Program : **B.Tech**

Subject Name: **Instrumentation and Control**

Subject Code: **ME-402**

Semester: **4th**

UNIT-4

Theory of strain gauge: The change in the value of resistance by straining the gauge may be partly explained by the normal dimensional behavior of elastic material. If a strip material is subjected to tension as shown in figure or in other words positively strained, its longitudinal dimension will increase while there will be a reduction in the lateral dimension. So when a gauge is subjected to a positive strain, its length increases while its area of cross section decreases as shown in figure.

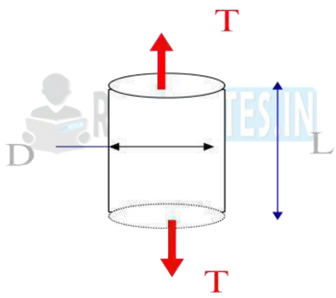
Since the resistance of a conductor is proportional to its length and inversely proportional to its area of cross section, the resistance of the gauge increases with positive strain. The change in the value of resistance of strained conductor is more than what can be accounted for an increase in resistance due to dimensional changes. the extra change in the value of resistivity of a change in the value of resistivity of a conductor when strained. This property, as described earlier is known as piezoresistive effect.

Strain Defined: Strain is defined as relative elongation in a particular direction

$\varepsilon_a = dL/L$ (axial strain)

$\varepsilon_t = dD/D$ (transverse strain)

$\mu = \varepsilon_t / \varepsilon_a$ (Poisson's ratio)



Strain gauges: The electrical resistance of a conductor changes when it is subjected to a mechanical deformation

Resistance = f (A…)

Electrical Resistance (R) is a function of…

ρ Resistivity of the material (Ohms*m)

L the length of the conductor (m)

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

R= ρ* L/A

Note R increases with:

- Increased material resistivity
- Increased length of conductor (wire)
- Decreased cross-sectional area (or diameter)
- Increased the temperatures

Deriving the Gauge Factor (GF)

- We know that L and A both change as a wire is stretched it is reasonable to think that we can rewrite the equation

  R= ρ* L/A

  to relate strain to changes in resistance.
- Start with the differential: dR = d ρ* (L/A) + ρ*d(L/A)

  Expanding with the chain rule again one gets:

  dR = d ρ* (L/A) + ρ/A*d(L)+ ρ*L*(-1/A^2)*d(A)
- Divide left side by R and right side by equivalent (ρ* L/A) to get:

$$\frac{dR}{R} = \frac{d\rho}{\rho} + \frac{dL}{L} - \frac{dA}{A}$$

Substituting into the equation

$$A = \pi\left(\frac{D}{2}\right)^2 \text{, so} \quad dA = \pi(2)\left(\frac{D}{2}\right)dD \text{, or } \frac{dA}{\mathrm{A}} = 2\frac{dD}{D} = 2\varepsilon_t$$

$$\text{also, } \frac{dL}{L} = \varepsilon_a \text{, so } \frac{\mathrm{dR}}{\mathrm{R}} = \frac{d\rho}{\rho} + \varepsilon_a - 2\varepsilon_t$$

Nothing the definition of Poisson's ratio

$$\frac{dR}{R} = \varepsilon_a(1-2\mu) + \frac{d\rho}{\rho} \text{,} \quad \text{or} \quad \mathrm{GF} \equiv \frac{\mathrm{dR}/\mathrm{R}}{\varepsilon_\mathrm{a}} = 1 + 2\mu + \frac{1}{\varepsilon_a}\frac{d\rho}{\rho}$$

Hence, we define the Gauge Factor GF as:

$$GF = 1 + 2\mu$$

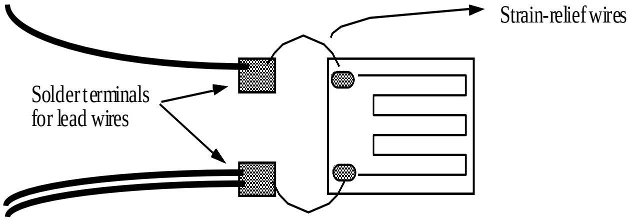
Using Gauge Factors with Strain Gauges

$$GF = 1 + 2\mu$$

$$\varepsilon_a = \frac{1}{GF}\frac{\Delta R}{R}$$

In most applications DR and e are very small and so we use sensitive circuitry (amplified and filtered bridge circuit) contained within a strain-indicator box to read out directly in units of micro-strain. Hence this strain-indicator will require R (gauge nominal resistance) and GF (gauge factor)

