Sensors & transducers

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Sensors

Sensors - A device that produces an output signal for the purpose of sensing a physical phenomenon. Sensors are also referred as transducers. It is a device that converts a signal from one physical form to a corresponding signal that has a different form. Quantities at input level are different from output level. Generally the output is in the form of electrical signal.

Sensors are used for measuring and recording a quantity. The measured quantity can be just recorded or further processed for controlling a system.

Sensors

Type of sensors : Analog, Digital, Active, Passive

Analog : Output is continuous, output is function of input. Requires ADC for interfacing.

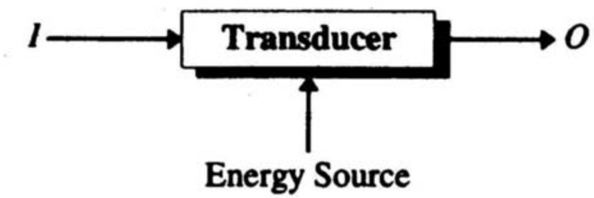
Digital : The output is in form of digital signal. Can be directly connected to computer. I2C, PWM, serial, parallel etc.

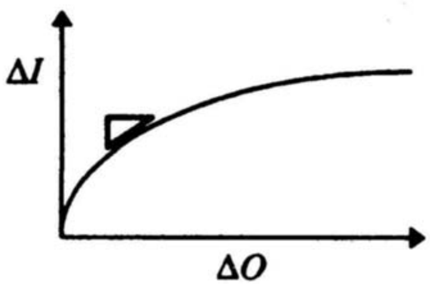
Active sensors **:** Need separate power source to obtain the output.

Passive sensors **:** These are self generating, produces electrical signal when subjected to sensed quantity. Piezoelectric, thermoelectric, radioactive etc.

Quality parameters of a sensor system

Sensitivity : It is the ability of the measuring instrument to respond to changes in measured quantity. It is ratio of change of output to change of input.





I - input, quantity to be sensed

O - output, signal which can be recorded

Sensitivity $S = \dfrac{\Delta O}{\Delta I}$

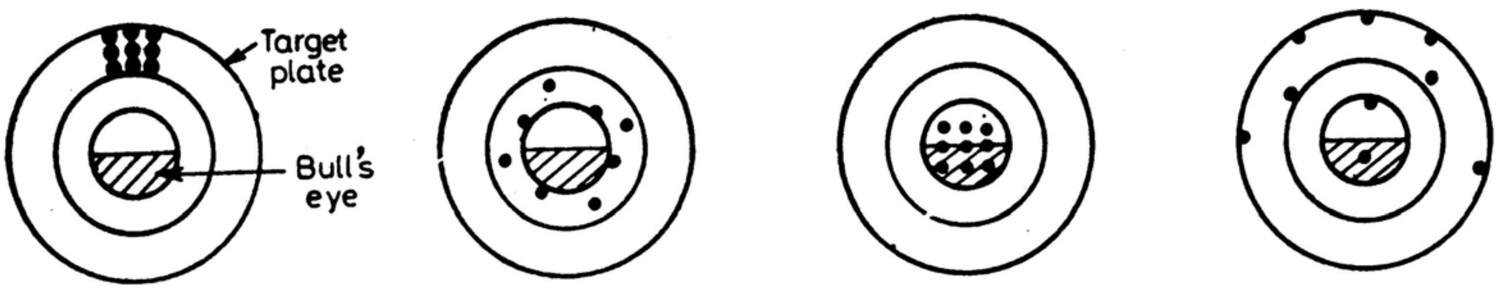
Quality parameters of a sensor system

Resolution : It is defined as the smallest increment in the measured value that can be detected.

Accuracy : It is a measure of difference between the measured value and actual value. Generally defined as percentage of actual value.

Precision : Precision is the ability of an instrument to reproduce a certain set of readings within a given deviation.

Repeatability :It is the ability to reproduce the output signal exactly when the same measured quantity is applied repeatedly under the same environmental conditions.



(a) High precision with poor accuracy

(b) Good average accuracy with poor precision

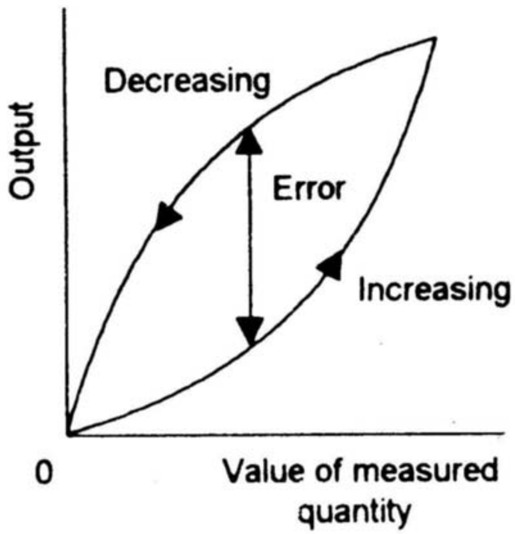
(c) High accuracy with high precision

(d) Poor accuracy with poor precision

Quality parameter of a sensor system

Range & span : It is defined as the limits between which inputs can vary. Span is maximum value minus the minimum value of the input.

Hysteresis : Different output for increasing and decreasing value of input.



Stability (drift) - It is the ability to give same output when a constant input is measured over a period of time. Drift is expressed as percentage of full range output.

Dead band : It is the range of input values for which there is no output.

Backlash : It is defined as the maximum distance or angle through which any part of a mechanical system can be moved in one direction without causing any motion of the attached part.

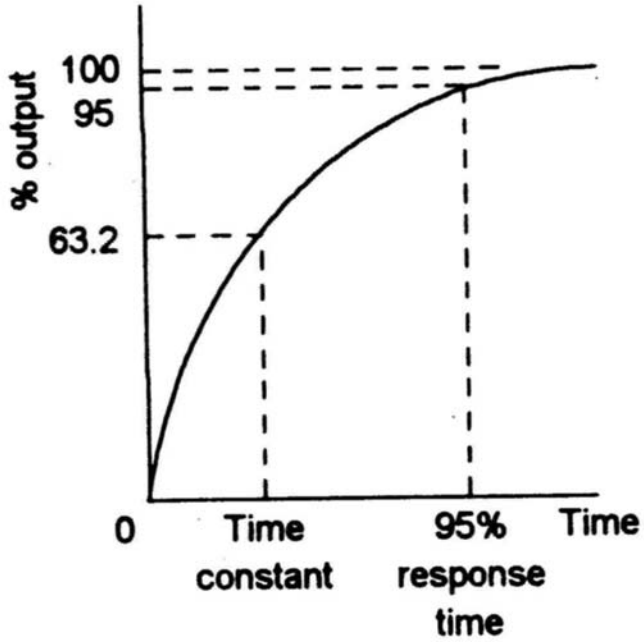
Static and dynamic characteristics of a sensor system

Static characteristics are the values given when steady state conditions occur. Input is not varying and output is constant. Output changes only due to drift.

Dynamic characteristics refer to time varying signal with corresponding time varying output.

Response time : This is the time which elapses after a step input, when the transducer gives the output corresponding to some specified percentage of steady state value e.g. 95%

Time constant : This is 63.2 % of response time.



Dynamic characteristics of a sensor system

Rise time : Time taken for the output to rise to some specified percentage of the steady state output. From 10% to 90%.

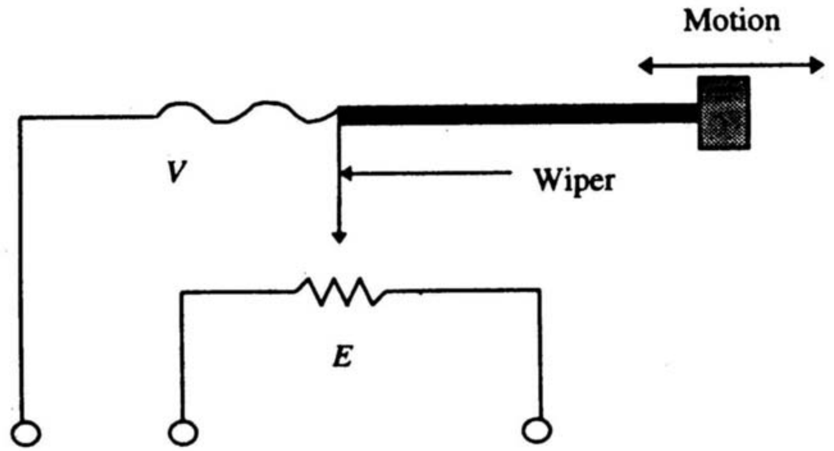
Settling time : This is the time taken for the output to settle to within some percentage e.g. 2% of steady state value.

Sensor output

Sensor output is generally in the form of resistance change or voltage change or capacitance change or current change when input quantity is changed. Appropriate circuit is required to measure the above changes.

Resistance transducer

Potentiometric principle



The object of whose motion is to be sensed is connected to the wiper of potentiometer. The movement changes voltage output. Voltage output will be linear for a linear potentiometer. These type of transducers have slow dynamic response, susceptible to vibration and noise, wear etc.

- Conductive plastics
- Wirewound

Resistance transducer

Strain gage principle

When a wire is stretched, it gets thinner and longer and the resistance changes. More the wire is strained more the change in resistance.

$$\frac{\Delta R}{R} = G_f \frac{\Delta L}{L} = G_f \varepsilon$$

G_f is gage factor, which defines the sensitivity. It is defined as change in resistance for unit strain. Gage factor can vary from 2-6 for metallic strain gages. For semiconductor it varies from 40 to 200. Gage factor value is supplied by the manufacturer.

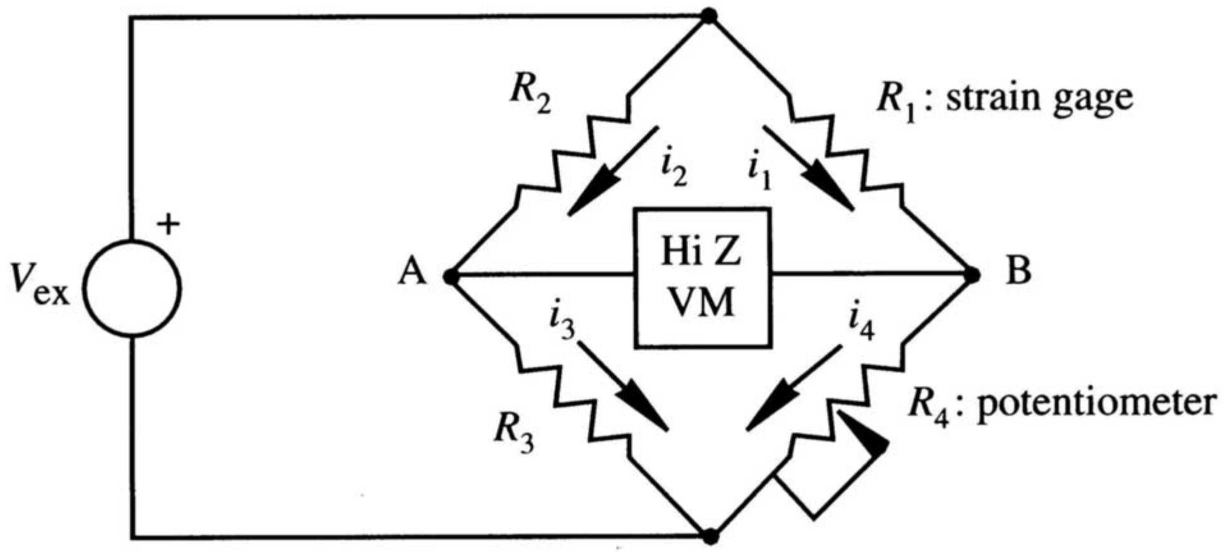
Wheatstone bridge for measuring resistance change

Balanced bridge condition

$$\frac{R_2}{R_3} = \frac{R_1}{R_4}$$

Potential difference between A & B is zero

When strain is applied, bridge is in unbalanced condition. Potential difference between A & B is measured by external circuitry.



Inductance transducer

Based on Faraday's law of induction in a coil. The induced voltage, or electromotive force, is equal to the rate at which the magnetic flux through the circuit changes.

The inductance change can be caused by any of the following:

❖ Variation in the geometry of the coil (change in number of turns in a coil)

❖ Change in the effective permeability of the medium in and around coil

❖ Change in the reluctance of the magnetic path or variation of the air gap

❖ Change in mutual inductance (by a change in the coupling between coils 1 and 2 with aiding or opposing fields)

$$R = \frac{l}{\mu A}$$

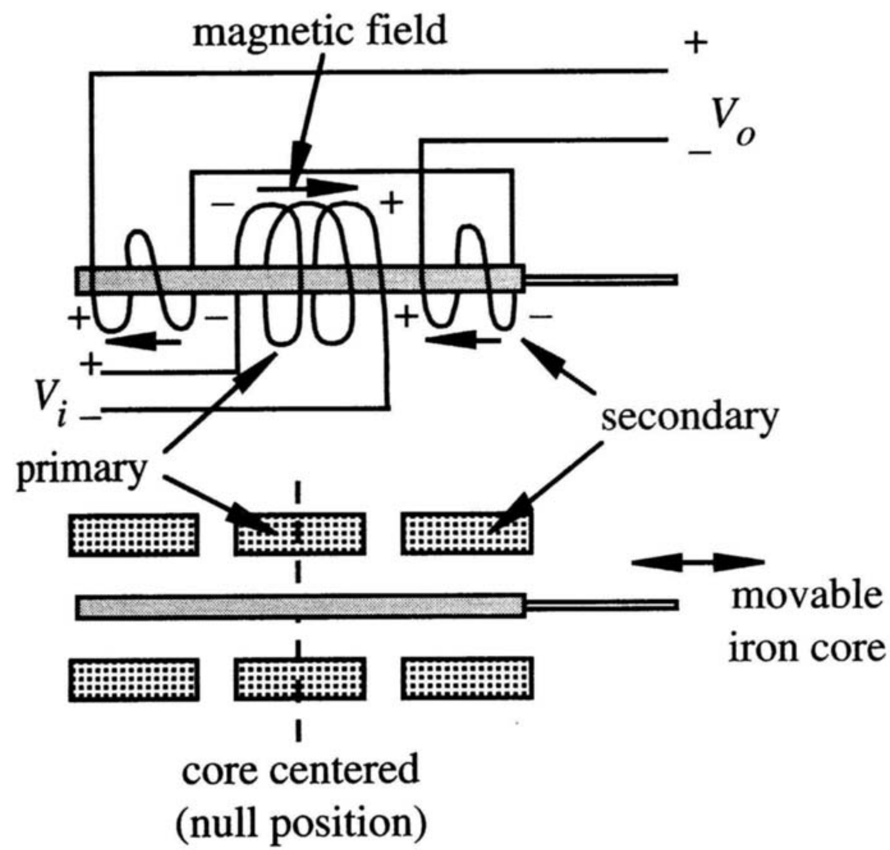
R= reluctance; l = length;

μ = permeability, A = Area of coil

Linear Variable Differential Transducer

LVDT most widely used for measurement of linear displacement. It is based on mutual inductance which changes with the position of central core.

