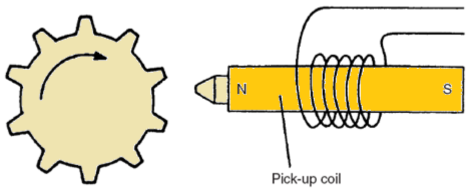
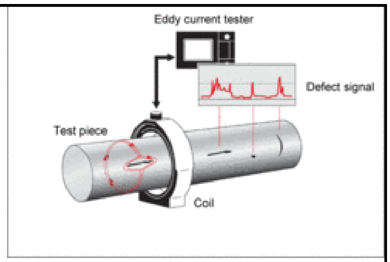
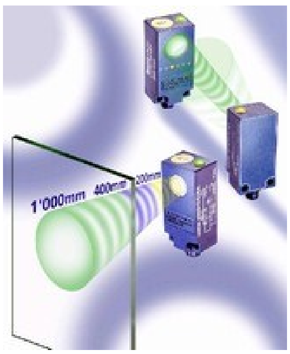
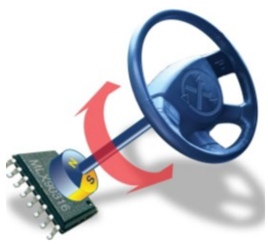
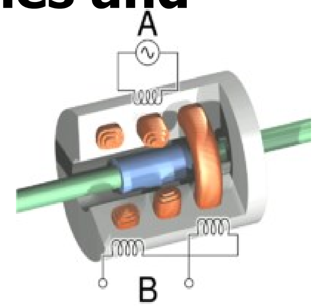




L6- Sensor Technologies and Sensors

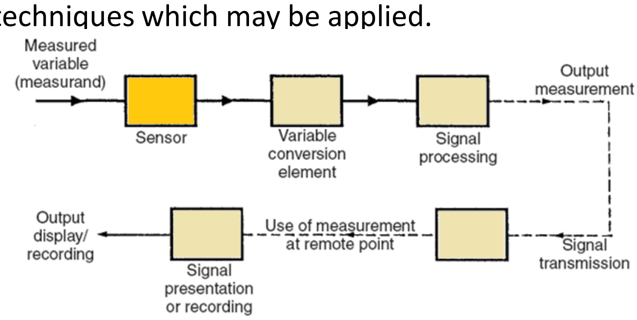






Sensors in Measuring Instruments

- A sensor is that part of a measuring instruments which responds the changes in the measured variable by giving an output that is a function of the measurand.
- A sensor utilizes the interaction of the physical parameters with each other—most notably electric properties with stress, temperature thermal gradients, magnetic fields, and incident light—yields a multitude of sensing techniques which may be applied.



Sensor/Transducer Technologies

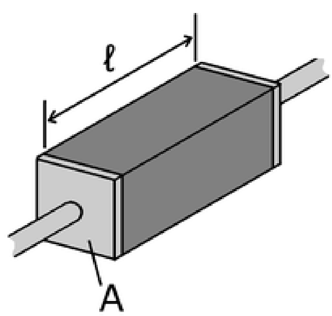
- **Resistive sensors**
- **Piezoresistive sensors**
- **Capacitive sensors**
- **Magnetic Sensors**
- **Hall Effect Sensors**
- **Piezoelectric transducers**
- **Light sensors**
- **Photo Interrupts**
- **Optical Sensors**
- **Infrared Sensors**
- **Ultrasonic Transducers**
- **Translational Motion Transducers**
- **Temperature Transducers**

Resistive sensors

- Resistive sensors rely on the variation of the resistance of a piece of material when the measured variable is applied to it.
- Many resistors and conductors have a uniform cross section and their resistance, *R*, is given by:

$$R = \rho(l/A)$$

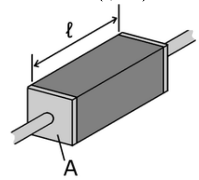
where ρ is the resistivity of the element's material, l is its length and A is its cross sectional area.

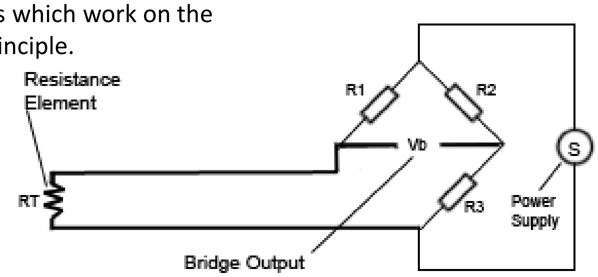


Resistive sensors:

- Many resistive sensors rely on the **variation of the resistivity of the element's material** when measured variable is changed. Common application of this principle is found in:
  - Resistance thermometers or resistive temperature detectors (RTDs)
  - Piezoresistive sensors and Piezoresistive strain gauges.
  - Some moisture meters which work on the resistivity-variation principle.

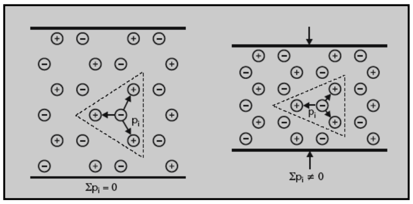
$$R = \rho(l/A)$$





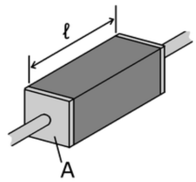
Piezoresistive sensors

- A piezoresistive sensor **is made from semiconductor material** in which a p-type region has been diffused into an n-type base. The resistance of this varies greatly when the sensor is compressed or stretched.
- This is frequently used as a strain gauge, where it produces a significantly higher gauge factor than that given by metal wire or foil gauges. Also, measurement uncertainty can be as low as ±0.1%.
- It is also used in semiconductor pressure sensors and in semiconductor accelerometers.

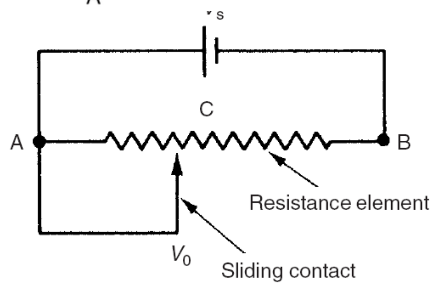


Resistive sensors: Potentiometers

- ❑ The resistive potentiometer is perhaps the best-known displacement-measuring device.
- ❑ It relies on changing the length l along which of the resistor is measured
- ❑ A linear relationship exists between the length and the resistance.

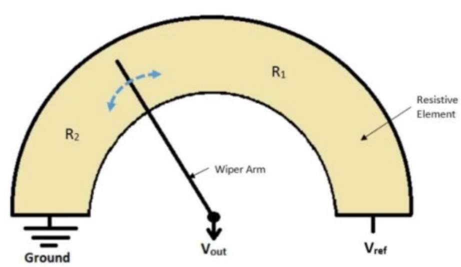


$$R = \rho(l/A)$$



Example : Electronic Throttle Control (ETC)

- ❑ In ETC systems, a vehicle's electronic control unit uses information from the throttle position sensor (TPS), accelerator pedal position sensor (APP sensor), wheel speed sensors, vehicle speed sensor and a variety of other sensors to determine how to adjust throttle position.
- ❑ TPS and APP sensors are very simple. The accelerator pedal position sensor and the throttle position sensor work together to translate user input into throttle plate movement.
- ❑ Until recently, these sensors have utilized potentiometers that worked as voltage dividers.
- ❑ The "divided" voltage is sent to a computer (ECU), which uses it to adjust the position of the throttle.