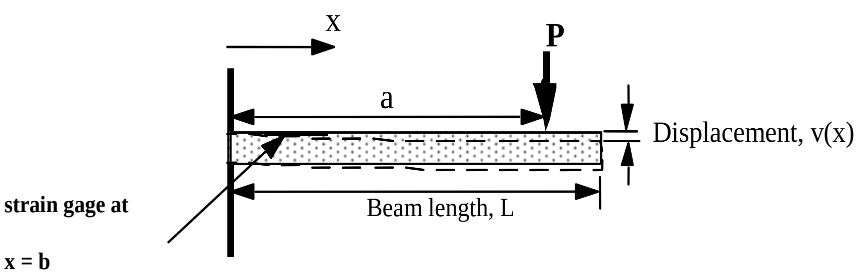
Typical Strain Gauge:



Steps for Installing Stain Gauges:

- Clean specimen – degreaser
- This are Chemically prepare gauge – Wet abrading with M-Prep Conditioner and Neutralizer
- Mount gauge and strain relief terminals on tape, align on specimen and apply adhesive
- Solder wire connections
- Test

Beam Loading Example

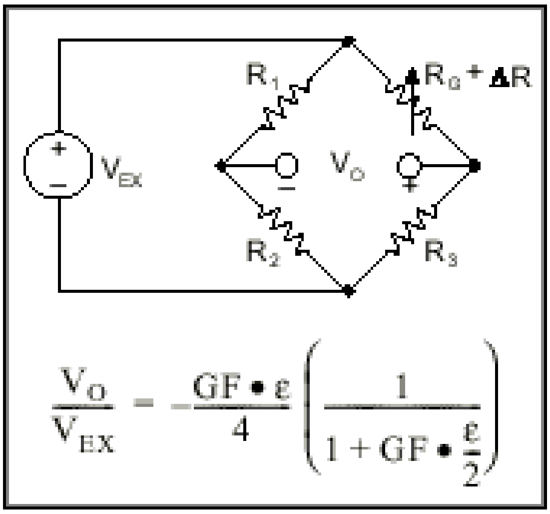


Measuring Strain with a Bridge Circuit:

- A quarter-bridge circuit is one in which a simple Wheatstone bridge is used and one of the resistors is replaced with a strain guage.
- V_o may still be small such that amplification (Amp>1.0) is usually desirable

$$\varepsilon \cong \frac{4}{Amp}\frac{V_o}{V_{ex}}\frac{1}{GF}$$

- Note: V_o and V_{ex} are also sometimes labeled as E_o and E_i (or E_{ex})

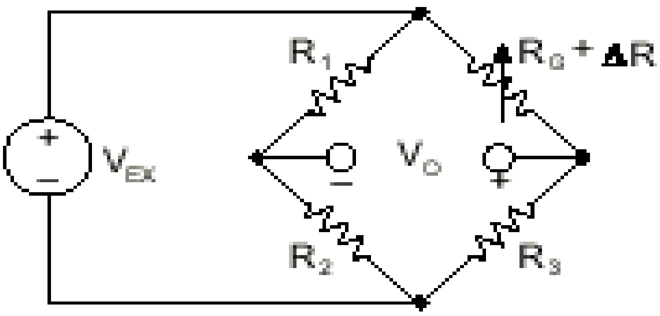


Current (i) Limitations:

- In general gauges cannot handle large currents
- The current through the gage will be driven by the voltage potential across it.