Primary coil is excited by AC signal. Voltage is induced in secondary coil and amplitude depends on the position of core.

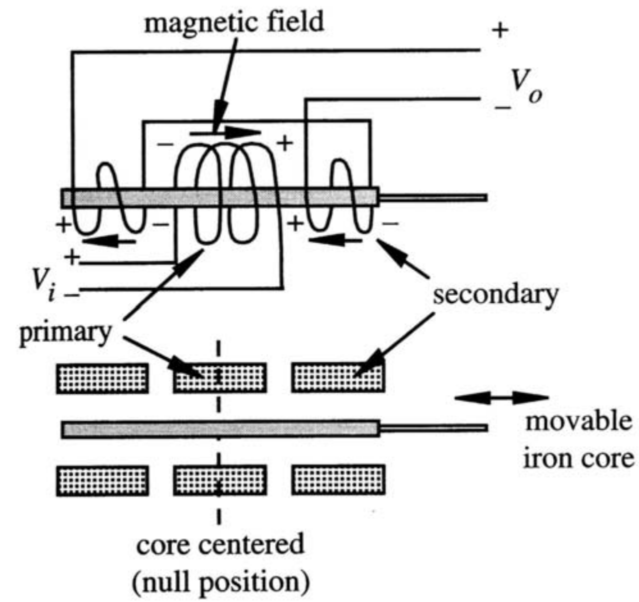


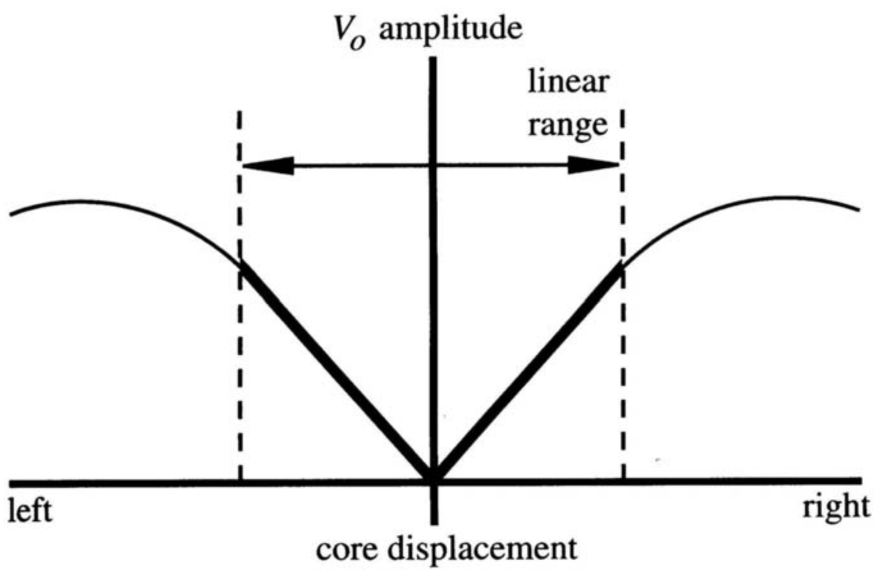
LVDTs are very stable, high resolution, high accuracy. Used for large as well as for small displacements. 1 meter to a cm full scale measurement.

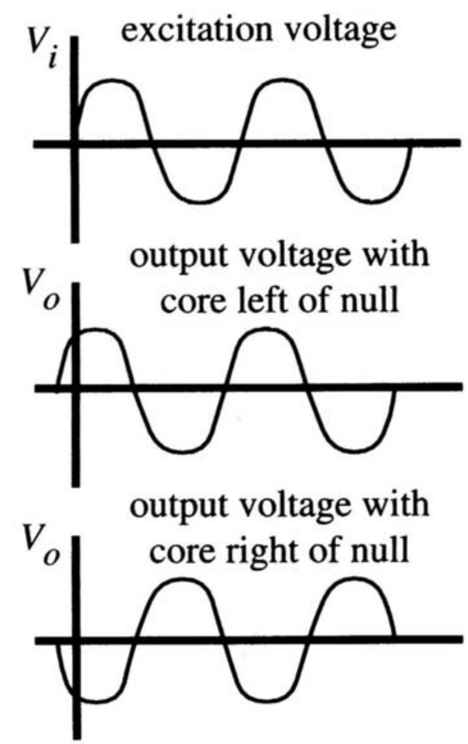
Dynamic response is 1/10 of excitation frequency and dependent on inertia of the core

Linear variable differential transducer

Two secondary coils are connected in series opposing configuration. At null position output will be zero. When away from null position, output will be in-phase or out of phase depending on the core movement. Amplitude will be proportional to the position of core in linear range.

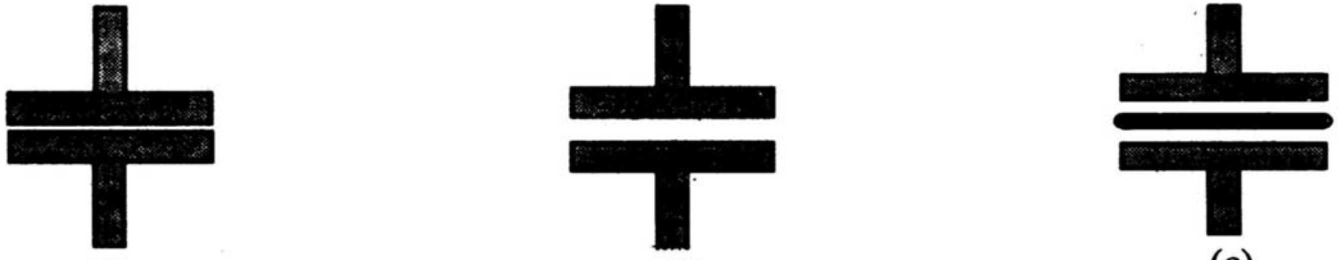






Capacitance transducers

Capacitance between two separated members is used for the measurement of many physical phenomena. It is a function of effective area of the conductors, separation between the conductors, the dielectric strength of the material. Change in capacitance can be brought about by varying any of the above parameters.



(a) (b) (c)

C - Capacitance

ε - Permittivity of material separating the plates

A - Overlapping area

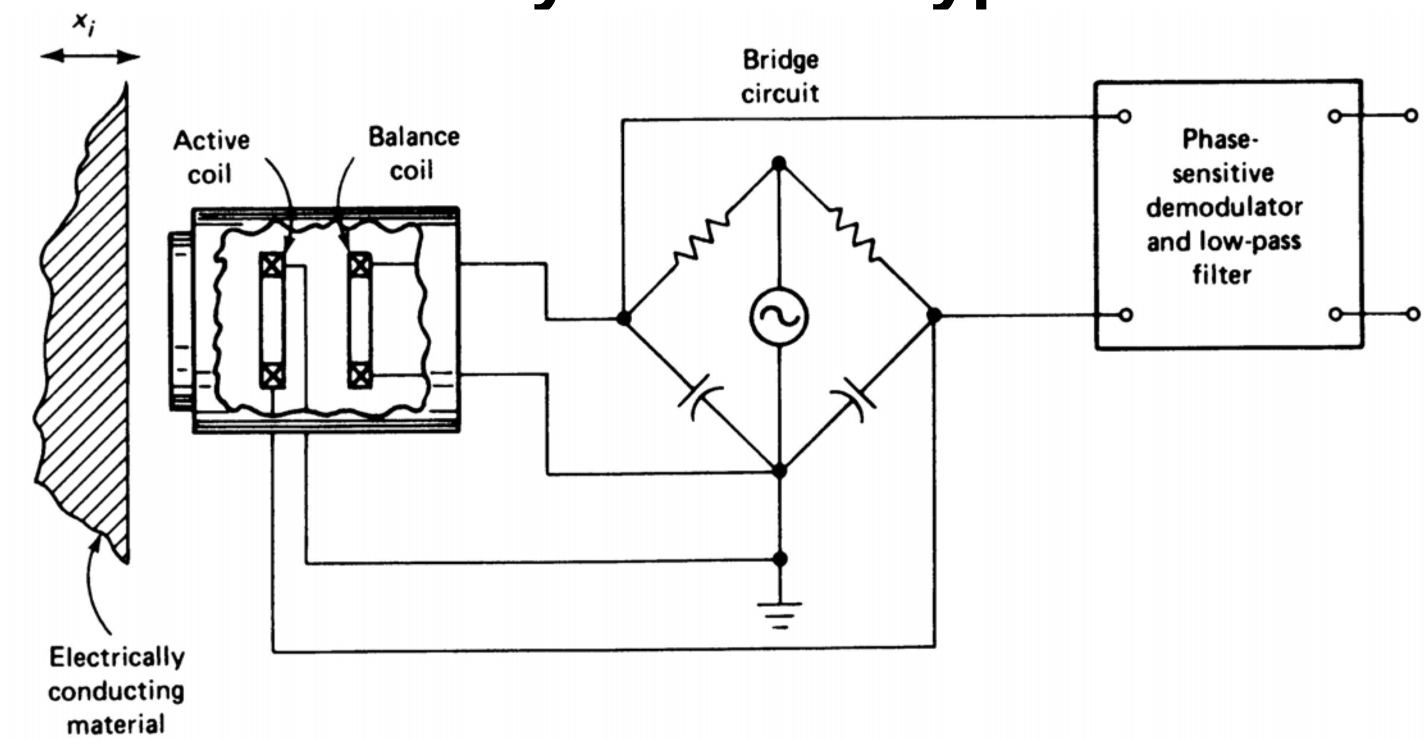
d - distance between two plates or electrodes

$$C = \frac{\varepsilon A}{d}$$

Piezoelectric transducers

Piezoelectric material generate electric voltage when deformed and vice versa. This is a reversible effect. This property is directional and the force to be measured is applied normal to the specific plane. The voltage across electrode is the charge generated due to mechanical action. The charge generated is proportional to the magnitude of applied force. This also produces similar effect in transverse direction.

Eddy Current Type

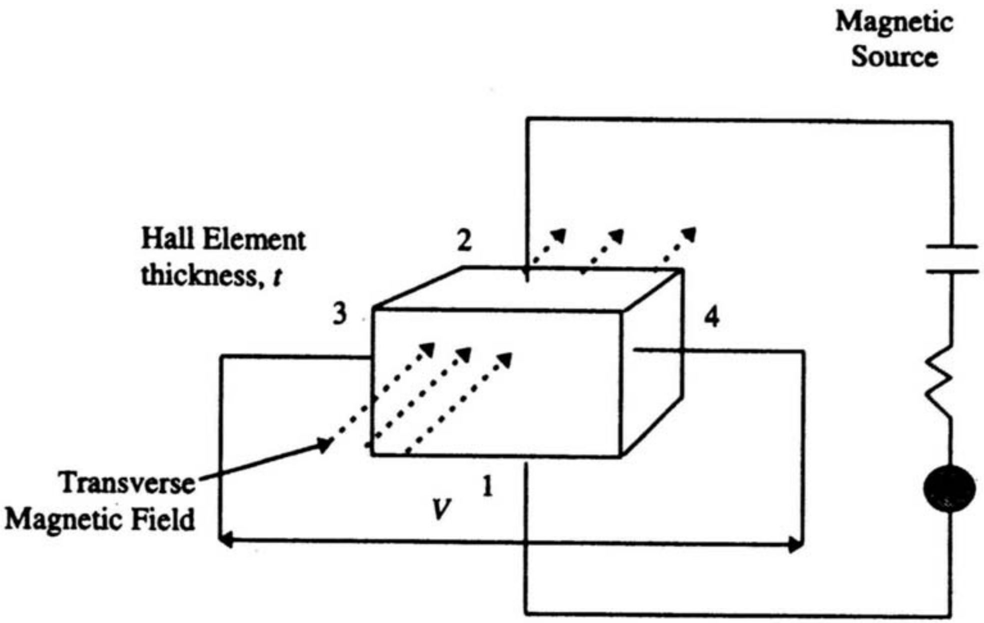


Probe contains two coils. One is active and the balance coil is excited with high frequency 1 MHz. In normal condition the bridge is balanced. When probe is close to a conducting surface, eddy currents are formed and disturbs the magnetic field in active coil. Un-balance in the bridge is measure of distance. Eddy currents are stronger when target is closer to sensor. Range from 0.25 mm to 30 mm. Target surface should be more than the probe diameter.

Hall effect transducers

Hall effect occurs when a strip of conducting material carries current in the presence of a transverse magnetic field. The hall effect results in the production of electric field perpendicular to the directions of both magnetic filed and the current with the magnitude proportional to the product of magnetic field strength, current and various properties of the conductor.