Example : Electronic Throttle Control (ETC)

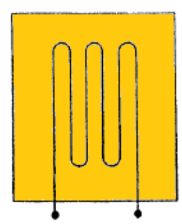
- The ECU takes in this signal, and sends an appropriate signal to a throttle actuator, which moves the throttle plate.
- The throttle position sensor works in a similar way. The potentiometer wiper is connected to the butterfly valve spindle. As the butterfly valve opens and closes, it varies the output voltage from 0 to the reference voltage. This output voltage is sent to the ECU. This is how the ECU knows the position of the throttle plate.
- The problem with potentiometer-based sensors is that, as the wiper arm and the resistive element rub against one another, they eventually wear out.
- Newer accelerator pedal position sensors use Hall effect as their basic operating principle.

https://jalopnik.com/how-electronic-throttle-control-works-499966101

https://www.infineon.com/dgdl/AppNote_Pedal_Position_Sensing_Rev.1.0.pdf?fileId=db3a30432313ff5e0123a38779c5262f

Resistive sensors: Metal Strain Gauges

- Strain gauges are devices that experience a change in resistance when they are stretched or strained.
- They are typically used as part of other transducers, for example diaphragm pressure sensors that convert pressure changes into small displacements of the diaphragm.
- The traditional metal strain gauge consists of a length of metal resistance wire formed into a zigzag pattern and mounted onto a flexible backing sheet.



- The wire is nominally of circular cross-section. As strain is applied to the gauge, the shape of the cross-section of the resistance wire distorts, changing the cross-sectional area.

$$R = \rho(l/A)$$

- As the resistance of the wire per unit length is inversely proportional to the cross-sectional area, there is a consequential change in resistance.
- The input–output relationship of a strain gauge is expressed by the gauge factor, which is defined as the change in resistance (R) for a given value of strain (S).

$$\text{gauge factor} = \frac{\delta R}{\delta S}$$

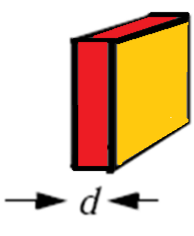
Strain gauges

- Strain gauges are manufactured to various nominal values of resistance, of which 120, 350 and 1000 are very common.
- The typical maximum change of resistance in a 120 device would be 5 at maximum deflection.
- Semiconductor strain gauges also are available with piezo-resistive elements, which are considered in greater detail in the next section.
- Compared with metal gauges, semiconductor types have a much superior gauge factor (up to 100 times better) but they are more expensive.
- Also, whilst metal gauges have an almost zero temperature coefficient, semiconductor types have a relatively high temperature coefficient

Capacitive sensors

- Capacitive sensors consist of two parallel metal plates in which a dielectric between the plates. A dielectric is an electrical insulator that can be polarized by an applied electric field. is either air or some other medium.
- The capacitance C is given by:

$$C = \varepsilon_o \varepsilon_r \frac{A}{d}$$

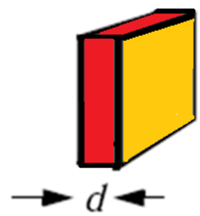


where ε_o is absolute permittivity, ε_r is the relative permittivity of the dielectric medium between the plates, A is the area of the plates and d is the distance between them.

Capacitive sensors

- Capacitive devices are often used as displacement sensors, **in which motion of a moveable capacitive plate relative to a fixed one changes the capacitance.**
- Often, the measured displacement is part of instruments measuring pressure, sound or acceleration.
- Alternatively, **fixed plate capacitors** can also be used as sensors, in which the capacitance value is changed by causing the measured variable **to change the dielectric constant** of the material between the plates in some way.
- **This principle is used in devices to measure moisture content, humidity values and liquid level.**
- **Also Capacitive proximity sensors exsist**

$$C = \varepsilon_o \varepsilon_r \frac{A}{d}$$

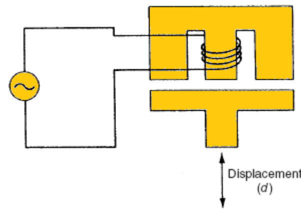


Magnetic Sensors

- **Magnetic sensors utilize the magnetic phenomena of:**
  - **inductance,**
  - **reluctance**
  - **eddy currents**
- **Used to indicate the value of the measured quantity, which is usually some form of displacement.**

Inductive Sensors

- In the inductive displacement transducer, the single winding on the central limb of an 'E'-shaped ferromagnetic body is excited with an alternating voltage.
- The displacement to be measured is applied to a ferromagnetic plate in close proximity to the 'E' piece.
- Movements of the plate alter the flux paths and hence cause a change in the current flowing in the winding. The current-voltage relationship in the winding is given by:
- For fixed values of ω and V, I depends only on *L*, which in turn, depends on the displacement *d* applied to the plate.
- The relationship between L and *d*, is a non-linear one, and hence the output-current/displacement characteristic has to be calibrated.



$$v = L\frac{di}{dt},$$

$$i = \frac{1}{L}\int v\,dt = \frac{V}{L}\int \cos\omega t\,dt$$

$$= \frac{V}{\omega L}\sin\omega t$$

$$I = \frac{V}{\omega L}$$

Magnetic Reluctance

- Magnetic Reluctance is analogous to resistance in an electrical circuit (although it does not dissipate magnetic energy).
- An electric field causes an electric current to follow the path of least resistance,
- **A magnetic field causes magnetic flux to follow the path of least magnetic reluctance**

- The definition can be expressed as: $\mathcal{R}=F/\Phi$

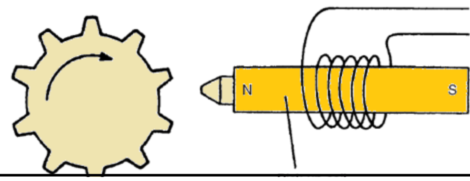
where

- ("$\mathcal{R}$") is the reluctance in ampere-turns per weber (a unit that is equivalent to turns per henry). "Turns" refers to the winding number of an electrical conductor comprising an inductor.
- ("F") is the magnetomotive force (MMF) in ampere-turns
- Φ ("Phi") is the magnetic flux in webers.

Variable Reluctance Sensors

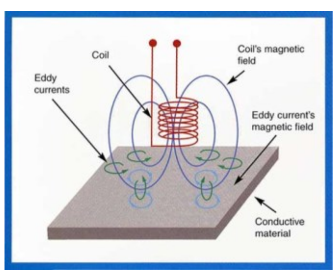
- Variable reluctance sensors are a class of magnetic sensors in **which a coil is wound on a permanent magnet** rather than on an iron core as in variable inductance sensors.
- Such devices are commonly used to measure rotational velocities.
- In a typical instrument a ferromagnetic gearwheel is placed next to the sensor.
- As the tip of each tooth on the gearwheel moves towards and away from the pick-up unit, the changing magnetic flux in the pick-up coil causes a voltage **to be induced in the coil** whose magnitude is proportional to the rate of change of flux.
- Thus, the output is a sequence of positive and negative pulses whose frequency is proportional to the rotational velocity of the gearwheel.