Note: Text denotes the excitation voltage as V_i. It is also often labeled V_e or V_{ex}.

$$i_G = \frac{V_G}{R_G} = \frac{V_{Ex}}{R_G + R_3}$$



Measuring Strain with a Strain-Indicator:

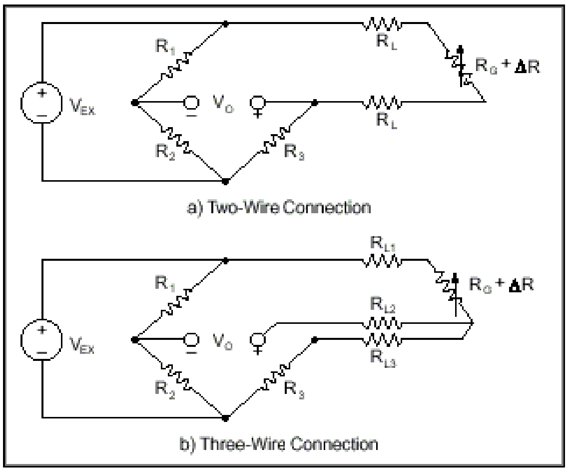
- First install a strain gauge
- Connect the wires from the strain gauge to the strain indicator.
- Apply loading conditions
- Read strain from strain indicator

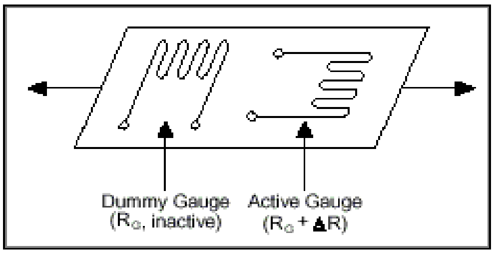
Note that the indicator always displays 4 digits and reads in microstrain

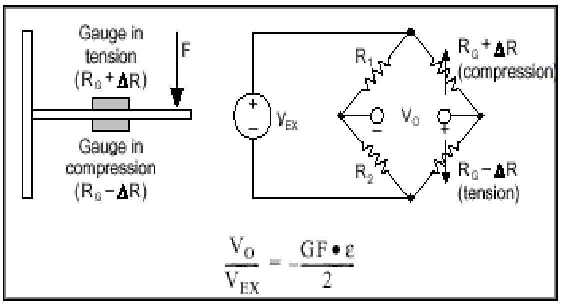
Thus, 0017 means 17 micro-inches / inch of strain.

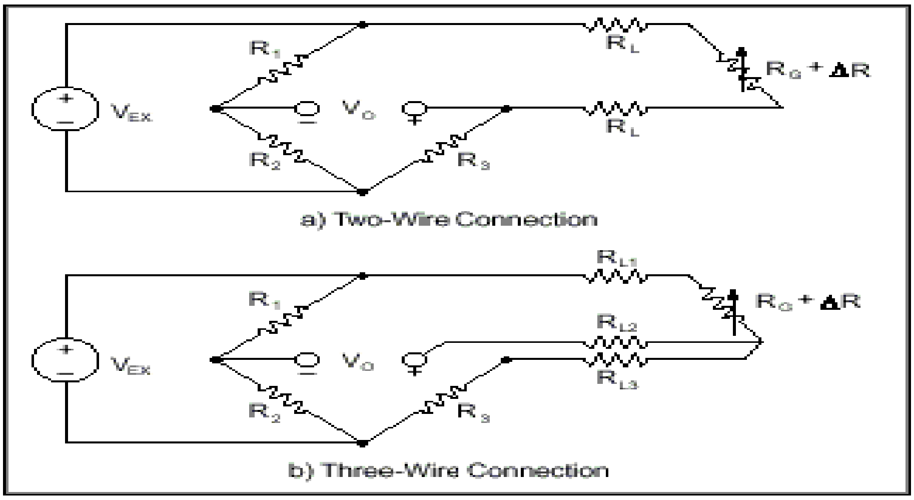
Strain gauge bridge enhancements:

- 3-wire combination addresses lead wire resistance
- Half-bridge– with a dummy gauge mounted transversely addresses gauge sensitivity to surface temperature
- Half bridge – amplification through use of dual gauges