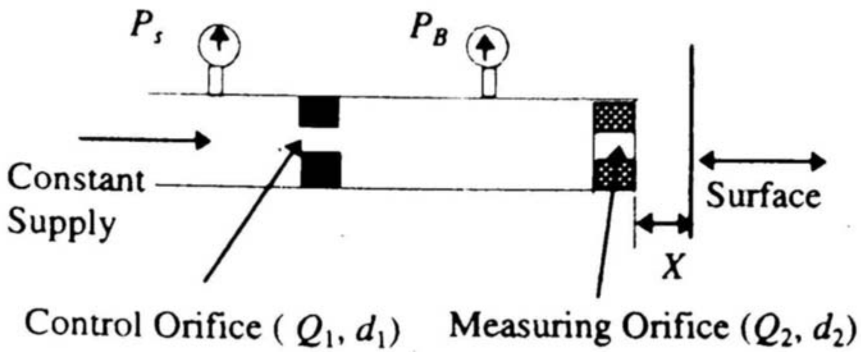
In the absence of magnetic field, potential between 3 & 4 are same. When magnetic flux passes through the conductor as shown, potential V appears between 3 &4.

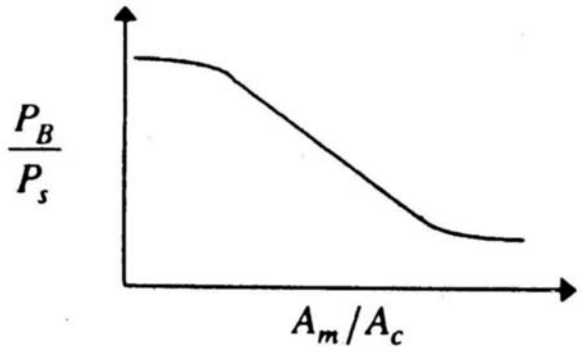


Pneumatic transducers

These transducers are non-electrical in nature and are widely used in industrial instrumentation for gaging and measurement. These are simple in design and sensitive in operation.

Back pressure changes with distance X and it is linear for a limited range. It is sensitive to input pressure P_s





$$A_m = \frac{\Pi}{4} d_2 X \qquad A_c = \frac{\Pi}{4} d_1^2$$

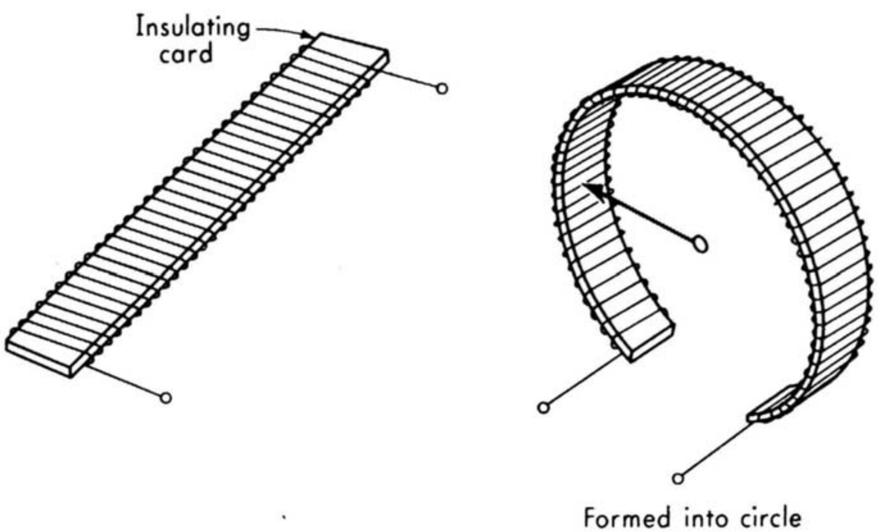
Quantities to be measured

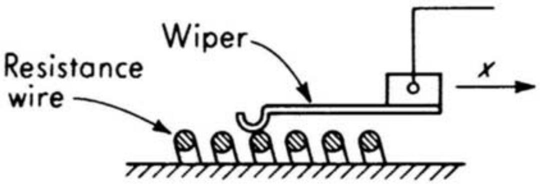
- Linear displacement
- Angular displacement
- Temperature
- Pressure
- Fluid flow rates
- Force
- Acceleration
- Velocity
- Angular rate

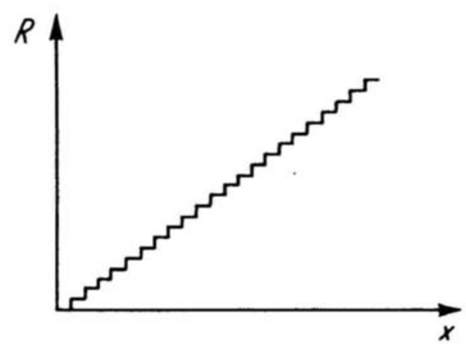
Linear displacement - contact type

Potentiometric based : Explained earlier

Potentiometer available in many forms - carbon coating, wire wound etc. In wire wound, output is in steps.

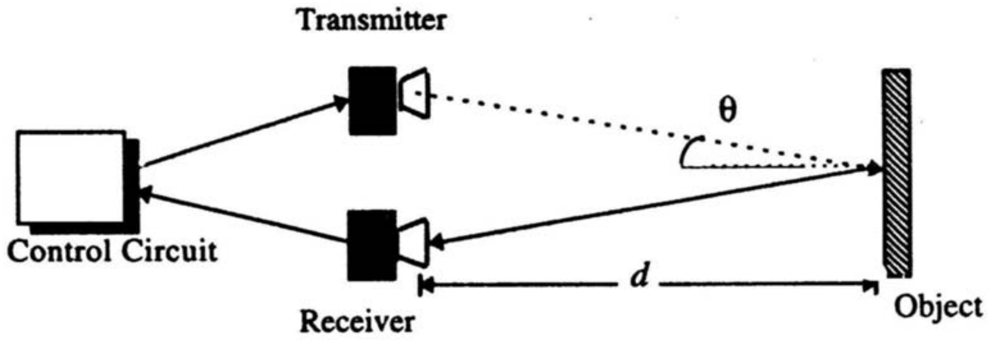






Linear displacement - non contact type

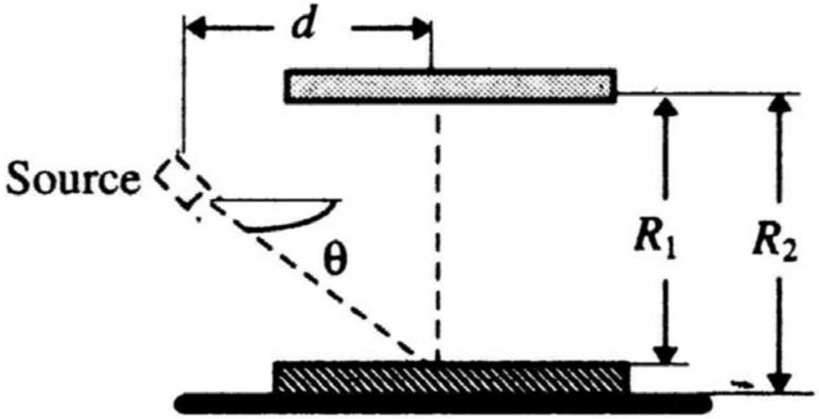
Ultrasonic distance sensing : Consist of transmitter and receiver unit. Transmitter are piezoelectric transducers, sends bursts of ultrasonic waves. Receiver senses the reflected waves from the object. Control circuits determines the travel time. Travel time depends on the distance *d* and the medium in which the waves travel. Accuracy is quite high, 1%. Used in robotics to avoid collisions.



$$d = \frac{vt\cos\theta}{2}$$

Linear displacement - non contact type

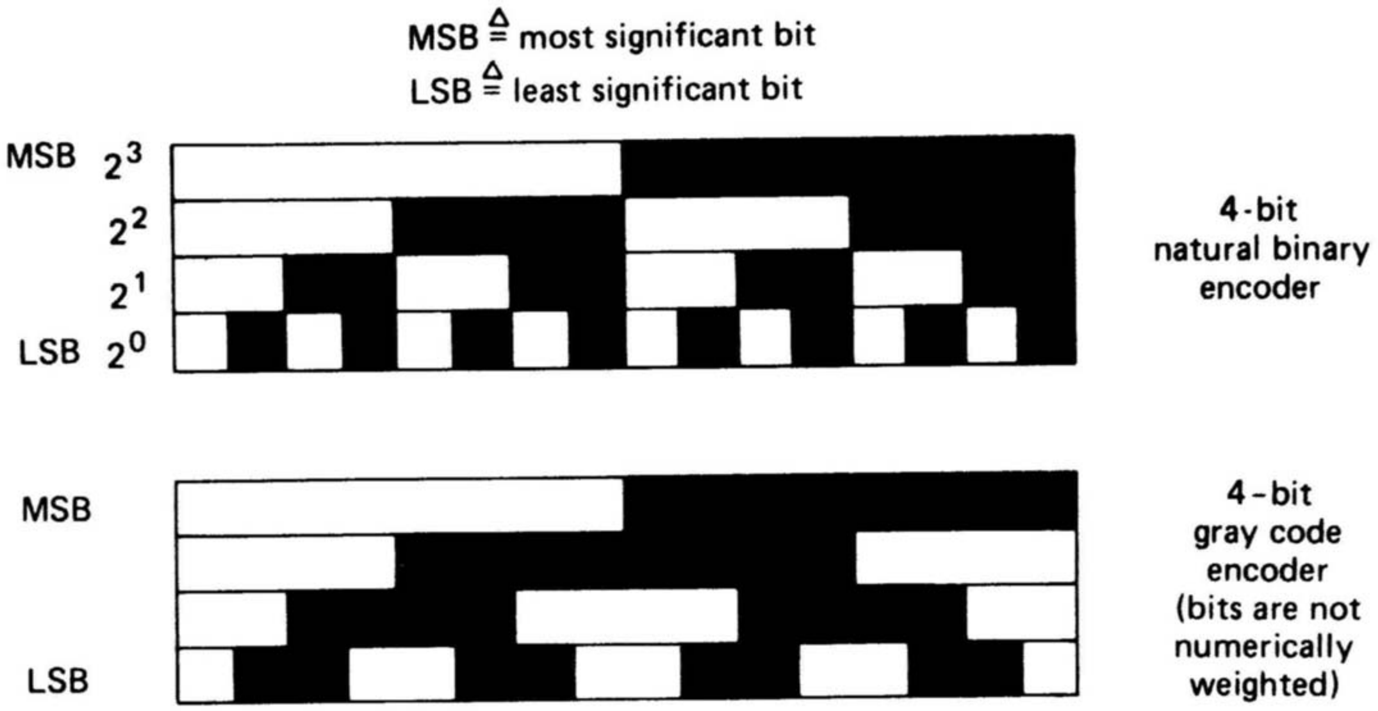
Optical range sensor : Basic triangulation principle is used. An IR laser diode is the light source which projects a spot on to the surface of the object. The image of the spot moves on the detector (formed by suitable lens system). The position of the spot changes the output of the detector. Measuring range from 0.3 to 20 inch are available. Very good dynamic response, 2KHz. Accuracy 0.025% is possible.



Triangulation principle to measure thickness (R_2-R_1)

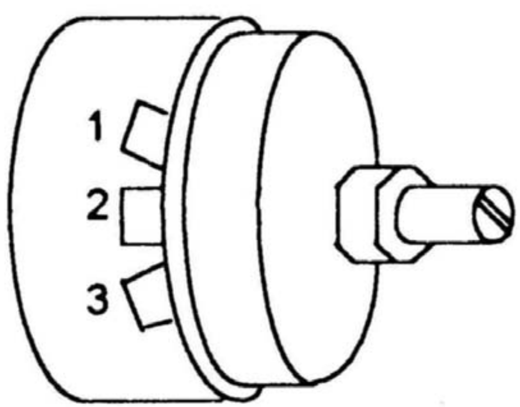
Linear displacement - non contact type

Optical encoder : Consist of a code pattern in the form of opaque and clear segments on a glass plate. When the object moves over this the detector senses this pattern and produces the output. Code pattern can be in the form of natural binary number or Gray code. Gray code has advantage that only one bit changes at a time. Impact of sensing bit error is minimised.

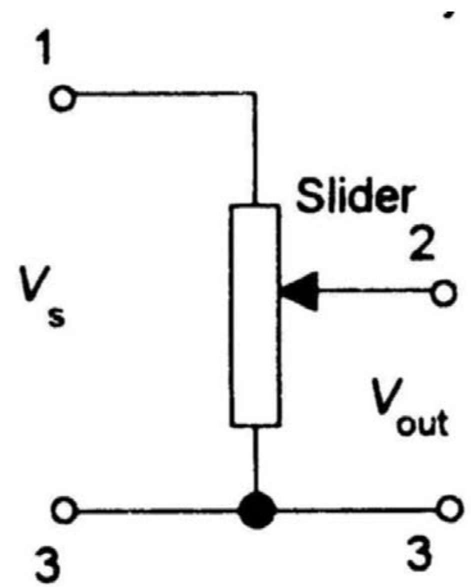


Angular position - contact type

Potentiometric based : The output shaft is connected directly to a rotary potentiometer.
For 360º rotation, non contact angle ~ 5º

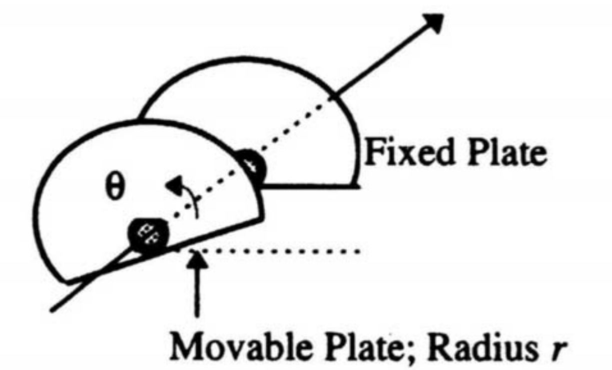


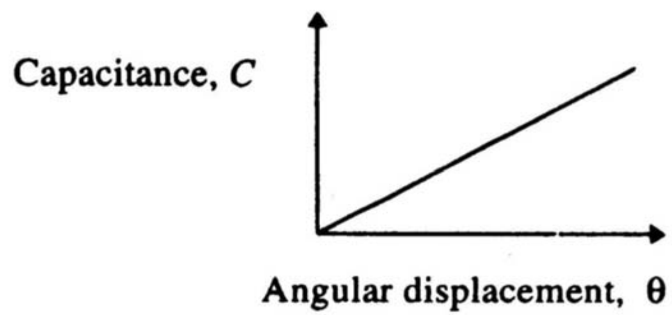
A rotary potentiometer



Angular position - non contact type

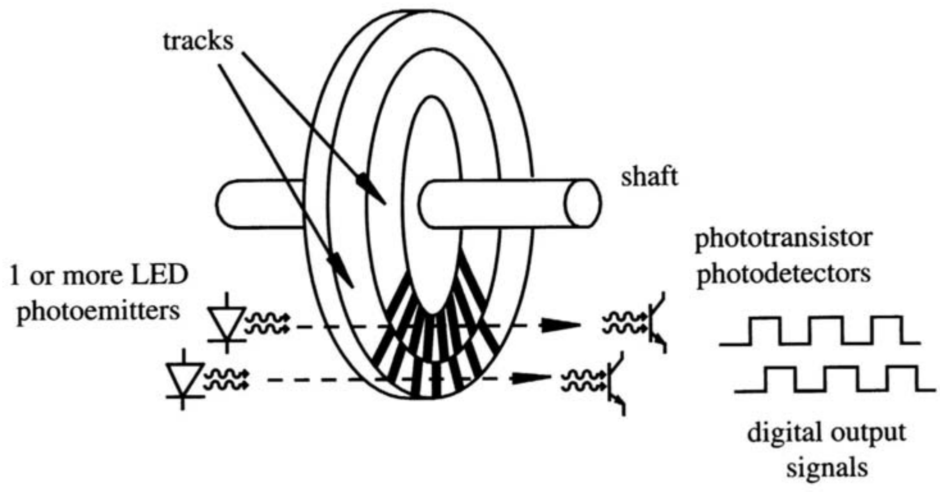
Capacitance based : Capacitance changes with the overlapping area. Capacitance is maximum when completely overlapped. Variation of capacitance with angle is linear.