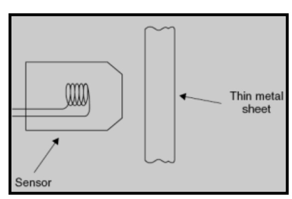
https://www.youtube.com/watch?v=37oJtcUTpL8



Eddy Current Sensors

- Eddy current sensors are a third class of magnetic sensors and **consist of a probe containing a coil that is excited at a high frequency, which is typically 1MHz**.
- This is used to measure the displacement of the probe relative to a moving metal target.
- Because of the high frequency of excitation, eddy currents are induced in the surface of the target and the current magnitude reduces to almost zero a short distance inside the target.
- This allows the sensor to work with very thin targets, such as the steel diaphragm of a pressure sensor.





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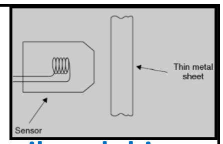
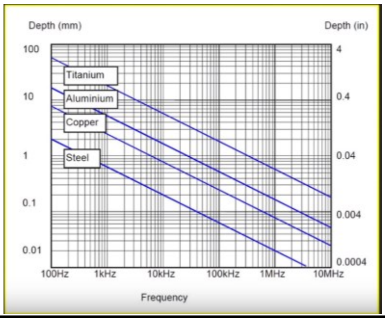
Eddy Current Sensors



- **The eddy currents alter the inductance of the probe coil, and this change can be translated into a d.c. voltage output that is proportional to the distance between the probe and the target**.
- Measurement resolution as high as 0.1 µm can be achieved.
- A signal conditioning circuit can be used to measure change in dc voltage/current as a function of distance

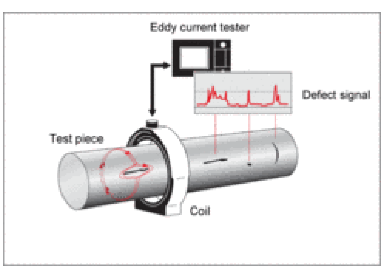


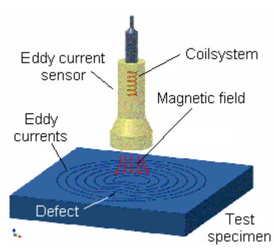
Eddy Current sensor applications

- The sensor can also work with a non-conductive target if a piece of aluminum tape is fastened to it.

For product testing

Distance measurement

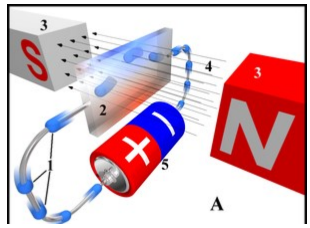




Hall Effect Sensors

The Hall effect refers to the potential difference (Hall voltage) on the opposite sides of an electrical conductor through which an electric current is flowing, created by a magnetic field applied perpendicular to the current. Edwin Hall discovered this effect in 1879.

Hall effect diagram, showing electron flow (rather than conventional current).



Legend:
1. Electrons
2. Hall element, or Hall sensor
3. Magnets; 4. Magnetic field ;
5. Power source

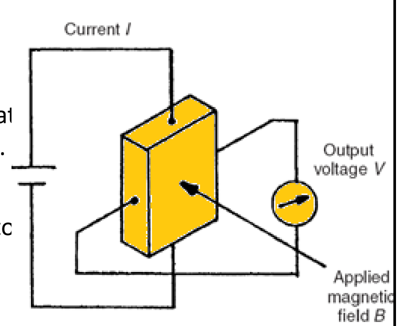
Description:
In drawing "A", the Hall element takes on a negative charge at the top edge (symbolised by the blue color) and positive at the lower edge (red color).

Hall-effect sensors

- A Hall-effect sensor is a device that is used to measure the magnitude of a magnetic field.
- It consists of a conductor carrying a current that is aligned orthogonally with the magnetic field.
- This produces a transverse voltage difference across the device that is directly proportional to the magnetic field strength.
- For an excitation current I and magnetic field strength B, the output voltage is given by

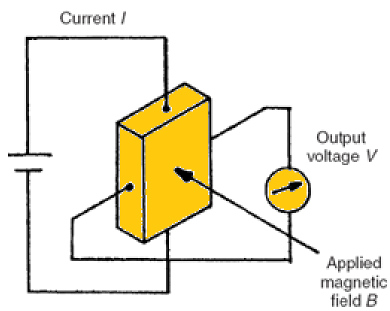
  $V = KIB$,

  where K is known as the Hall constant.
- The conductor in Hall-effect sensors is usually made from a semiconductor material as opposed to a metal, because a larger voltage output is produced for a magnetic field of a given size.



Hall-effect sensors

- In one common use of the device as a **proximity sensor**, the magnetic field is provided by a permanent magnet that is built into the device.
- The magnitude of this field changes when the device becomes close to any ferrous metal object or boundary.
- **The Hall effect is also commonly used in keyboard pushbuttons**, in which a magnet is attached underneath the button.
- When the button is depressed, the magnet moves past a Hall-effect sensor. The induced voltage is then converted by a trigger circuit into a digital output. **Such pushbutton switches can operate at high frequencies without contact bounce.**



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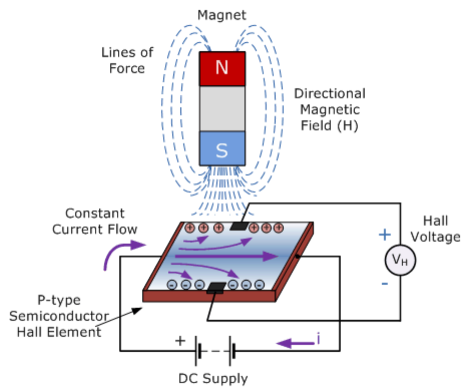
Hall Effect Current Sensor

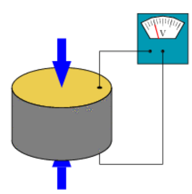


Example : Electronic Throttle Control (ETC)

- Newer accelerator pedal position sensors and throttle position sensors use Hall effect as their basic operating principle.
- These sensors contain transducers that convert external magnetic fields into voltage.
- Using magnets placed on the pedal and throttle shaft as reference points, Hall effect sensors output a different voltage depending on the intensity of the magnetic field.
- As the pedal or throttle moves, so does the magnet. This movement changes the magnetic field strength and thus alters output voltage from the sensor to the ECU.
- MLX90316 Non-contact absolute non-contacting rotary sensor IC allows simple implementation of rugged 360 degree position indicators.
- Applications include Throttle position sensing, pedal position drive by wire sensors, ride height, shaft position and other 0 to 360 degree absolute rotary position indication applications.
- The IC is fully programmable to allow the user to set the angular range to any value and still have rail to rail signal for the chosen angular displacement

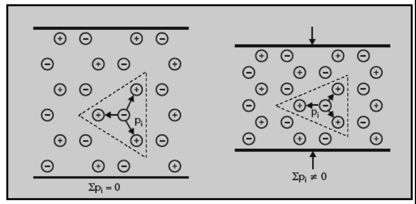
Piezoelectricity

- **Piezoelectricity** is the ability of some materials (notably crystals and certain ceramics) to generate an electric potential in response to applied mechanical stress. This may take the form of a separation of electric charge across the crystal lattice. If the material is not short-circuited, the applied charge induces a voltage across the material.
- The word is derived from the Greek *piezein*, which means to squeeze or press.
- The piezoelectric effect is reversible in that materials exhibiting the *direct piezoelectric effect* (the production of electricity when stress is applied) also exhibit the *converse piezoelectric effect* (the production of stress and/or strain when an electric field is applied).
- For example, lead zirconate titanate crystals will exhibit a maximum shape change of about 0.1% of the original dimension.