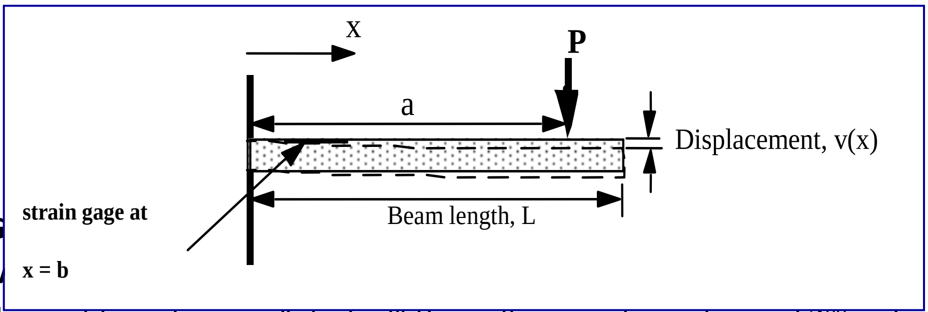
Theoretical Determination of Strain in a Loaded Cantilever Beam:

- You must either know the load P or the displacement (v)
- Determine displacement (v) at x=a
- to Know beam dimensions and material (and hence EI) estimate the load P

$$v = \frac{-Px^2(3a-x)}{6EI}, \text{so} \quad P = 3\frac{vEI}{a^3}$$

- Calculate stress at location of gauge
- Calculate e from σ=ƐE

$$\sigma = \frac{My}{I} = \frac{P*b*h/2}{I} \text{, where h = beam thickness}$$



Strain G

Cantilev

When the cantilever beam is "plucked" this will respond as a damped 2nd order system. The amplitude of vibration has the general form:

Where the damped frequency (what you measure) is related to the natural frequency (ω_n) by:

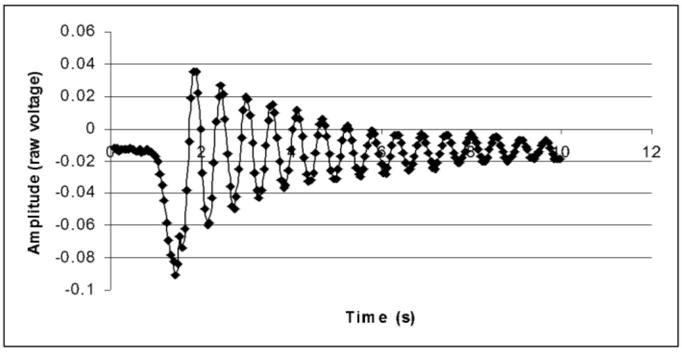
$$Y(t) = Ce^{-\zeta\omega_n t}\sin(\omega_d t)$$

$$\omega_d = \omega_n\sqrt{1-\zeta^2}$$

The damping ratio (zeta) can be determined by plotting the natural log of the Amplitude or magnitude (M) vs time:

$$M(t) = Ce^{-\zeta\omega_n t} \quad \text{so,} \quad \ln(M) = C_2 + (-\zeta\omega_n)\cdot t$$

So, the slope of the plot of ln(M) vs. t is (– z w_n)



Additional Considerations for natural frequency of "plucked" beams

- Note: Unless otherwise indicated, natural frequencies are expressed in terms of radians/sec.
- The natural frequency of a uniform beam is given by:

$$\omega_n = (1.875)^2\sqrt{\frac{EI}{m' L^4}}$$

- E is the modulus of elasticity, I is the moment of intertia about the centroid of the beam cross-section ($bh^3/12$), m' is the mass per unit length of the beam (ie kg/m), and L is the cantilevered beam length

- If the beam is not uniform…

A mass at the end can be represented as an effective change in beam mass per unit length
A hole in the end can be accounted for in a similar fashion…

Types of Strain Gauges

1. Unbonded metal strain gauges
2. Bonded metal wire strain gauges
3. Bonded metal foil strain gauges
4. Vacuum deposited thin metal film strain gauges
5. Sputter deposited thin metal strain gauges
6. Bonded Semiconductor strain gauges.
7. diffused metal strain gauges.