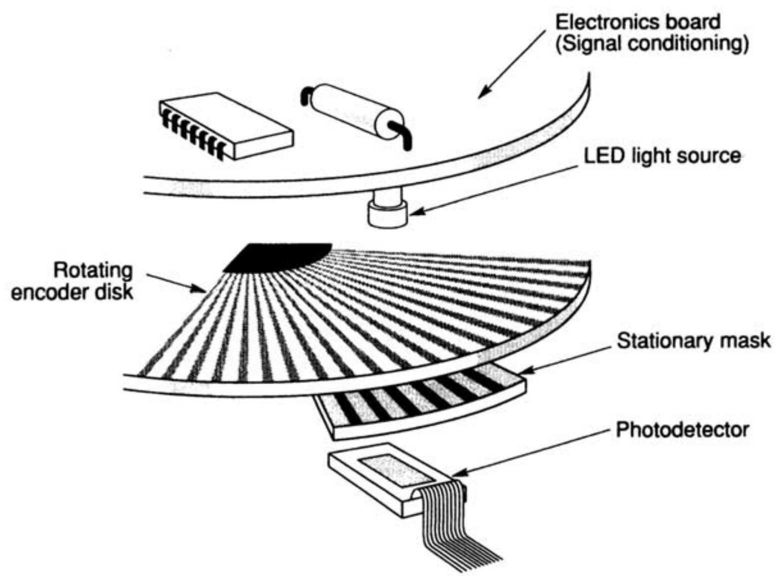


Angular position - non contact type

Shaft encoder : Consist of a rotating encoder disk. Output is sensed by photo detectors and are fed to logic circuits to count and to find out direction. Available as absolute and incremental.



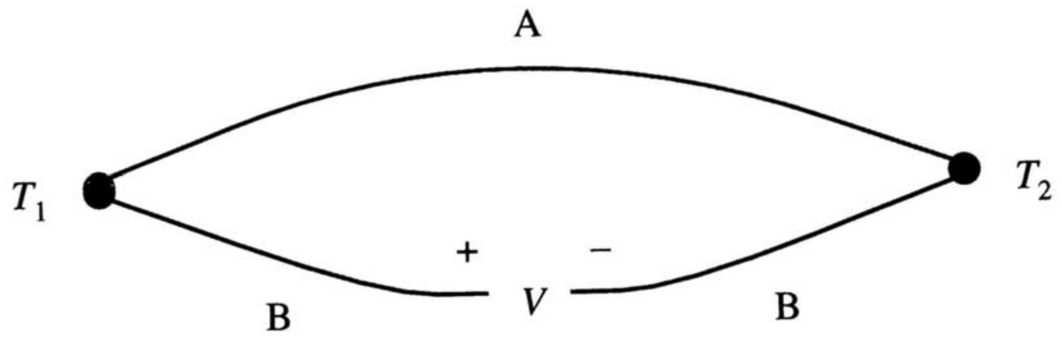
(*a*) schematic



Temperature - contact type

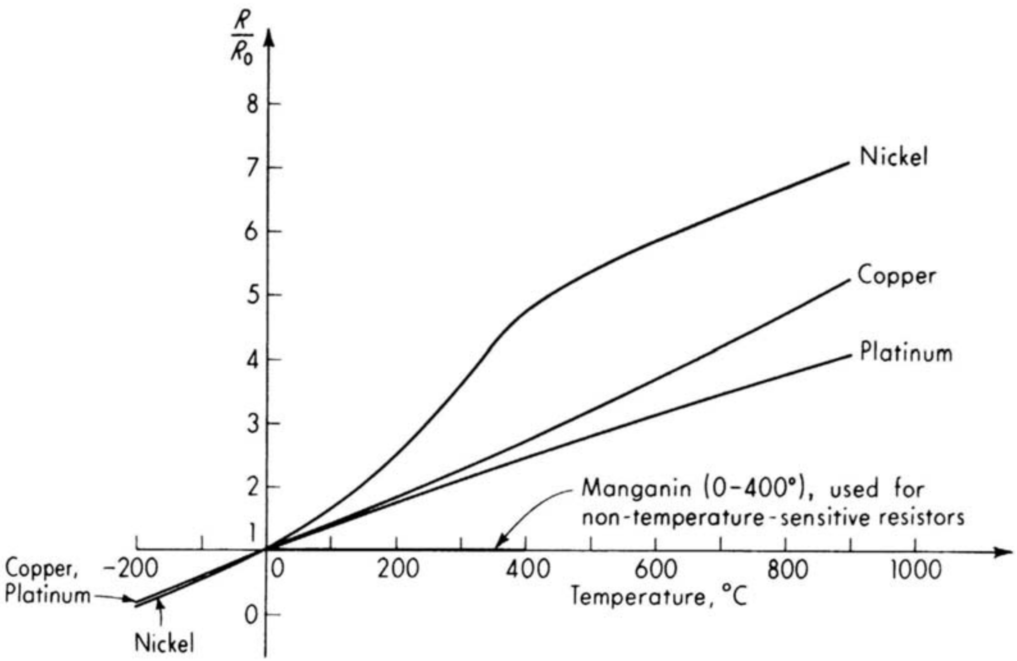
Thermocouple : Two dissimilar material in contact from a thermoelectric junction. The voltage is proportional to the temperature of the junction. This is known as Seebeck effect. Thermoelectric junctions appear in pairs and called thermocouple.

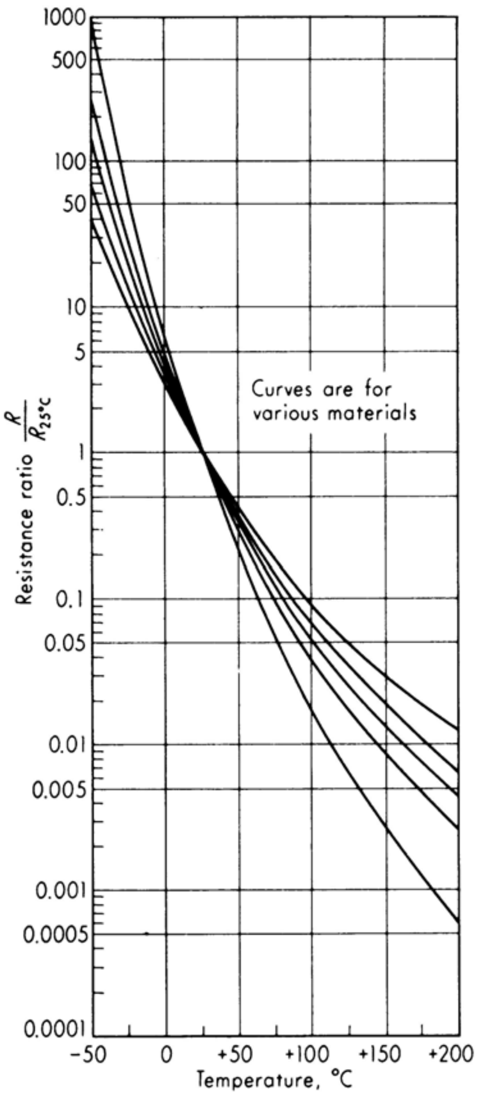
Two wires of metal A and B forms two junctions at temperature T_1 and T_2
The thermocouple voltage $V = \alpha (T_1 - T_2)$, α is Seebeck coefficient, it is linear over a small temperature range.



Temperature - contact type

Electrical resistance sensors : Electrical resistance of various material changes with temperature. Mainly two classes : conductors (metals) and semiconductors. Metal based resistance thermometers are called Resistance Temperature Detector RTD. Semiconductor types are called Thermistor. Circuitry involved is basically bridge type or directly measuring the resistance. Thermistor have non linear behavior.

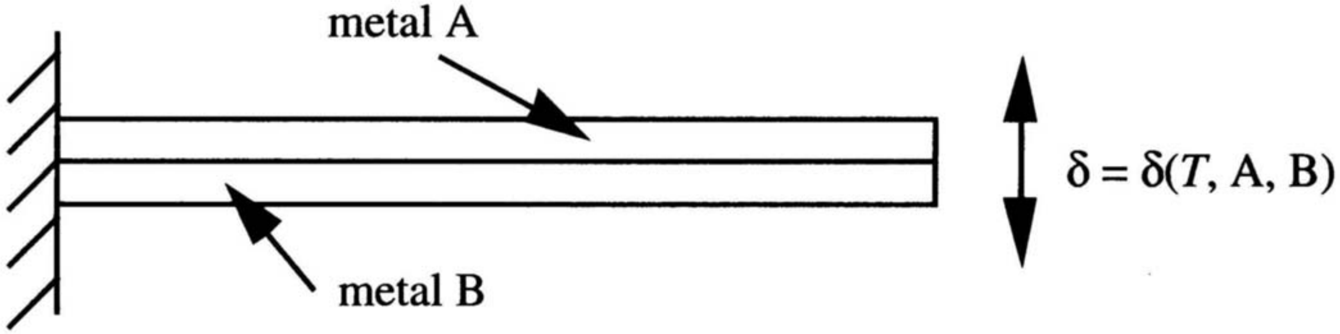




Bulk semiconductor

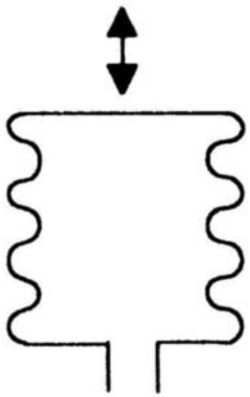
Temperature - contact type

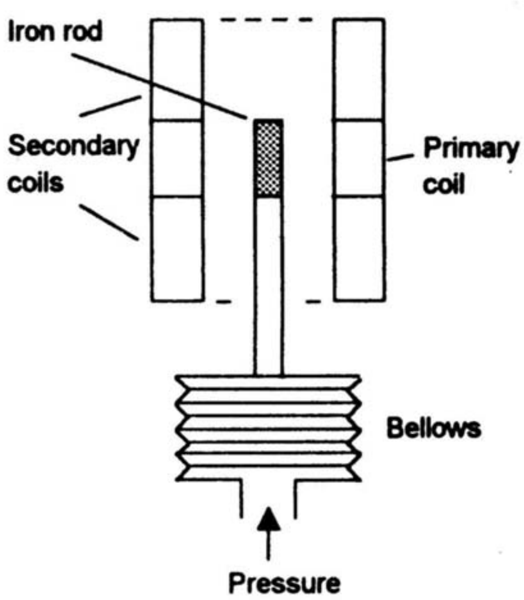
Bimetallic strip : It is non-electrical temperature measuring device. It is composed of two or more metal layers bonded together and having different coefficient of thermal expansion. The structure will deform when the temperature changes. These are used in household thermostats where the mechanical motion of strip makes or breaks the circuit.



Pressure measurement

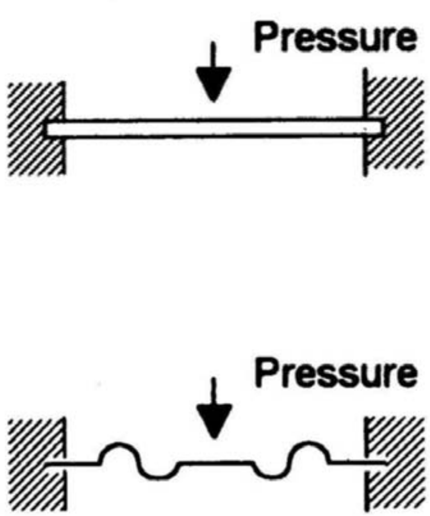
Bellow type: The pressure change inside the bellow results in mechanical movement. This can be connected to LVDT and linear displacement can be measured corresponding to pressure change. Dynamic response is poor.

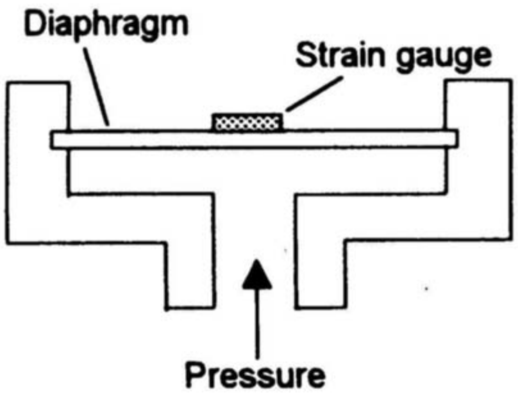




Pressure measurement

Strain gage based : This consist of a diaphragm, it deforms when subjected to differential pressure. This deformation is sensed by the strain gage mounted on it. Strain gages are directly etched on the silicon diaphragm along with the bridge and associated circuitry by modern microelectronics technology.