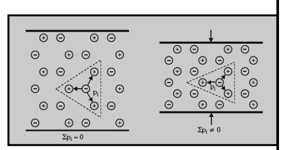
Piezoelectric transducers

- Piezoelectric transducers produce an output voltage when a force is applied to them.
- They are frequently used as ultrasonic receivers and also as displacement transducers, particularly as part of devices measuring acceleration, force and pressure.



Piezoelectric transducers

- Piezoelectric transducers are made from piezoelectric materials. These have an asymmetrical lattice of molecules that distorts when a mechanical force is applied to it.
- This distortion causes a reorientation of electric charges within the material, resulting in a relative displacement of positive and negative charges.
- The charge displacement induces surface charges on the material of opposite polarity between the two sides. By implanting electrodes into the surface of the material, these surface charges can be measured as an output voltage. For a rectangular block of material, the induced voltage is given by:



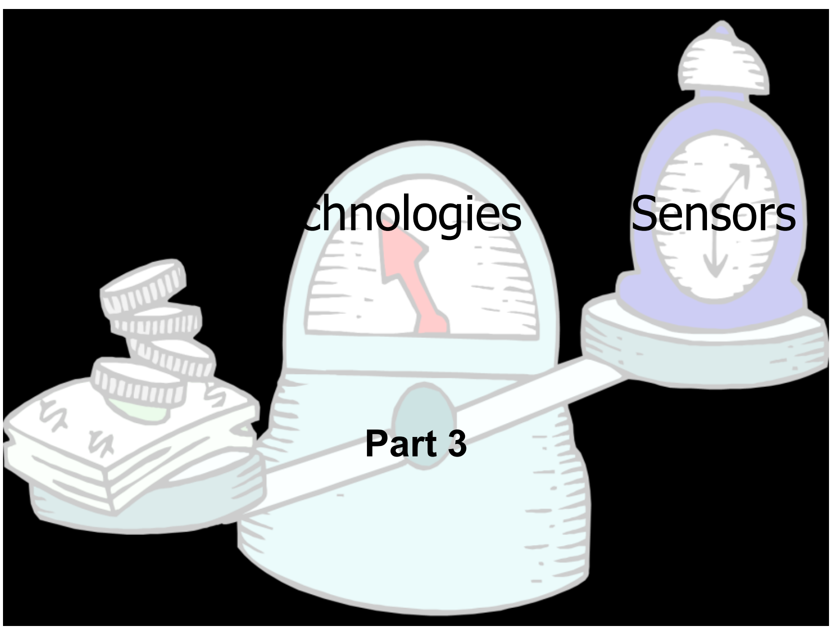
$$V = \frac{kFd}{A}$$

where F is the applied force, A is the area of the material, d is the thickness of the material and k is the piezoelectric constant. The polarity of the induced voltage depends on whether the material is compressed or stretched.

- Materials exhibiting piezoelectric behaviour include natural ones such as **quartz**, **synthetic ones such as lithium sulphate and ferroelectric ceramics such as barium titanate.**
- The piezoelectric constant varies widely between different materials. Typical values of k are 2.3 for quartz and 140 for barium titanate.
- Applying equation for a force of 1 g applied to a crystal of area 100 mm2 and thickness 1 mm gives an output of 23 μV for quartz and 1.4 mV for barium titanate.

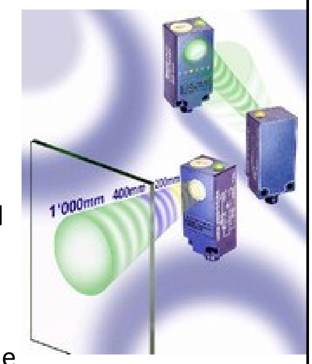
$$V = \frac{kFd}{A}$$

- The piezoelectric principle is invertible, and therefore distortion in a piezoelectric material can be caused by applying a voltage to it.
- This is commonly used in ultrasonic transmitters, where the application of a sinusoidal voltage at a frequency in the ultrasound range causes a sinusoidal variation in the thickness of the material and results in a sound wave being emitted at the chosen frequency.



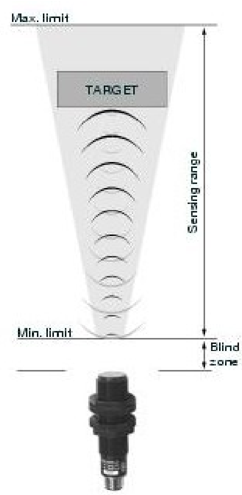
Ultrasonic transducers

- Ultrasonic devices are used for measuring fluid flow rates, liquid levels and translational displacements.
- Ultrasound is a band of frequencies in the range above 20 kHz up to 15 MHz, that is, above the sonic range that humans can usually hear.
- Measurement devices that use ultrasound consist of one device that transmits an ultrasound wave and another device that receives the wave
- Changes in the measured variable are determined either by measuring the change in time taken for the ultrasound wave to travel between the transmitter and receiver, or, alternatively, by measuring the change in phase or frequency of the transmitted wave.



Ultrasonic transducers

- The most common form of ultrasonic element is a piezoelectric crystal contained in a casing. Such elements can operate interchangeably as either a transmitter or receiver. These are available with operating frequencies that vary between 20 kHz and 15 MHz.
- As a piezoelectric crystal, , it generates an ultrasonic wave when an alternating voltage is applied.
- It also works in reverse. When it receives a sound wave, it generates an alternating voltage.



- Also capacitive ultrasonic elements exist. These consist of a thin, dielectric membrane between two conducting layers.
- The membrane is stretched across a backplate and a bias voltage is applied.
- When a varying voltage is applied to the element, it behaves as an ultrasonic transmitter and an ultrasound wave is produced.
- The system also works in the reverse direction as an ultrasonic receiver.
- Elements with resonant frequencies in the range between 30 kHz and 3MHz can be obtained.

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- When transmitted through air,
 the speed of ultrasound is affected
 by environmental factors such as temperature, humidity and air turbulence.
 Of these, temperature has the largest effect. The velocity of sound through air varies with temperature according to:

$$V = 331.6 + 0.6T \text{ m/s} \qquad (6.2)$$

- where T is the temperature in ° C. Thus, even for a relatively small temperature change of 20 degrees from 0° C to 20° C, the velocity changes from 331.6 m/s to 343.6 m/s.

Table 13.1 Transmission speed of ultrasound through different media

Medium	*Velocity* (m/s)
Air	331.6
Water	1440
Wood (pine)	3320
Iron	5130
Rock (granite)	6000

Other factors affecting Ultrasonic waves

- Humidity changes have a much smaller effect. If the relative humidity increases by 20%, the corresponding increase in the transmission velocity of ultrasound is 0.07% (corresponding to an increase from 331.6m/s to 331.8m/s at 0° C).
- Changes in air pressure itself have negligible effect on the velocity of ultrasound.
- Similarly, air turbulence normally has no effect (though note that air turbulence may deflect ultrasound waves away from their original direction of travel).
- However, if turbulence involves currents of air at different temperatures, then random changes in ultrasound velocity occur according to equation (6.2).

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Ultrasound as Range Sensor

- $X = v_{sound} \cdot t$
- Where:
  - V_{sound} is known
  - t = 0.5 (time of flight)
  - X is distance between sensor head and object
- Range of sensor varies between 5 cm to 20 m
- Sensor is not appropriate for very short distance measurements
- Frequency response (distance measurement update rate) varies with distance measured
  - In general, it is about 100 Hz

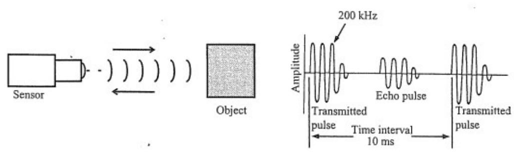


FIGURE 6.26: Operating principle of a sonic distance sensor.