Unbonded Metal Strain Gauge: An unbonded metal strain gauge is shown in Fig.1. This gauge consists of a wire stretched between two points in an insulating medium such as air. The wires are of copper nickel, chrome nickel or nickel iron alloys. The flexture element is connected via a rod to a diaphragm which is used for sensing of pressure. The wires are tensioned to avoid buckling when they experience a compressive force

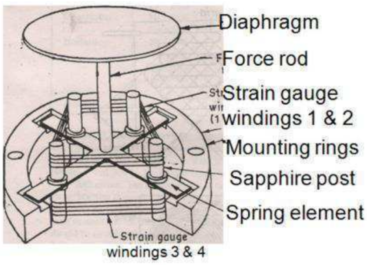


Fig.1

The unbonded metal wire gauges, used almost exclusively in transducer applications, employ preloaded

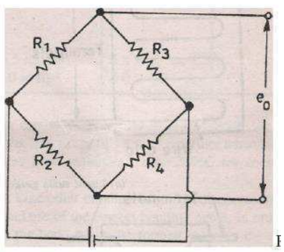


Fig.2

Resistance wires connected in a Wheatstone bridge as shown in fig.2 At initial preload, the strains and resistances of the four arms are nominally equal, with the result the output voltage of the bridge, $e_o = 0$. Application of pressure produces a small displacement which is about 0.004 mm (full scale), the displacement increases tension in two wires and decreases it in the other two thereby increasing the resistance of two wires which are in tension and decreasing the resistance of the remaining two wires. This causes an unbalance of the bridge producing an output voltage which is proportional to the input displacement and hence to the applied pressure. Electric resistance of each arm is 120 to 1000, the input voltage to the bridge is 5 to 10 V, and the full scale output of the bridge I typically about 20 mV to 50 mV. Some of the unbonded metal wire gauges are shown in Fig. 3

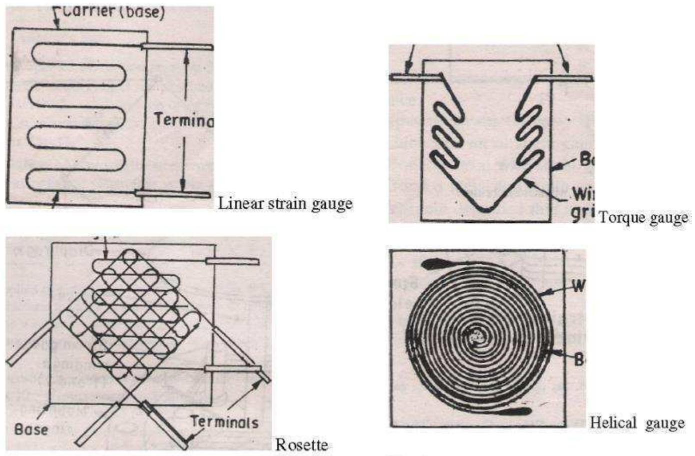


Fig.3

Force: Force is a measure of the interaction between bodies. Force takes a number of forms including short-range atomic forces, electromagnetic, and gravitational forces. Force is a vector quantity, with both direction and magnitude. If the forces acting on a body in equilibrium are summed around the periphery of the body then they add to zero. If there is any resultant force acting then the body is not in equilibrium and it will accelerate such that the rate of change of the body's momentum (velocity times mass) is equal to the force. If the body is held stationary in some way, then there will be reaction acting on the body from the support structure that is equal in magnitude and opposite in direction to the force imposed. Although the definition of force units (as given below) is based on acceleration of a free body, most force measurements are made on bodies in equilibrium, and are therefore measures of forces within a structure. Conceptually a structure can be 'cut' across any section and the forces acting within the body at that section are those which would act at the free surfaces if such a cut were made. This property is the basis of most force measurements – a physical support or link in a structure is replaced with a device that measures the forces acting at that point.