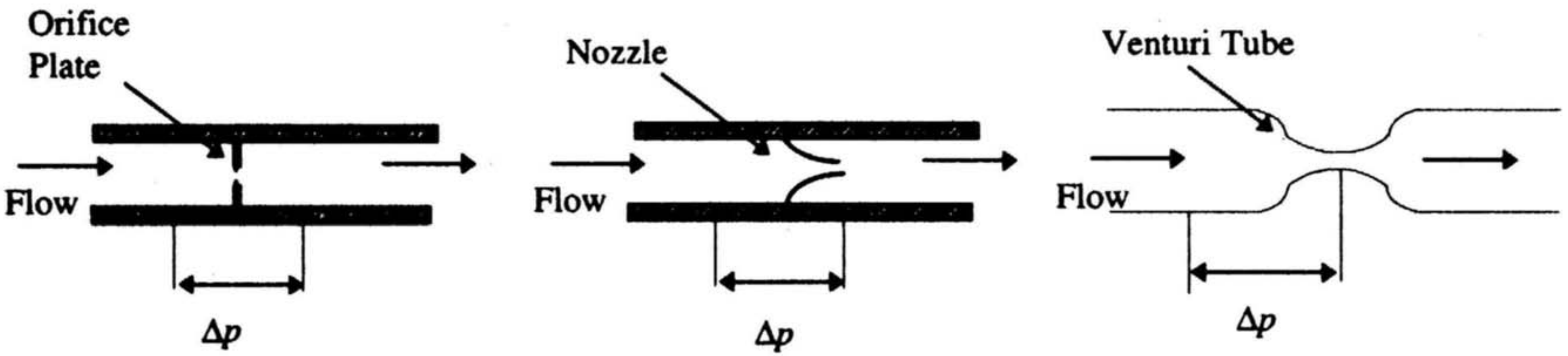




Diaphragm - flat and corrugated

Fluid flow measurement

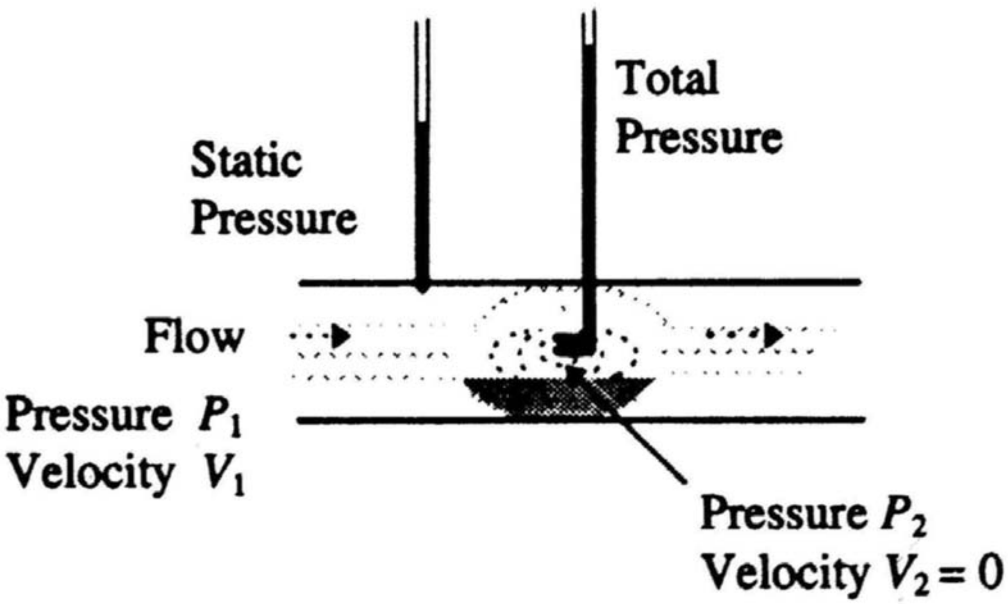
Based on Bernoulli's principle.These are generally pre-calibrated and used. Pressure tappings are taken at prescribed location from the orifice on upstream and down stream. Maintenance free and inexpensive, not very accurate.



(a) Orifice Plate (b) Flow Nozzle (c) Venturi Tube

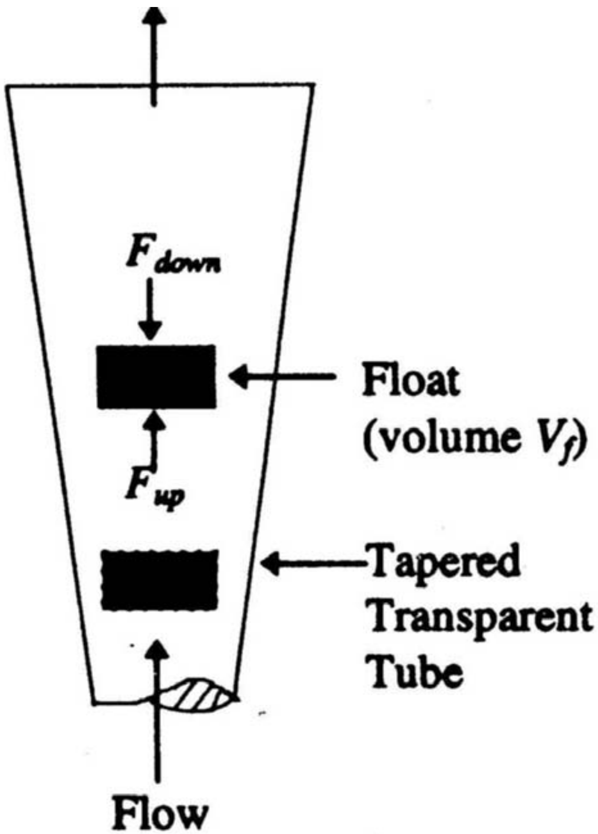
Fluid flow measurement

Pitot tube : In this arrangement difference between static and dynamic pressure is the measure of flow velocity. It is widely used for airspeed measurement. Usually it consist of two concentric tubes. Inner tube which measures dynamic pressure connects to one port of differential pressure transducer. Outer tube which measures static pressure is connected to the other port of the pressure transducer.



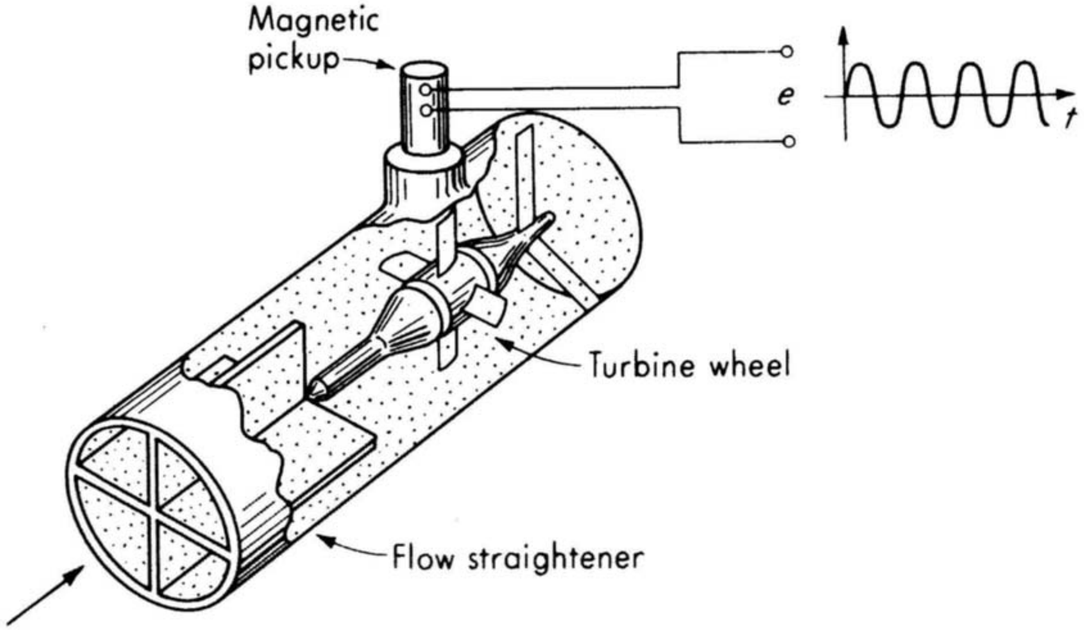
Fluid flow measurement

Rotameter : It consist of a tapered glass tube and a float. Float rises due to buoyancy and fluid flow. Position of the float gives the flow rate. It has to be vertical to obtain correct results. Not very accurate.



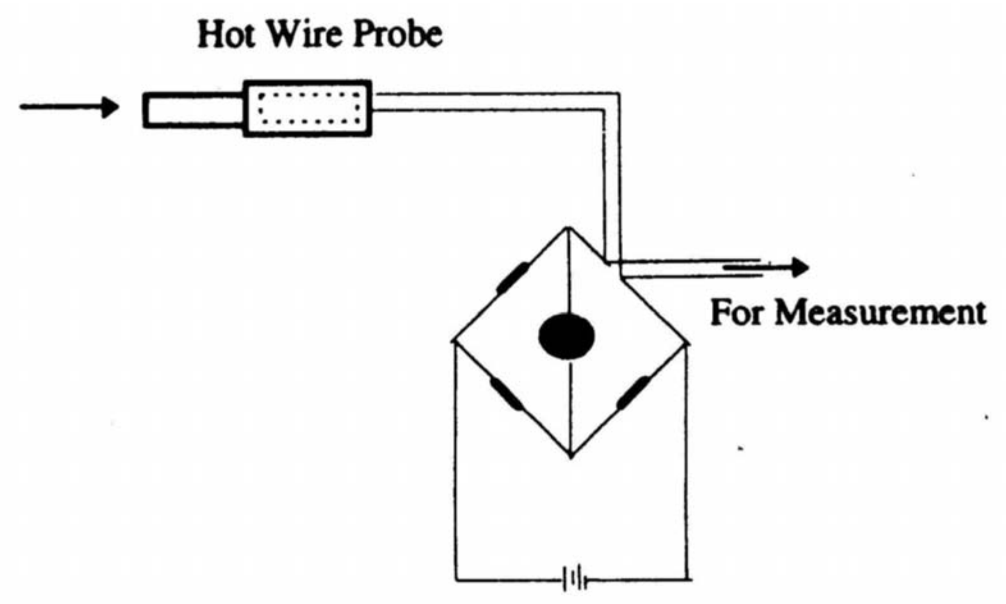
Fluid flow measurement

Turbine flow meter : It consist of a turbine on which a magnet is mounted. Each time magnet passes the pickup coil it produces output in form of pulse and these can be counted, or frequency to voltage converter can be used to measure the fluid flow.



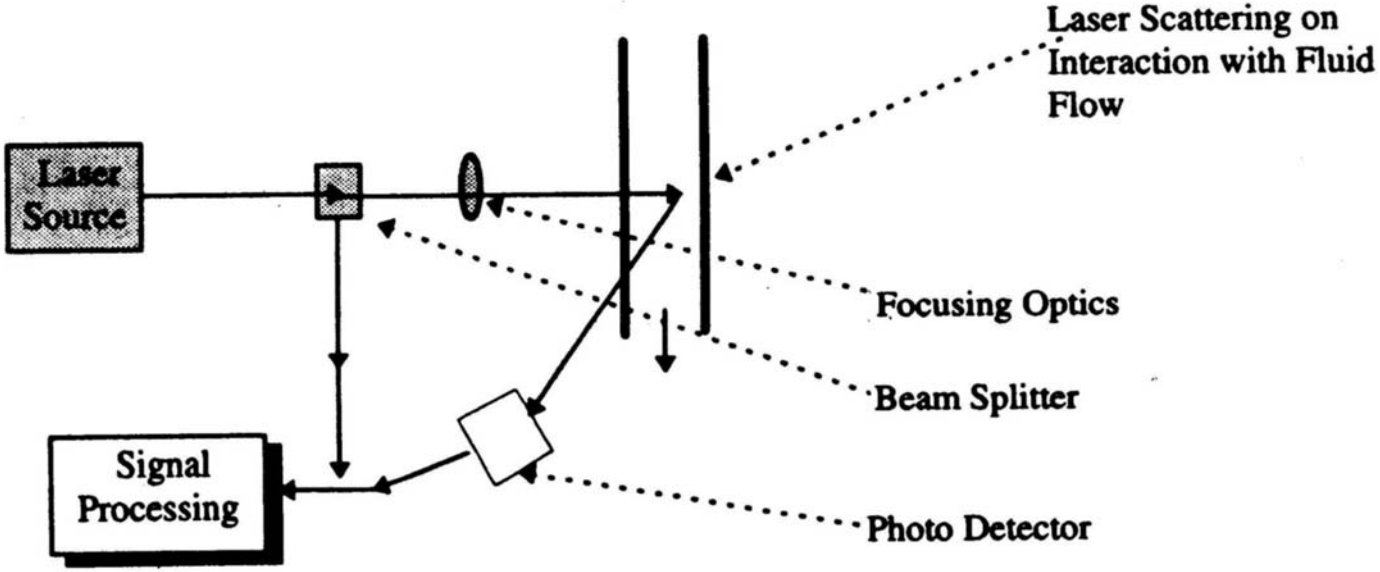
Fluid flow measurement

Hot wire anemometer : It is based on convective heat transfer from a 5-μ meter diameter platinum-tungsten wire. The wire is heated by passage of current through it. The heat is dissipated from the wire during fluid flow and it decreases the resistance of the wire. Rate of heat loss depends on wire shape, properties of fluid and fluid velocity. Used for dynamic measurement and in clean fluid.