- An obvious difficulty in applying this equation is the variability of v with temperature .
- One solution to this problem is to include an extra ultrasonic transmitter/ receiver pair in the measurement system in which the two elements are positioned a known distance apart.
- This allows measurement of transmission time of energy between this fixed pair which provides compensation of temp effects

- Technology can be used for measuring:
  - wind speed and direction (anemometer),
  - speed through air or water
  - fullness of tank
  - amount of liquid in tank
    - sensor measures distance to surface of fluid.
- Other applications include:
  - in robots for obstacle avoidance
  - burglar alarms
  - non-destructive testing, and etc

wavelength, frequency and directionality of ultrasound waves

- The frequency and wavelength of ultrasound waves are related according to:

  $\lambda = v/f$

- where λ is the wavelength,
- v is the velocity and
- f is the frequency of the ultrasound waves.
- v is also affected by Humidity and temperature

Attenuation of ultrasound waves

- Ultrasound waves suffer attenuation in the amplitude of the transmitted energy according to the distance traveled.
- The amount of attenuation also depends on the nominal frequency of the ultrasound and the absorption characteristics of the medium through which it travels.
- The amplitude Xd of the ultrasound wave at a distance d from the emission point can be expressed as:

$$\frac{X_d}{X_0} = \frac{\sqrt{e^{-\alpha d}}}{fd}$$

-
- where X_0 is the magnitude of the energy at the point of emission, f is the nominal frequency of the ultrasound
- and α is the attenuation constant that depends on frequency, medium and pollution such as dust

Resolution and Accuracy

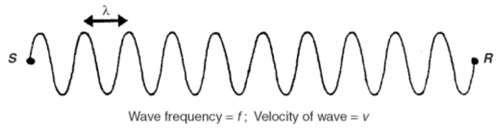
- Best resolution of ultrasonic ranging system is equal to wavelength of the transmitted wave

$$\lambda = v/f$$

- High frequency elements seem to be preferable since λ is smaller, but range is less for higher frequency due to higher attenuation of the wave as it travels from Tx to Rx
- Here frequency choice is a compromise between resolution and range.

Doppler shift effect in ultrasound / FYI/

- Doppler Effect is present in all types of wave motion
- It describes the apparent change in frequency of the wave when there is relative motion between Tx and Rx
- If a continuous ultrasound wave with speed v and frequency f takes t seconds to travel from Source "S" to Receiver "R" ➔ then R receives f.t cycles of sound during t



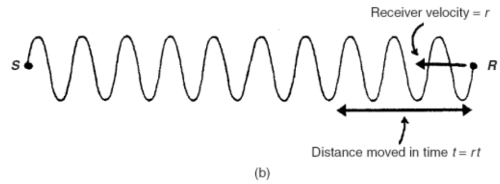
(a)

Doppler shift effect in ultrasound /FYI/

- Now, with R moving towards S at velocity r (S is still stationary) ➔ R will receive rt/λ extra cycles during time t (note r/λ=fnew) and total number of cycles in t is: **f.t+fnew.t**
- Apparent frequency f′ is defined as:

$$f' = \frac{ft + rt/\lambda}{t} = f + r/\lambda = f + \frac{rf}{v} = \frac{f(r+v)}{v}$$

- Frequency difference Δf=f′-f=f.r/v



- Velocity of the receiver r=v. Δf/f

/FYI/

- When R is moving a way from S with velocity r:

$$\Delta f = f' - f = \frac{f(v+r)}{v} - f = \frac{fr}{v}$$

$$r = v\Delta f/f.$$

$$f' = \frac{f(v-r)}{v}$$

$$\Delta f = -\frac{fr}{v}$$

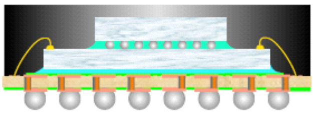
Ultrasonic Imaging

- The main applications of ultrasound in imaging are found in medical diagnosis and in industrial testing procedures.
- In both of these applications, a short burst of ultrasonic energy is transmitted from the ultrasonic element into the medium being investigated and the energy that is reflected back into the element is analyzed.
- Ultrasound is reflected back at all interfaces between different materials, with the proportion of energy reflected being a function of the materials either side of the interface.
- The principal components inside a human body are water, fat, muscle and bone, and the interfaces between each of these have different reflectance characteristics.
- Measurement of the time between energy transmission and receipt of the reflected signal gives the depth of the interface.

- Therefore, in medical diagnosis procedures:
- 1) the reflected energy appears as a series of peaks, with the magnitude of each peak corresponding to the type of interface that it is reflected from
- 2) The time of each peak corresponding to the depth of the interface in the body.
- 3) Thus, a ‘map’ of fat, muscle and bone in the body is obtained. A fuller account can be found elsewhere (Webster, 1998).
- Applications in industrial test procedures usually involve detecting internal flaws (defects) within components.
- Such flaws cause an interface between air and the material that the component is made of.
- By timing the reflections of ultrasound from the flaw, the depth of each flaw is determined.

Identifications of Solder Bump Defects in Chip Packages

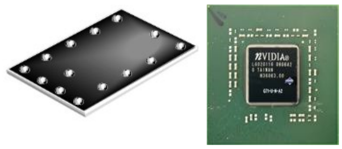
Examples of Emerging Microelectronic Packages:



3-D Packaging: Stacked Die

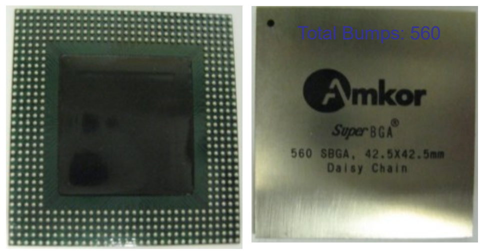
Chip Scale Package

Quad Flat Package (QFP)



Flip Chip

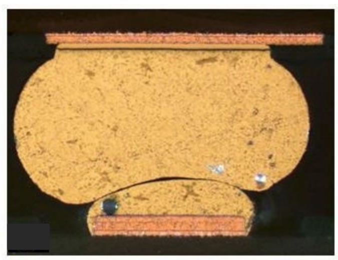
Ball Grid Array (BGA)