A force measurement system is made up of a transducer and associated instrumentation. The transducer is subjected to the force to be measured, and some resultant change in the element is measured by the associated instrumentation. The instrumentation may power the transducer in some way and also may process the output from the transducer before it is shown on an indicator to be read by the user. Strictly a transducer is a device that receives a physical stimulus and changes it into another measurable physical quantity through a known relationship. In practice a force transducer is a chain of several transducers, for example the force may act upon a metal cylinder which is compressed by the force, the change in size alters the electrical resistance of a strain gauge bonded to the surface of the cylinder, and the instrumentation measures this change in resistance. In this guide the term force transducer will be used loosely to describe the part of the force measurement system which converts the applied force into an output which is measured by some associated instrumentation. For many types of force measurement system the term load cell is in common usage in place of force transducer. Also, the term device is from time to time used in place of transducer within the text of this guide to avoid distracting repetition of the word transducer. For the same reasons, the term measuring instrument will occasionally be used with the same meaning as force measurement system. As will be seen in the following sections, the instrumentation may be as simple as a dial gauge or as complex as a computer with associated analogue to digital converters and excitation circuitry. The indicated value is the output of the force measurement system, which may be in units of force or other units such as volts. If the indicated value is not in units of force, then the user may need to perform a calculation based on a calibration to obtain the calculated value.

Strain gauge load cells the most common type of force transducer, and one which is a clear example of an elastic device, is the strain gauge load cell,

The elastic element the shape of the elastic element used in load cells depends on a number of factors including the range of force to be measured, dimensional limits, and required performance and production costs. Figure 4 shows a selection of different elastic elements and gives their typical rated capacities. Each element is designed to measure the force acting along its principal axis, and not to be affected by other forces such as side loads. The arrows in the figure indicate the principal axis of each element.

The material used for the elastic element is usually tool steel, stainless steel, aluminium or beryllium copper, the aim being a material which exhibits a linear relationship between the stress (force applied) and strain (output) with low hysteresis and low creep in the working range. There also has to be high level of repeatability between force cycles to ensure that the load cell is a reliable measuring device. To achieve these characteristics it is usual to subject the material to a special heat treatment.

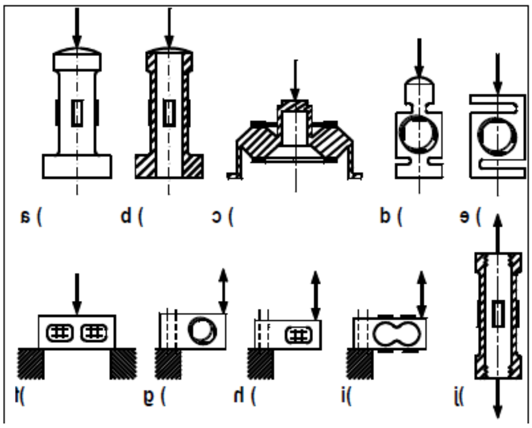


Fig. 4 Typical elastic elements and their usual rated capacities

The electrical resistance strain gauge

In electrical terms, all **electrical resistance strain gauges** may be considered as a length of conducting material, like a wire, when a length of wire is subjected to a tension within its elastic limit, its length increases with corresponding decrease in its diameter and increase of its electrical resistance. If the conducting material is bonded to an elastic element under strain then the change in resistance may be measured, and used to calculate the force from the calibration of the device.

The most common materials used for the manufacture of strain gauges are copper-nickel, nickel-chromium, nickel-chromium-molybdenum and platinum-tungsten alloys. There are a variety of resistance strain gauges available for various applications, some of which are described below. Each strain gauge is designed to measure the strain along a clearly defined axis so that it can be properly aligned with the strain field.

The **foil strain gauge** is the most widely used type and several examples are shown in Figure 5. It has significant advantages over all other types of strain gauge and is employed in the majority of precision load cells.