Fluid flow measurement

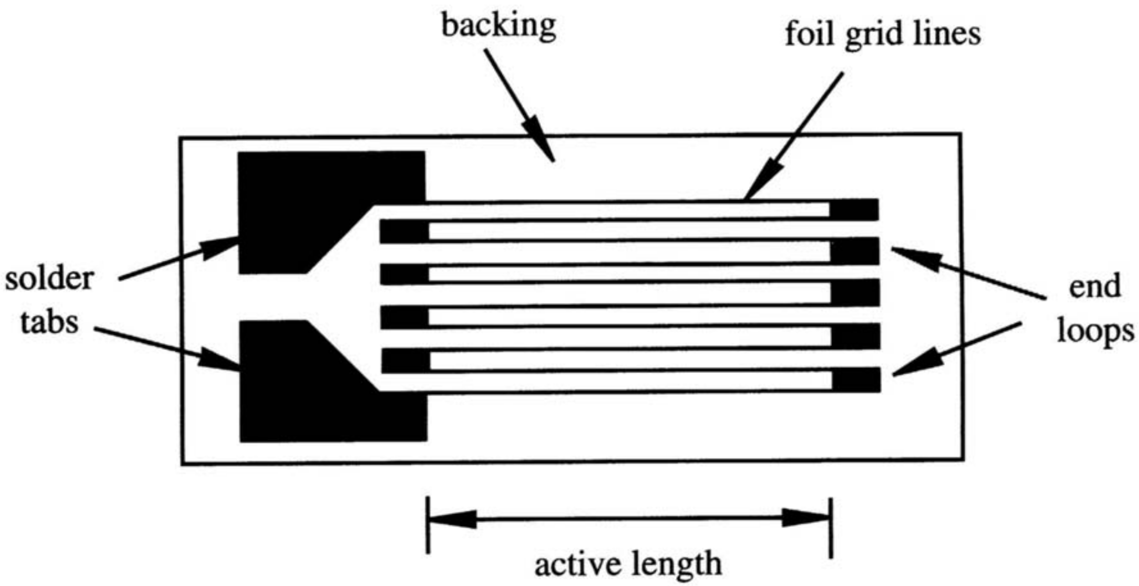
Laser Doppler effect: It is a non-contact method of finding instantaneous flow velocity of fluid. The fluid requires contamination for scattering of laser beam. It is based on Doppler shift phenomenon, in which the frequency of the scattered light from the moving object is different from that of incident beam by an amount proportional to the fluid velocity. Shift in frequency is determined by signal processing.



Force measurement

Strain gage based : Strain gage is thin foil as shown below, with a polymer backing material. The resistance of the foil changes when strained and this change in resistance is measured by Wheatstone bridge.

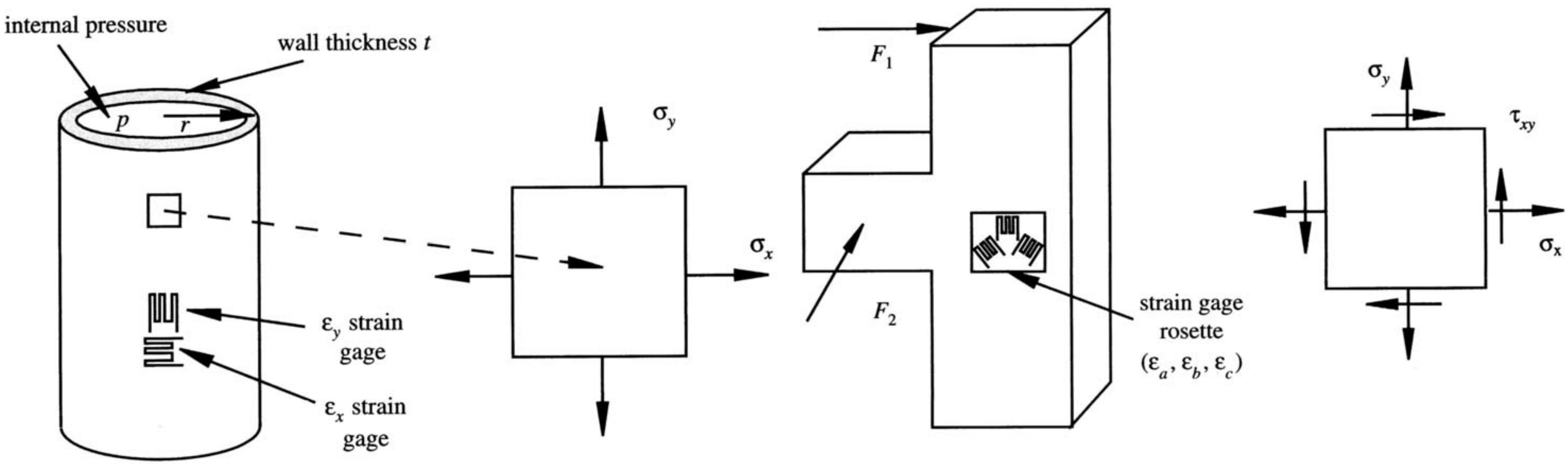
Wide end loops reduces the transverse effect. Temperature compensation is required for high temperature application. It is skilled job to fix the strain gage. Used in different configuration: Full bridge, Half bridge and quarter bridge.



Strain Gage

Force measurement

Strain gage mounting : Strain gage are also available in combination of two or three at an angle of 45^o, 90^o or 120^o

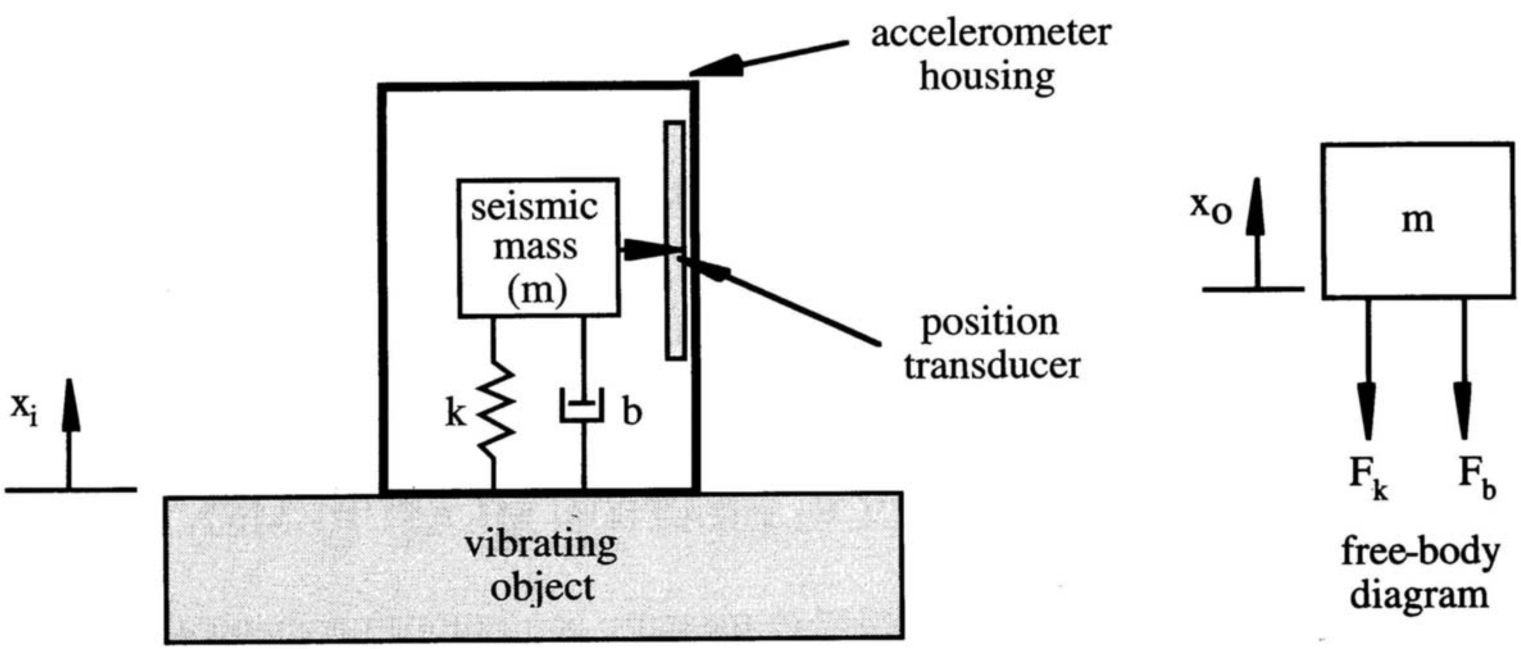


Bi-axial stress in a thin walled pressure vessel

General state of stress on the surface of a component

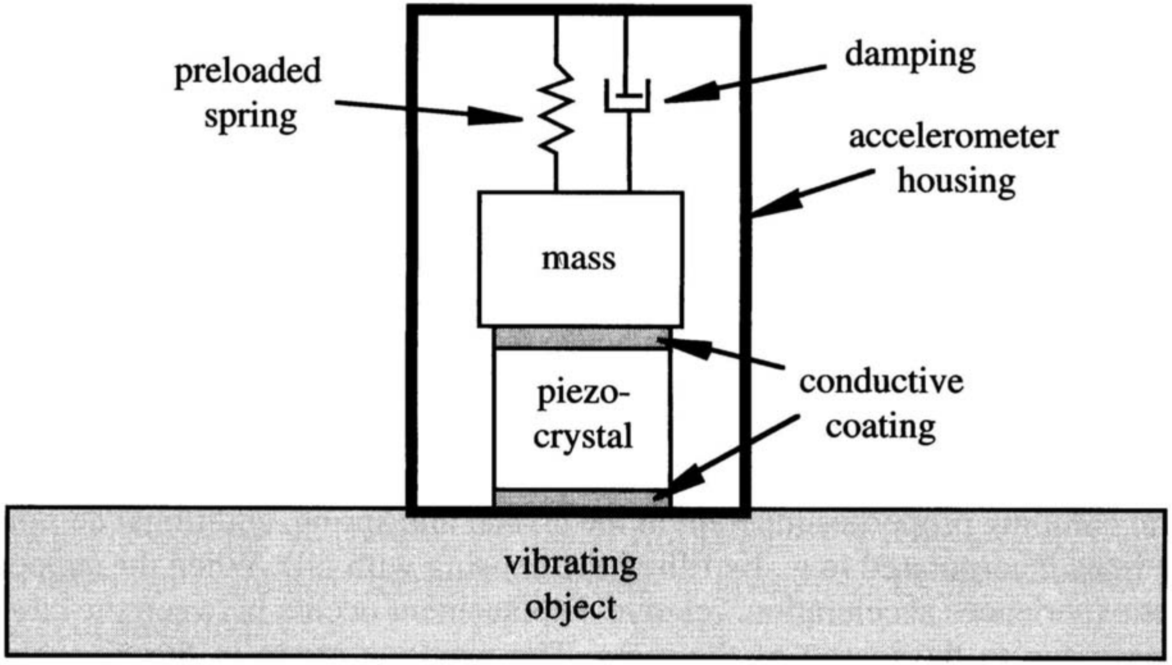
Acceleration measurement

Accelerometer is used to measure linear acceleration. The design is based on the inertial effects associated with a mass connected to a moving object through a spring, damper and displacement sensor. Characteristics of a accelerometer are like spring mass system, second order system.



Acceleration measurement

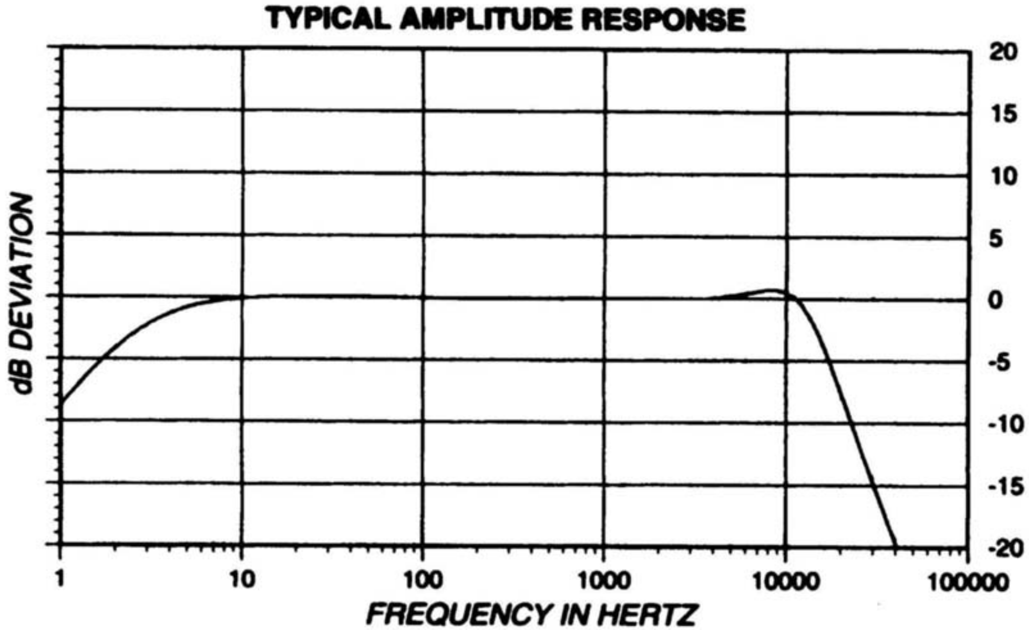
Piezoelectric accelerometer : In this seismic mass is attached to Piezoelectric crystal, which produces charge when it is loaded. Here spring is only for pre-loading the crystal. These accelerometers requires no external power supply. These accelerometers produces large output for its size.



Acceleration measurement

Piezoelectric accelerometer : The output of the accelerometer is connected to charge amplifier, which converts the charge on the crystal to a voltage that can be measured. In general, piezoelectric accelerometers cannot measure constant or slowly varying accelerations. Response at low frequency is limited by the low-frequency cut-off of charge amplifier.

Response is almost flat from few Hz to fraction of natural frequency of the crystal. Useful for vibration measurement.