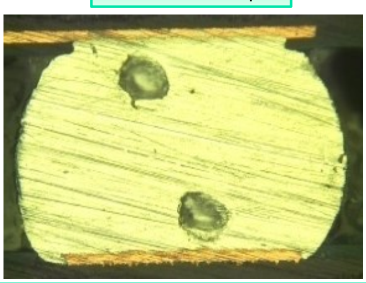
Amkor Super BGA

Optical Micrographs of Good and Bad Solder Bump Cross Sections

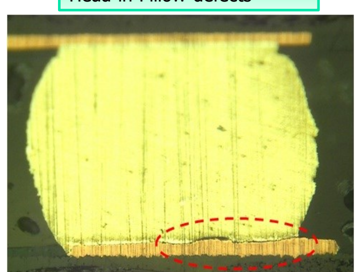
Good Solder Bump



Head-in-Pillow defects

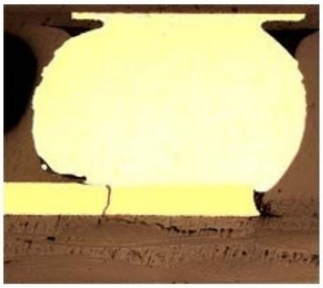


Two medium size voids near the interface

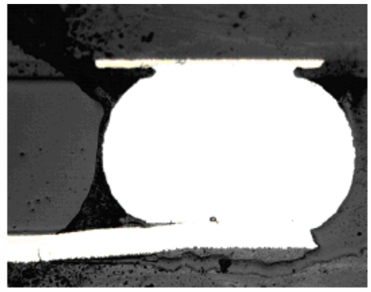


Poor wetting, an intermittent connection

Optical micrographs of Good and Bad Solder Bump Cross Sections



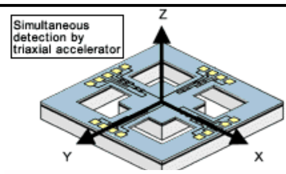
Pad crater with crack initiating at the trace



Crack initiates at the edge of the pad

Inspection of solder bumps is crucial process in microelectronics manufacturing industry.

Accelerometers



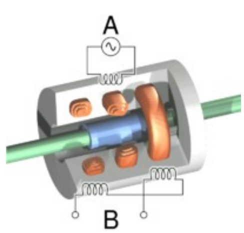
- Because of earth's gravity, the sensor will read 1 to 0 g as the sensor is rotated from being vertical to horizontal.
  - This can be used to measure angle of tilt
- Most have analog outputs that need amplification
  - Some have built-in amplifiers for direct connection into microcontroller

Accelerometers
Applications

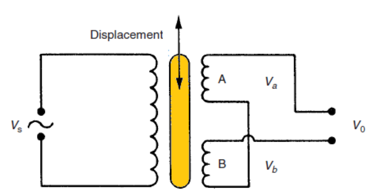
- Can be used to sense orientation, vibration and shocks.
- Used in electronics like the Wii and iPhone for user input.
- Acceleration integrated once gives velocity, integrated a second time gives position.
  - The integration process is not precise and introduces error into the velocity and position.

Translational Motion Transducers

- Translational displacement is movement in a straight line between two points
- Translational Displacement transducers can be used as primary or secondary transducers
- Simple type as resistive potentiometer
- LVDT: linear variable differential transformer



Cutaway view of an LVDT. Current is driven through the primary coil at *A*, causing an induction current to be generated through the secondary coils at *B*.



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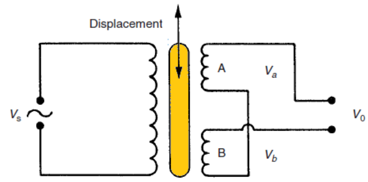
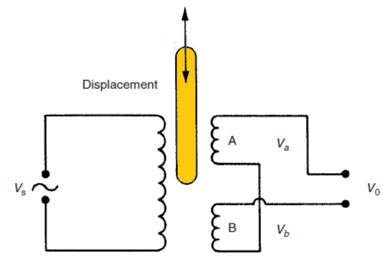
Linear Variable Differential Transformer

- The linear variable differential transformer, (LVDT), consists of a transformer with a single primary winding and two secondary windings connected in the series in opposing manner.
- The object whose translational displacement is to be measured is physically attached to the central iron core of the transformer, so that all motions of the body are transferred to the core.
- For an excitation voltage Vs given by $V_s = V_p \sin(\omega t)$, the e.m.f.s induced in the secondary windings V_a and V_b are given by:

$$V_a = K_a \sin(\omega t - \varphi), V_b = K_b \sin(\omega t - \varphi)$$



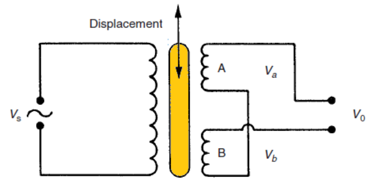


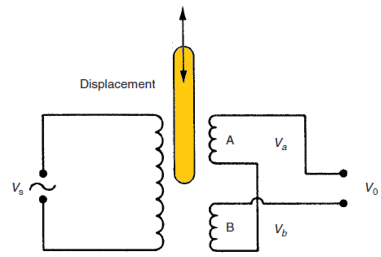
Linear Variable Differential Transformer

- The parameters K_a and K_b depend on the amount of coupling between the respective secondary and primary windings and hence on the position of the iron core.
- Because of the series opposition mode of connection of the secondary windings, the output voltage, V_0 is the difference between V_a and V_b,

$$V_o = V_a - V_b = (K_a - K_b)\sin(\omega t - \varphi)$$

- With the core in the central position, $K_a = K_b$, and $V_0 = 0$. The relationship between the magnitude of V_0 and the core position is approximately linear over a reasonable range of movement of the core on either side of the null position.

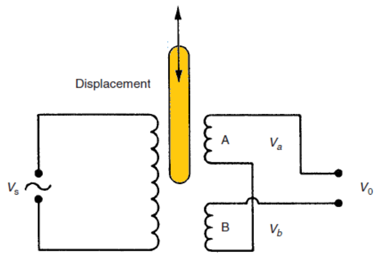




Linear Variable Differential Transformer

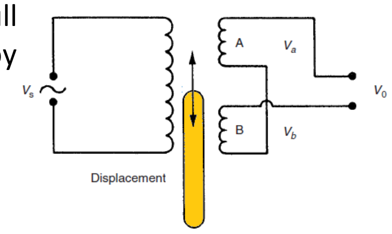
- Suppose that the core is displaced upwards (i.e. towards winding A) b a distance x. then K_a increases to become K_L and K_b decreases to become K_S. We thus have:

$$V_o = V_a - V_b = (K_L - K_S)\sin(\omega t - \varphi)$$



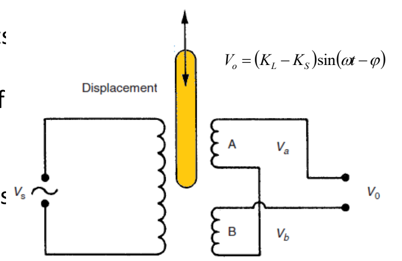
- If, alternatively, the core were displaced downwards from the null position (i.e. towards winding B) by a distance x, then K_a decreases to become K_S and K_b increases to become K_L, and we would have:

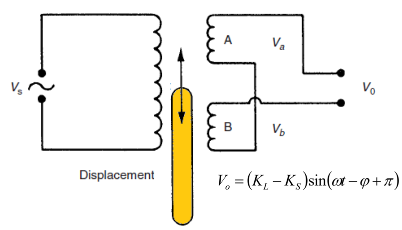
$$V_o = V_a - V_b = (K_S - K_L)\sin(\omega t - \varphi)$$
$$V_o = V_a - V_b = (K_L - K_S)\sin(\omega t - \varphi + \pi)$$



Linear Variable Differential Transformer

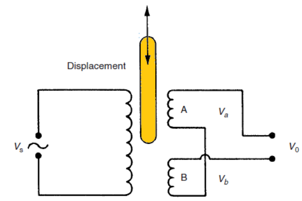
- Thus for equal magnitude displacement $+x$ and $-x$ of the core away from the central (null) position, the magnitude of the output voltage V_0 is the same in both cases. The only information about the direction of movement of the core is contained in the phase of the output voltage, which differs between the two cases by 180°.
- If, therefore, measurements of core position on both sides of the null position are required, it is necessary to measure the phase as well as the magnitude of the output voltage.