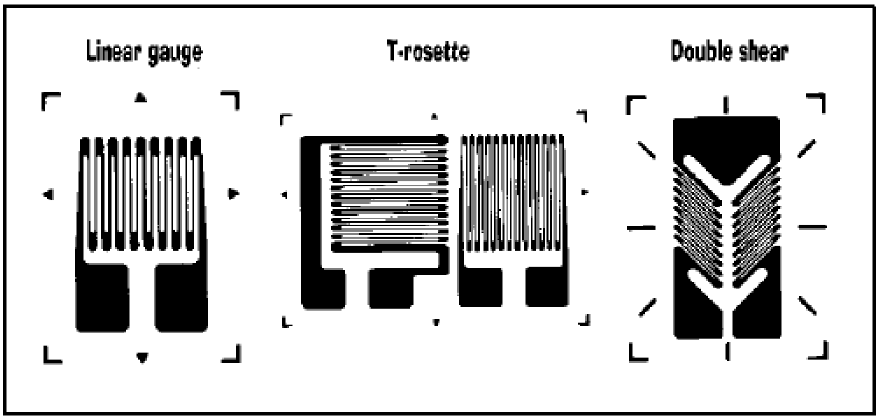


Fig 5 Typical metal foil strain gauges

Measuring force through pressure

Hydraulic load cell

The hydraulic load cell is a device filled with a liquid (usually oil), which has a pre-load pressure. Application of the force to the loading member increases the fluid pressure, which is measured by a pressure transducer or displayed on a pressure gauge dial via a Bourdon tube.

When used with a pressure transducer, hydraulic load cells are inherently very stiff, deflecting only about 0.05 mm under full force conditions. Although capacities of up to 5 MN are available, most devices fall in to the range of 500 N to 200 kN. The pressure gauge used to monitor the force can be located several metres away from the device by the use of a special fluid-filled hose. In systems where more than one load cell is used a specially designed totaliser unit has to be employed.

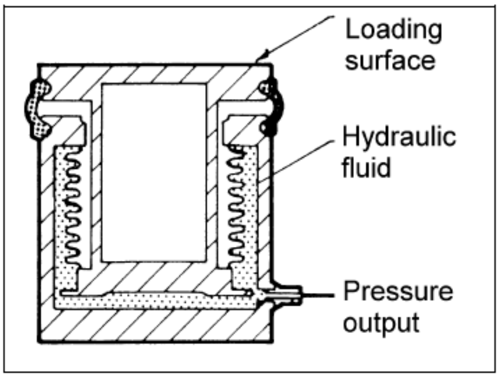


Fig. 6 An example of a hydraulic load cell

Hydraulic load cells are self-contained and need no external power. They are inherently suitable for use in potentially explosive atmospheres and can be tension or compression devices. Uncertainties of around 0.25 % can be achieved with careful design and favourable application conditions. Uncertainties for total systems are more realistically 0.5 % - 1 %. The cells are sensitive to temperature changes and usually have facilities to adjust the zero output reading, the temperature coefficients are of the order of 0.02 % to 0.1 % per °C.

Pneumatic load cell

The operating principles of the pneumatic load cell are similar to those of the hydraulic load cell. The force is applied to one side of a piston or a diaphragm of flexible material and balanced by pneumatic pressure on the other side. This counteracting pressure is proportional to the force and is displayed on a pressure dial.

The sensing device consists of a chamber with a close-fitting cap. The air pressure is applied to the chamber and builds up until it is equal to the force on the cap. Any further increase in pressure will lift up the cap allowing the air to bleed around the edge until pressure equilibrium is achieved. At this equilibrium position the pressure in the chamber is an indication of the force on the cap and can be read by the pneumatic pressure dial gauge.

Measurement of torque on rotating shafts

For rotating motion, power is the product of torque and angular velocity

$$P = M \cdot \omega = M \cdot 2\pi \cdot n$$

Thus, to determine the power of the rotating motion the torque (M) and the revolution number (n) must be measured.