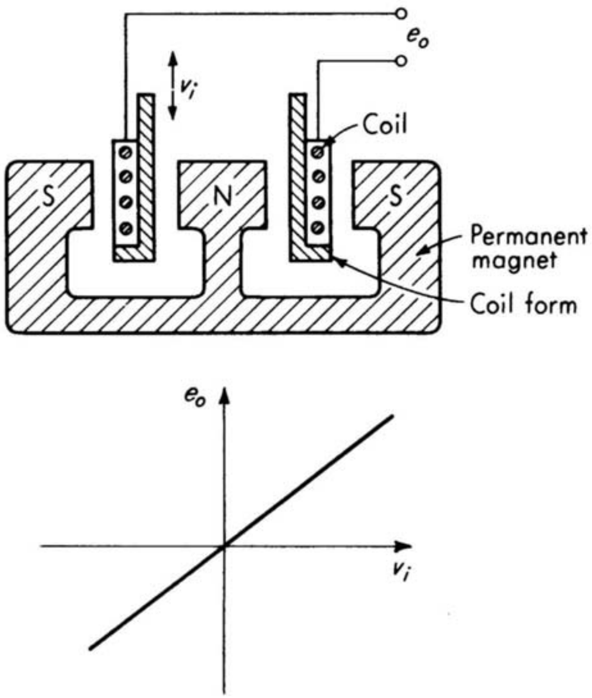


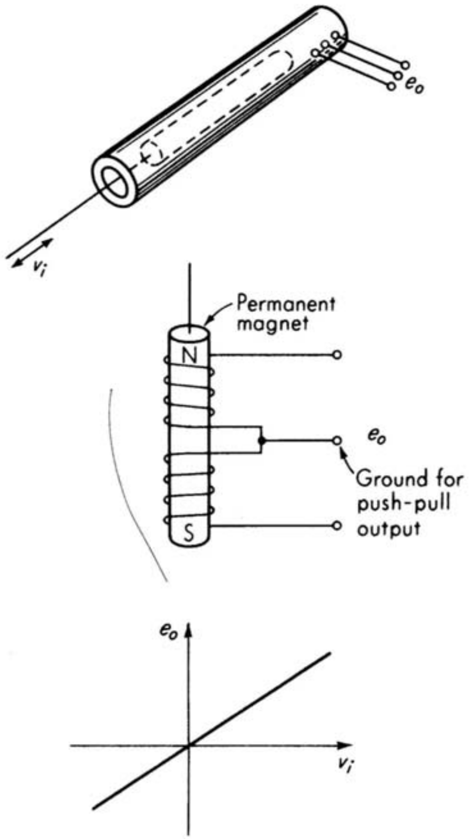
Frequency response of a piezoelectric accelerometer

Velocity measurement

Linear velocity is generally obtained by integrating the acceleration or differentiating linear displacement.

Linear velocity can also be measured by moving coil or moving magnet pickup. Transducer generally uses a permanent magnet core and a coil. When coil moves relative to magnet produces output voltage and is proportional velocity.

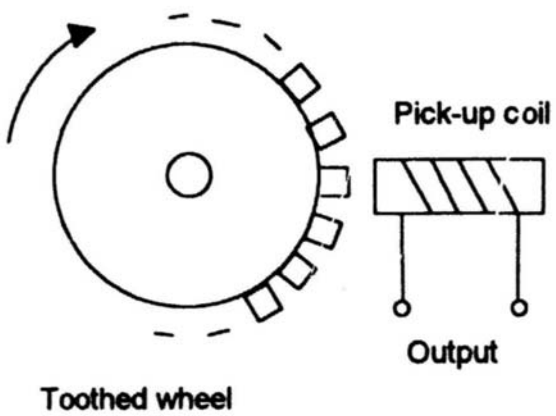


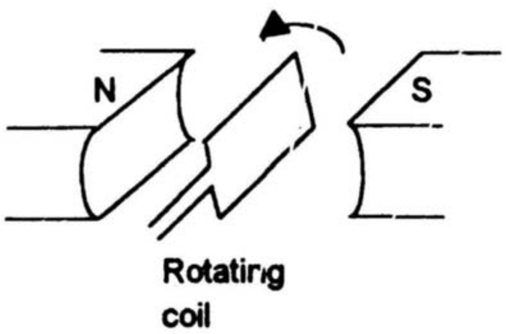


Angular rate measurement

Shaft RPM : Toothed wheel of ferromagnetic material attached to the rotating shaft. Pickup coil produces AC signal due to change in magnetic flux when ferromagnetic tooth passes. The frequency of the signal is proportional to the RPM.

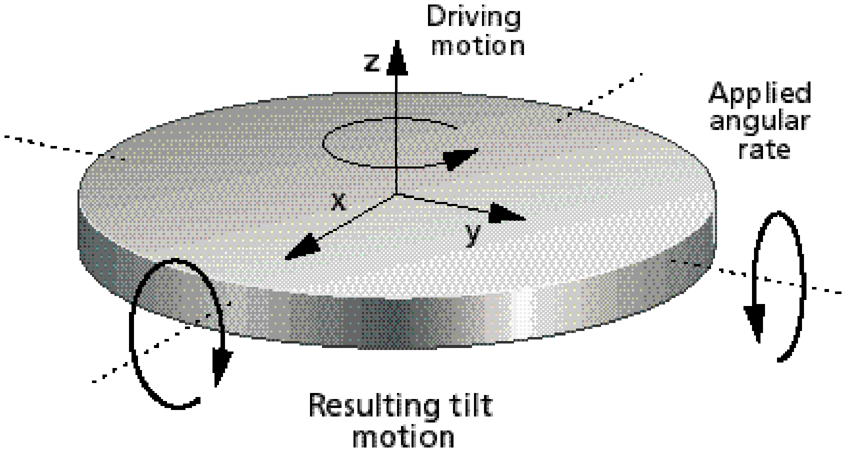
A coil attached to the shaft can be rotated in a magnetic filed and the AC signal can be used for RPM measurement.





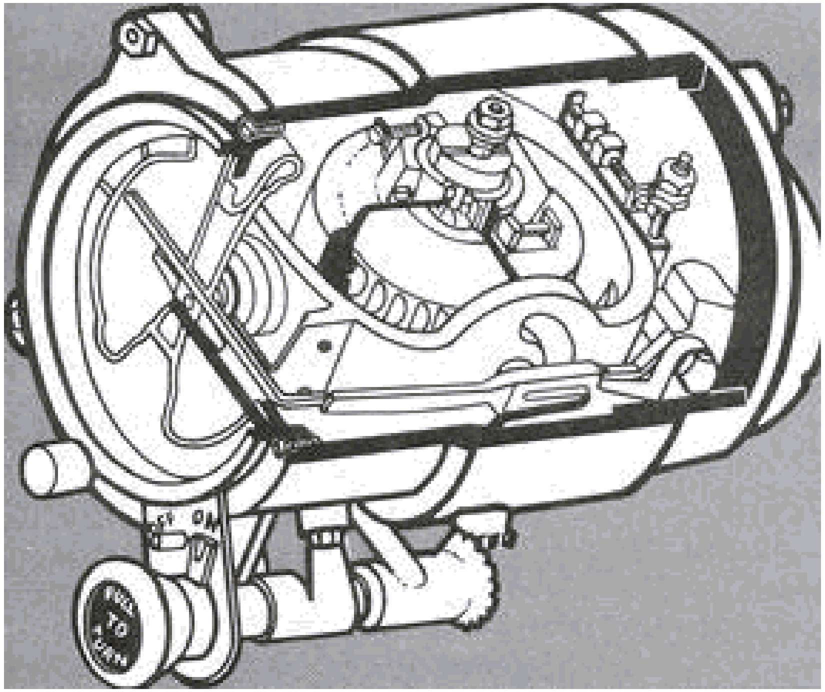
Angular rate measurement

Rate gyros - Based on gyroscopic effect. When a spinning mass is subjected to angular motion perpendicular to spinning axis it produces the motion in third axis which is perpendicular to both. Extensively used in ships, missiles, aircraft for stabilization. Integration of the output will give angular rotation.



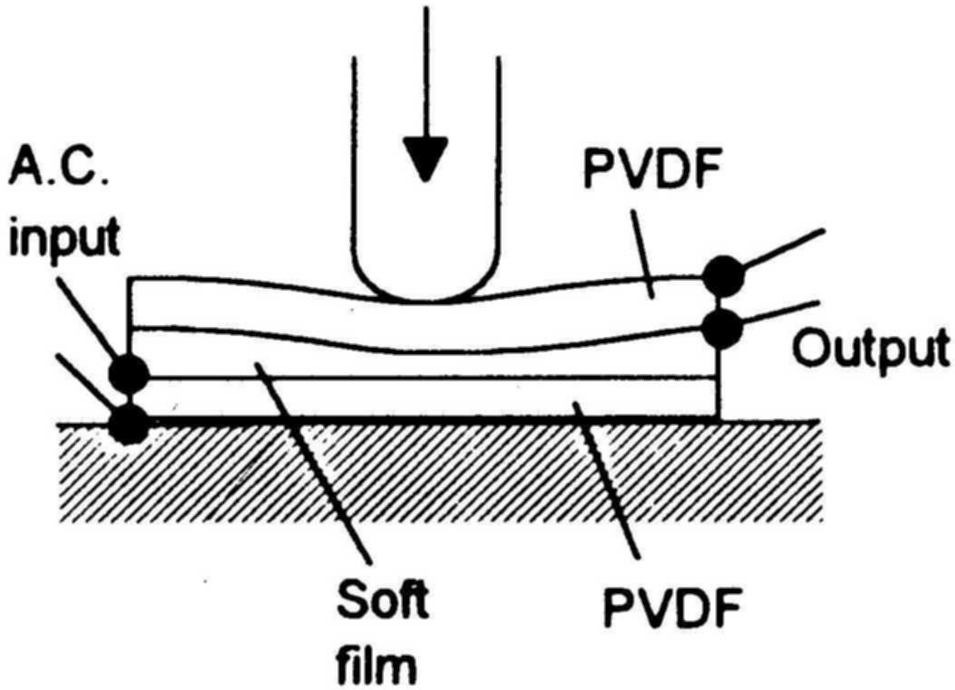
Angular rate measurement

Rate gyros - Bulky and requires lot of power for spinning the wheel. It is a precise mechanical instrument and expensive. Large warm up time due to spinning mass.



Tactile sensors

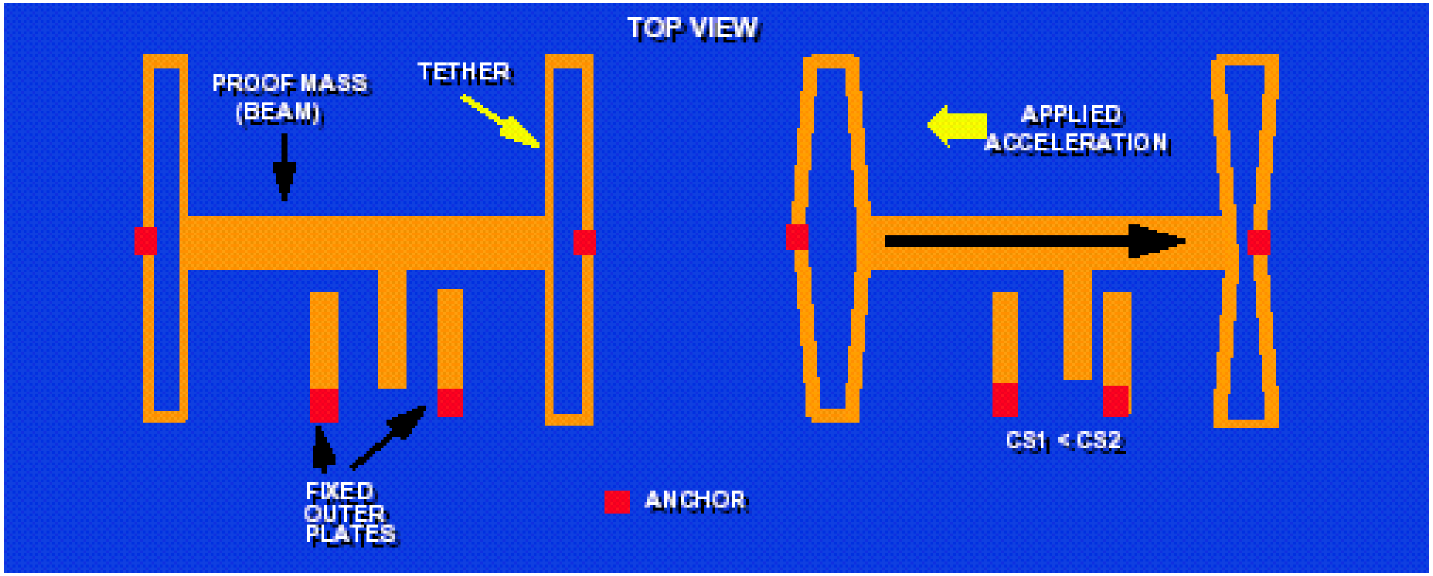
It is a form of pressure sensor. Used as finger tips in robotics. Consist of two piezoelectric polyvinylidene fluoride films. Lower film is excited by an alternating voltage, this produces output in the upper film. When pressure is applied the output changes due to change in vibration.



