnetic circuit with a constant air gap

✓ Whole device is contained in antimagnetic case which reduces the effects of stray magnetic fields

Doppler Effect Transducers

- If a narrow beam or ultrasonic beam is aimed at an object, the beam will be reflected back to the source
- If the object is moving, frequency of signals received back differs from that of the transmitted signal
- Difference of frequencies is a measure of velocity of moving object
- Received frequency is higher than transmitted frequency if the object is travelling towards receiver and lower if the object is travelling away





Doppler Effect Transducers

- In physics (waves in a medium), relationship between observed frequency f and emitted frequency f_0 is given by:

$$f = \left(\frac{v + v_r}{v + v_s}\right) f_0$$

where

υ is velocity of waves in the medium

υ_s is velocity of the source relative to the medium

υ_r is velocity of the receiver relative to the medium

Observed frequency

$$f = \left(1 - \frac{v_{s,r}}{c}\right) f_0$$

Change in frequency

$$\Delta f = -\frac{v_{s,r}}{c} f_0 = -\frac{v_{s,r}}{\lambda_0}$$