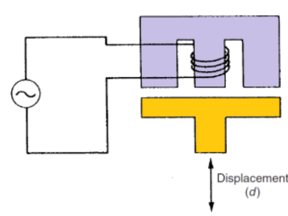
Linear Variable Differential Transformer

- Some problems that affect the accuracy of the LVDT are the presence of harmonics in the excitation voltage and stray capacitances, both of which cause a non-zero output of low magnitude when the core is in the null position.
- It is also impossible in practice to produce two identical secondary windings, and the small asymmetry that invariably exists between the secondary windings adds to this non-zero null output. The magnitude of this is always less than 1% of the full-scale output and in many measurement situations is of little consequence.
- Where necessary, the magnitude of these effects can be measured by applying known displacements to the instrument. Following this, appropriate compensation can be applied to subsequent measurements.



Variable Inductance Transducers

- One simple type of variable inductance transducer was described earlier. Movements of the plate alter the flux paths and hence cause a change in the current flowing in the winding.
- This has a typical measurement range of 0–10 mm.



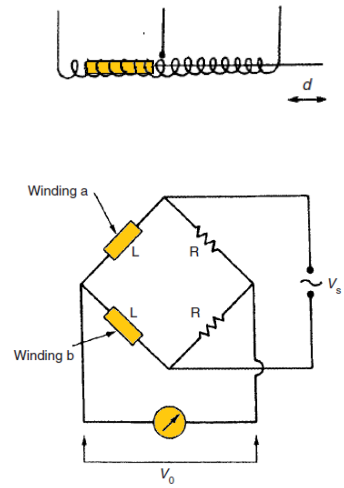
$$v = L\frac{di}{dt},$$

$$i = \frac{1}{L}\int v\,dt = \frac{V}{L}\int \cos\omega t\,dt = \frac{V}{\omega L}\sin\omega t$$

$$I = \frac{V}{\omega L}$$

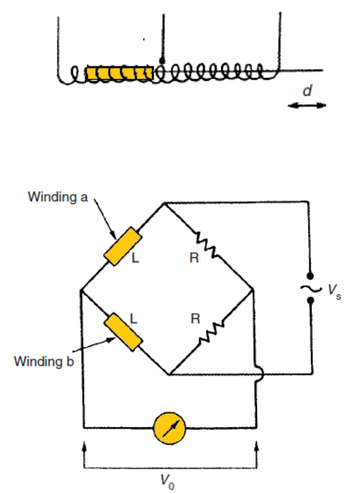
Variable Inductance Transducers

- An alternative form has a very similar size and physical appearance to the LVDT, but has a centre-tapped single winding. The two halves of the winding are connected to form two arms of a bridge circuit that is excited with an alternating voltage.
- With the core in the central position, the output from the bridge is zero. Displacements of the core either side of the null position cause a net output voltage that is approximately proportional to the displacement for small movements of the core.



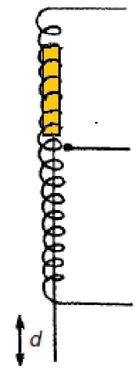
Variable Inductance Transducers

- Instruments in this form are available to cover a wide span of displacement measurements. At the lower end of this span, instruments with a range of 0–2mm are available, whilst at the top end, instruments with a range of 0–5m can be obtained.



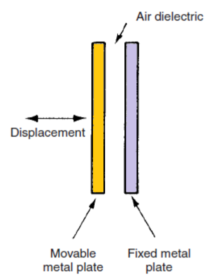
Variable Inductance Transducers

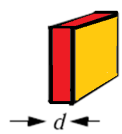
- An alternative form has a very similar size and physical appearance to the LVDT, but has a centre-tapped single winding. The two halves of the winding are connected to form two arms of a bridge circuit that is excited with an alternating voltage.
- With the core in the central position, the output from the bridge is zero. Displacements of the core either side of the null position cause a net output voltage that is approximately proportional to the displacement for small movements of the core. Instruments in this second form are available to cover a wide span of displacement measurements.
- At the lower end of this span, instruments with a range of 0–2mm are available, whilst at the top end, instruments with a range of 0–5m can be obtained.



Variable Capacitance Transducers

- The principle of variable capacitance is used in displacement measuring transducers in various ways.
- The two plates variable capacitance transducer consists of two flat, parallel, metal plates, one of which is fixed and one of which is movable.
- Displacements to be measured are applied to the movable plate, and the capacitance changes as this moves. Air serves as the dielectric medium between the plates.

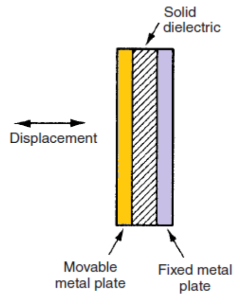


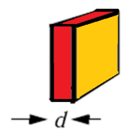


$$C = \varepsilon_o \varepsilon_r \frac{A}{d}$$

Variable Capacitance Transducers

- In an alternative form, a sheet of solid dielectric material between can be placed between the two parallel plates instead of the air layer.
- The displacement to be measured causes a capacitance change by moving the dielectric sheet.

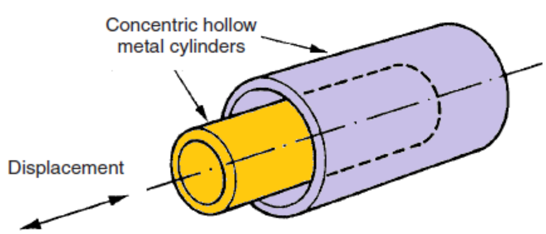




$$C = \varepsilon_o \varepsilon_r \frac{A}{d}$$

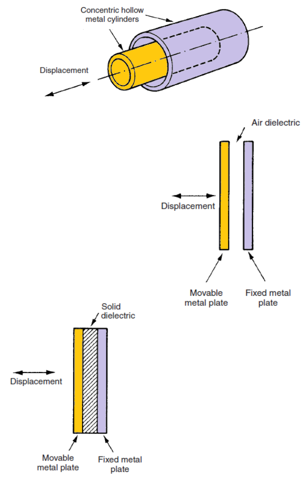
Variable Capacitance Transducers

- In the concentric cylinders variable capacitance transducer, capacitance plates are formed by two concentric, hollow, metal cylinders.
- The displacement to be measured is applied to the inner cylinder, which alters the capacitance



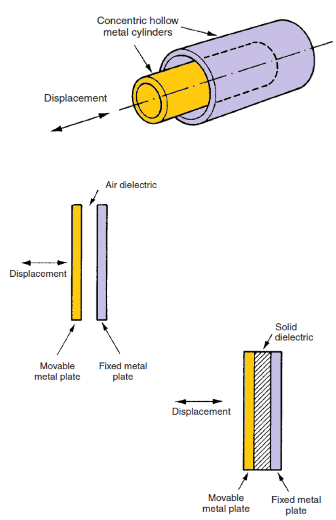
Variable Capacitance Transducers

- Inaccuracies as low as ±0.01% are possible with these instruments, with measurement resolutions of 1 micron. Individual devices can be selected from manufacturers' ranges that measure displacements as small as 10-11 m or as large as 1m.
- The fact that such instruments consist only of two simple conducting plates means that it is possible to fabricate devices that are tolerant to a wide range of environmental hazards such as extreme temperatures, radiation and corrosive atmospheres.
- As there are no contacting moving parts, there is no friction or wear in operation and the life expectancy quoted is 200 years.