Measurement of the revolution number from the point of view of the measuring concept the instruments measuring the revolution number can be divided into three groups:

- speed indicators measuring the average revolution number,
- Tachometers measuring the momentary revolution number and
- Stroboscopes working on the principle of comparison.

a) Measurement of small revolution number can be performed simply with stopwatch and by counting revolutions with naked eye. When the mark on the rotating machine part gets to the marked position, we start the stopwatch and begin counting (with 0). Having measured the time (T) and the number of revolutions (N) the revolution number is simply n=N/T.

b) For higher speed of rotation a special counting device must be used. One of the simplest of these is the so-called jumping-figure speed counter. The rotating shaft of this device turns gears. One of them completes one revolution while the other rotates only 1/10, and so on. Reading the numbers uniformly painted from 0-9 on the cylinder jacket we get the number of revolutions. Such a device is used in kilowatt-hour meters, water consumption, tape recorders, speedometers of cars etc.

c) Mechanical tachometers count the revolutions only for a fixed time, generally for 6 seconds. The time measuring device of the instrument connects its pointer for 6 seconds with that shaft of the instrument which joints the rotating machine part. After these six seconds there is no more connection which means at the same time the end of the measurement. A widely used example of this device is the Jacquet indicator. With pressing the starting button the instrument is zeroed and after releasing it the counting and the clockwork starts.

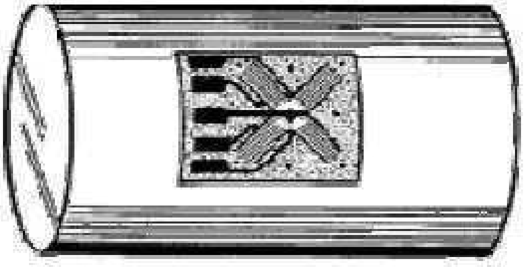
d) Electric tachometers operate with the same principle (counting the number of revolutions during some period of time), but the number of revolutions is measured in an optical way.

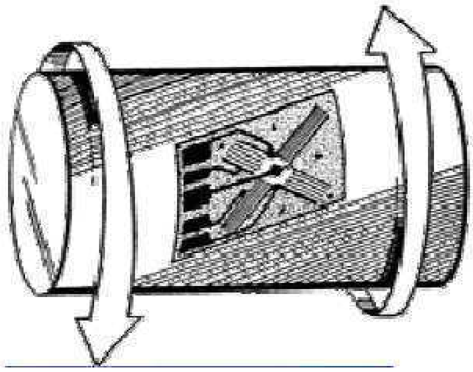
e) A stroboscope, also known as a strobe, is an instrument used to make a cyclically moving object appear to be slow-moving, or stationary. In its simplest form, a marker is placed to the rotating shaft and a lamp capable of emitting brief and rapid flashes of light is used. The frequency of the flash is adjusted so that it equals to the shaft's cyclic speed, at which point the object is seen to be either stationary or moving backward or forward, depending on the flash frequency.

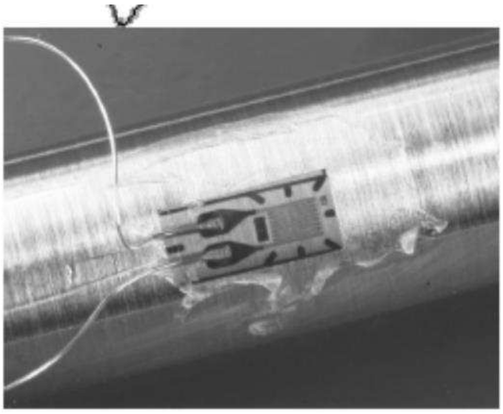
Measurement of torque There are many ways of measuring torque, out of which the two most important ones are

- Strain gauges and
- balancing motors

a) A strain gauge is a small electrical 'element' printed on a non-conductive substrate. The pattern of the element is arranged so that if the gauge is stretched (or compressed) in one direction (along operating axis of the gauge), the resistance of the element increases (or decreases) in relation to that stretch. A stretch perpendicular to the axis of the strain gauge has little effect on the resistance of the element. If a gauge is bonded to the shaft, with its axis aligned with the direction in which the shaft material stretches when a torque is applied, the strain gauge will also stretch and therefore the element will increase in resistance. By measuring the change of resistance, after appropriate calibration, one can measure the torque applied to the shaft.







b) Balancing machines (motor or generator) are special machines, whose housing is free to rotate and arms are mounted onto it.