MEMS based sensors

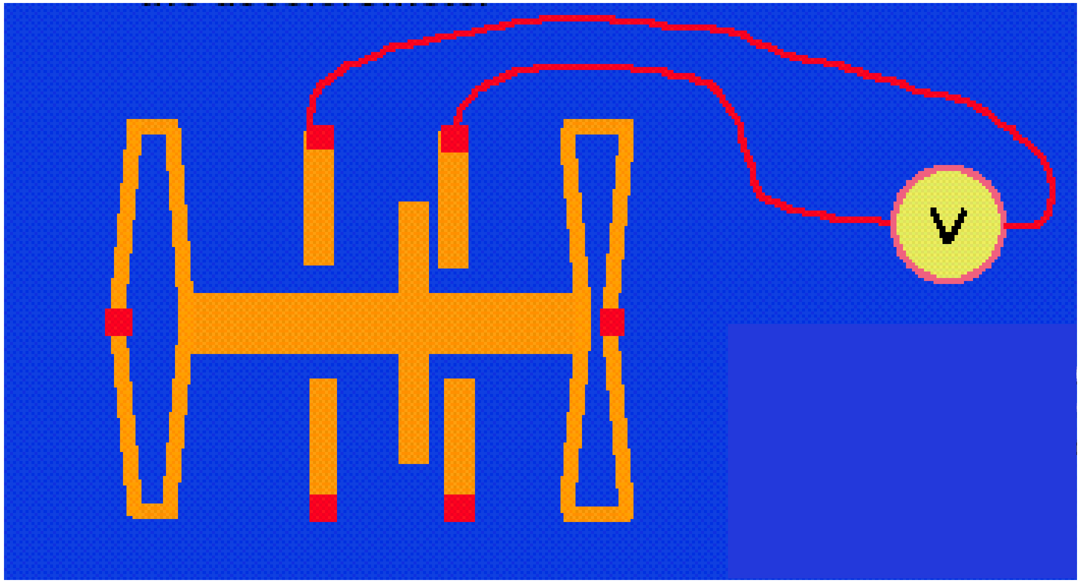
Micro Electrical Mechanical Systems
Practice of making and combining miniaturized mechanical and electrical components

MEMS based Single Chip acceleration Sensor



Sensor forms Differential Capacitor, circuitry to measure change in capacitance, it is also the part of the sensor package.

Self Test Operation



Extra fixed outer plates are added which when excited, force the proof mass to move. So it can electronically test the accelerometer.

Interesting Facts

- 0.1μgrams Proof Mass
- 0.1pF per side for the Differential Capacitor
- 20aF (10^{-18}f) least detectable Capacitance change
- Total Capacitance change for Full Scale is 10fF
- 1.3μm gaps between Capacitor Plates
- 0.2A minimum detectable beam deflection
- 1.6μm between suspended beam and substrate
- 10 to 22 kHz resonant frequency of beam

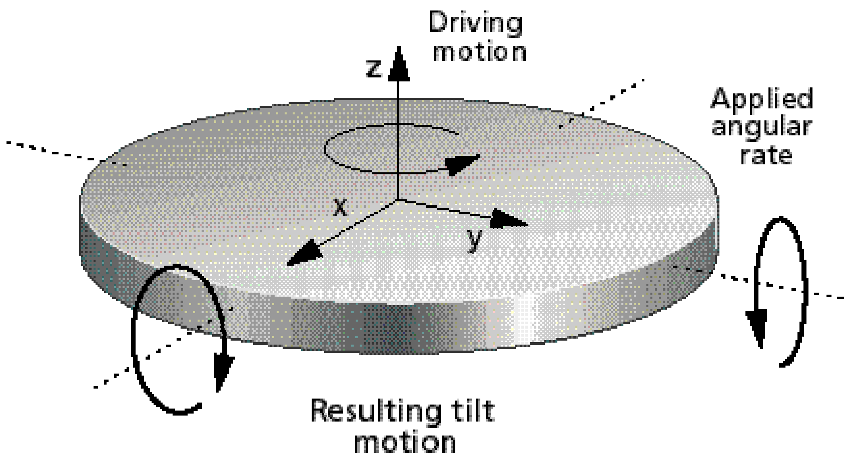
Advantages

- Low cost (can even be made “disposable”)
- FFTs can be used to increase the performance
- Onboard signal conditioning. No charge amplifiers required.

Disadvantages

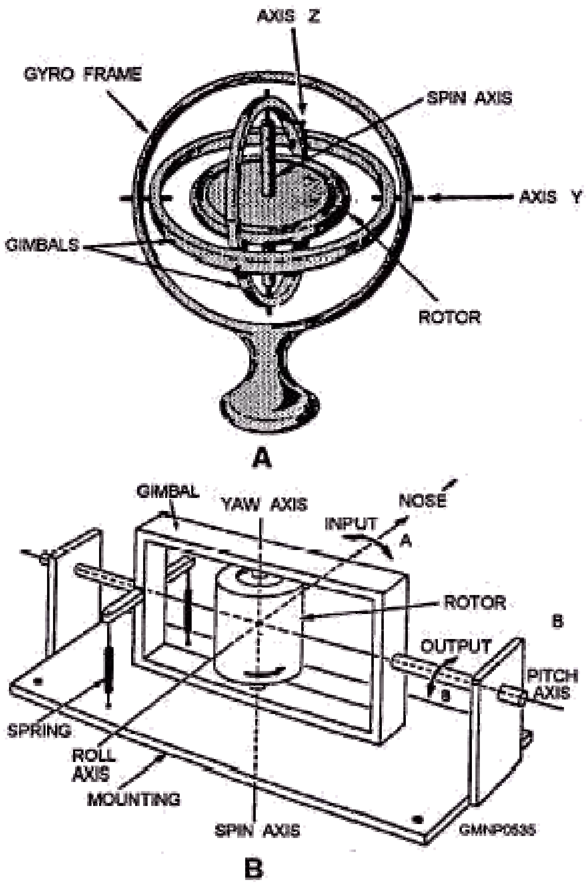
- Performance still below that of more expensive sensors
- May not be available in industrial hardened packages

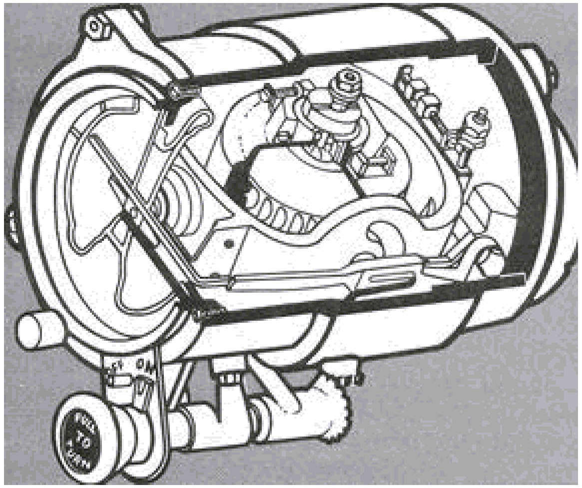
Angular Rate Sensor



- Coriolis forces
  - generated when a moving mass is rotated about an axis at right angles
  - are along the third orthogonal axis
  - are proportional to the amplitude of the moving mass

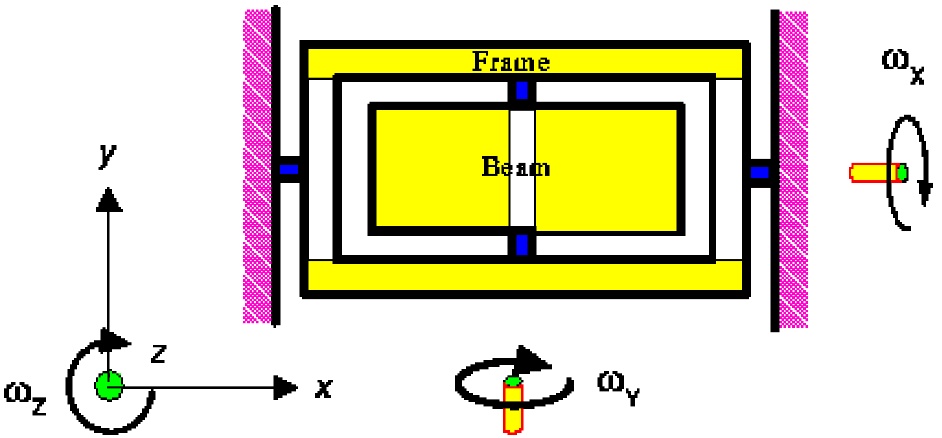
Angular Rate Sensor





Mechanical - Spinning mass

Angular Rate Sensor



- Two masses supported by torsional springs
- Electrical excitation to oscillate in rotating mode around x axis
- If rotated about *z* axis, coriolis force about y axis
- Motion of beam mass is sensed
- Structure enclosed in low pressure chamber and remaining gas in air gaps cause damping

Gyroscopes - Comparison

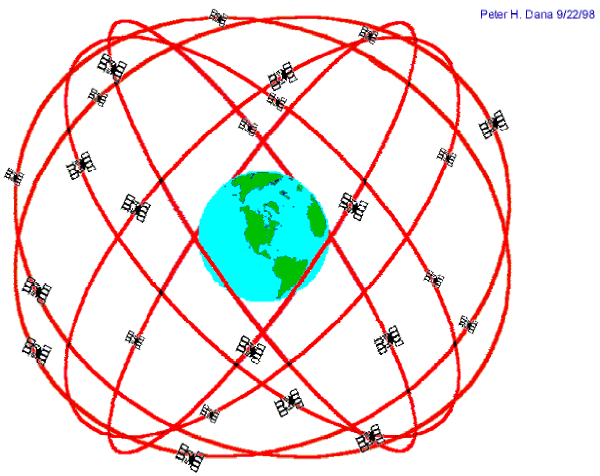
- Conventional
  - Bulky
  - Power hungry
  - Mechanical wear and tear
  - Highly accurate
  - Expensive
- MEMS based
  - Miniaturised
  - Low power consumption
  - Less moving parts
  - Accuracy not up to inertial class
  - Less weight
  - Low cost

Global Positioning System

A gadget which gives your longitude, latitude, altitude and UTC at any location on earth. Maintained by US Department of Defense. Future technology for civilian aircraft auto landing. Presently used heavily by automobiles for road navigation. Works on the signal received from satellites. Outputs in the form of serial data. NMEA standard is used for understanding GPS output. Limited programming capability is given in GPS. This is for giving the initial condition to obtain quick first fix, to change output format etc.

Global Positioning System

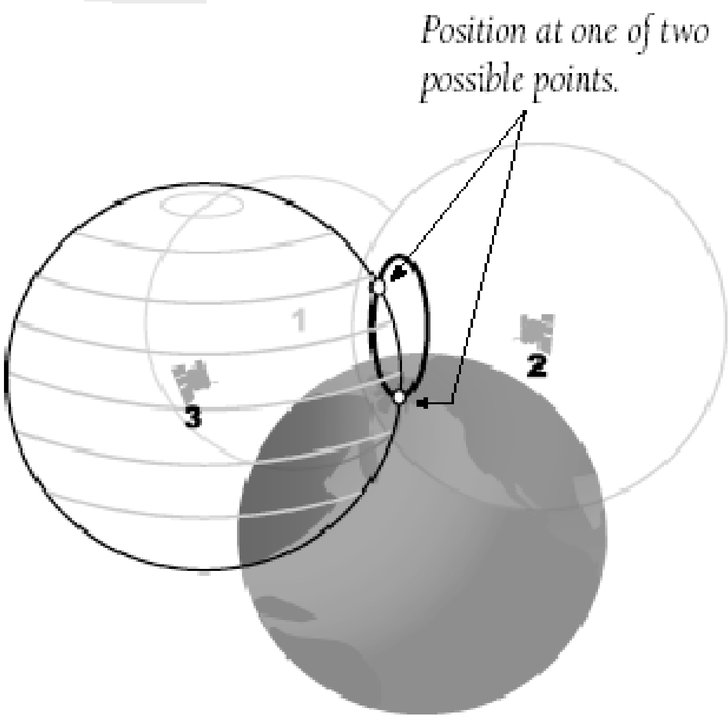
- 24 GPS space vehicles(SVs).
- Satellites orbit the earth in 12 hrs.
- 6 orbital planes inclined at 55 degrees with the equator.
- This constellation provides 5 to 8 SVs from any point on the earth.



GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination

How does the GPS work?

- Triangulation from satellite
- Distance measurement through travel time of radio signals
- Very accurate timing required
- To measure distance the location of the satellite should also be known
- Finally delays have to be corrected



- Position is calculated from distance measurement
- Mathematically we need four satellites but three are sufficient by rejecting the ridiculous answer

Error Sources

- 95% due to hardware, environment and atmosphere
- Satellite errors
  - Errors in modeling clock offset
  - Errors in Keplerian representation of ephemeris
  - Latency in tracking
- Atmospheric propagation errors
  - Through the ionosphere,carrier experiences phase advance and the code experiences group delay
  - Dependent on
    - Geomagnetic latitude
    - Time of the day
    - Elevation of the satellite

Errors

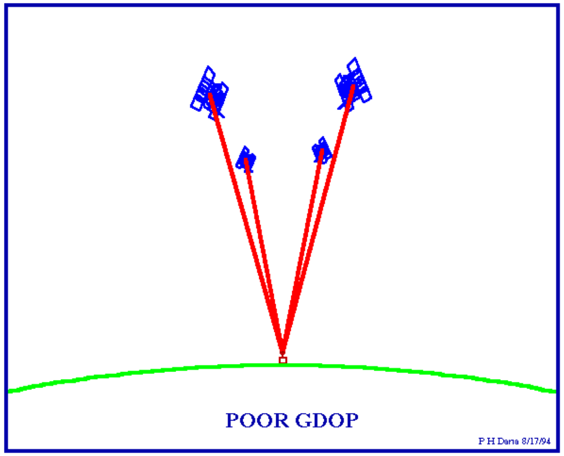
- Atmospheric errors can be removed by
  - Dual freq measurement
  - low freq get refracted more than high freq
  - thus by comparing delays of L1 and L2 errors can be eliminated
- Single freq users model the effects of the ionosphere
- Troposphere causes delays in code and carrier
- But they aren’t freq dependent
- But the errors are successfully modeled
- Errors due to Multipath
- Receiver noise

Errors

- Forces on the GPS satellite
  - Earth is not a perfect sphere and hence uneven gravitational potential distribution
  - Other heavenly bodies attract the satellite, but these are very well modeled
  - Not a perfect vacuum hence drag but it is negligible at GPS orbits
  - Solar radiation effects which depends on the surface reflectivity, luminosity of the sun, distance of to the sun. this error is the largest unknown errors source

Errors due to geometry

- Poor GDOP
  - When angles from the receiver to the SVs used are similar



- Good GDOP
  - When the angles are different