Variable Capacitance Transducers

- The major problem with variable capacitance transducers is their high impedance. This makes them very susceptible to noise and means that the length and position of connecting cables need to be chosen very carefully.
- In addition, very high impedance instruments need to be used to measure the value of the capacitance.
- Because of these difficulties, use of these devices tends to be limited to those few applications where the high accuracy and measurement resolution of the instrument are required.



Sensor Technologies and Sensors

Temperature Transducers

Temperature Measurement

- Instruments to measure temperature can be divided into separate classes according to the physical principle on which they operate. The main principles used are:
- The thermoelectric effect ➔ Thermocouples
- Resistance change ➔ RTD's and Thermistors

Other Principles (FYI)

- Sensitivity of semiconductor device
- Radiative heat emission
- Thermography
- Thermal expansion
- Resonant frequency change
- Sensitivity of fibre optic devices
- Acoustic thermometry
- Colour change
- Change of state of material.

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Thermocouples- important

- Consist of a pair of dissimilar metal wires joined together at one end (sensing, hot junction) and terminated at the other end (reference, cold junction) which is kept at known constant temperature.
- emf (voltage) is produced when there is a difference in temperature between the two junctions, this is called the **thermocouple effect or Seebeck effect**.
- $$e = a_1T + a_2T^2 + a_3T^3 + \cdots + a_nT^n$$ ← FYI

  Which can be approximated for certain pairs of metals by

  $$e \approx a_1T$$
- Thermal emf magnitude depends on the materials used and on temperature difference .
- Remember how to convert from degrees C to degrees F
- Many types of thermocouples exist which differ in the metals used to construct them,
- among these are type E,J,K and S which differ in the combination of the used materials and their temperature range and application

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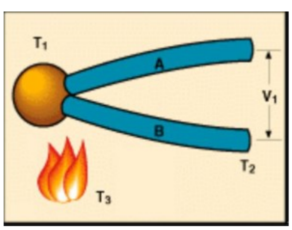

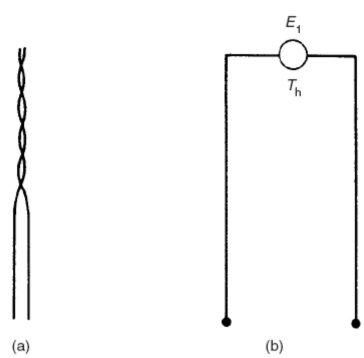

Fig. 14.2 (a) Thermocouple; (b) equivalent circuit.

- The emf generated at the hot junction is presented by E1 and temperature is known as Th
- E1 is measured at the open ends of the thermocouple (known as reference junction)

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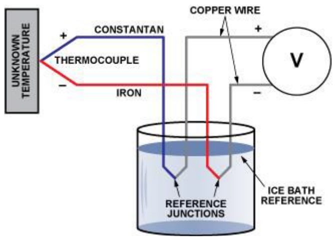
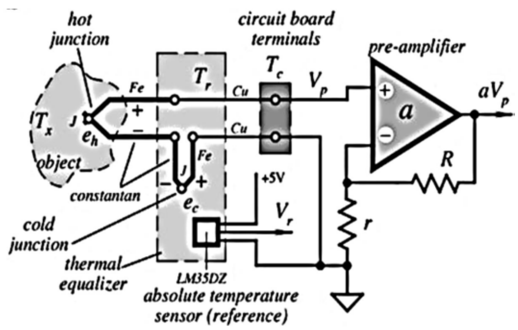




Thermocouple Types

- Type E ➔ Chromel-Constantan
- Type J ➔ Iron-Constantan
- Type K ➔ Chromel-Alumel
- Type S ➔ Platinum-Platinum/Rhodium

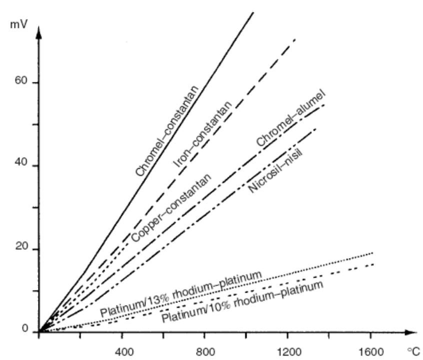
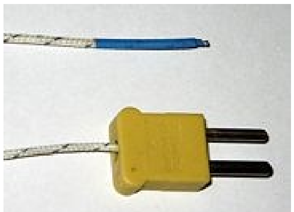
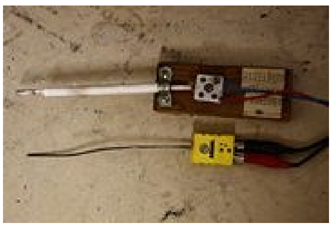
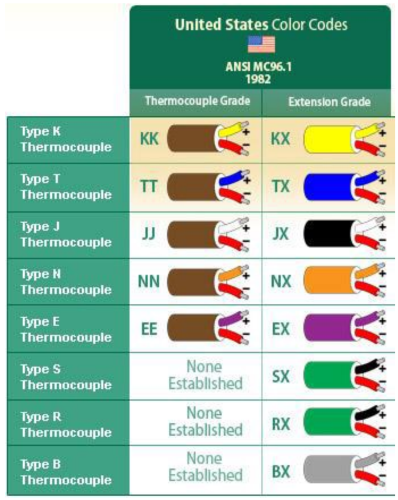


Fig. 14.1 E.m.f. temperature characteristics for some standard thermocouple materials.

FYI







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Thermistors / Important

- A **thermistor** is a type of resistor with resistance varying according to its temperature. The word is a combination of *thermal* and *resistor*.
- Thermistors are widely used as inrush current limiters, temperature sensors, self-resetting overcurrent protectors, and self-regulating heating elements.
- Assuming, as a first-order approximation, that the relationship between resistance and temperature is linear, then:

$$\Delta R = k \Delta T$$

where

ΔR = change in resistance

ΔT = change in temperature

k = first-order temperature coefficient of resistance

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Thermistors / Important

- Thermistors can be classified into two types depending on the sign of *k*. If *k* is positive, the resistance increases with increasing temperature, and the device is called a positive temperature coefficient (**PTC**) thermistor, or **posistor**.
- If *k* is negative, the resistance decreases with increasing temperature, and the device is called a negative temperature coefficient (**NTC**) thermistor.
- Resistors that are not thermistors are designed to have the smallest possible *k*, so that their resistance remains nearly constant over a wide temperature range
- Thermistors differ from resistance temperature detectors (RTD) in that the material used in a thermistor is generally a ceramic or polymer, while RTDs use pure metals. The temperature response is also different; RTDs are useful over larger temperature ranges.

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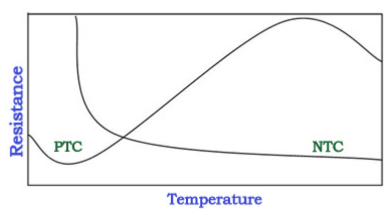
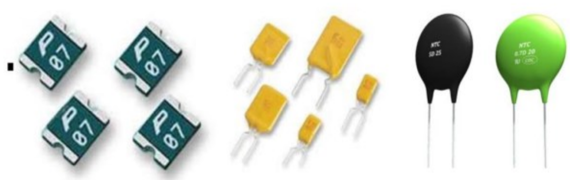


Thermistors



RTD's / Important

Resistance thermometers, which are alternatively known as *resistance temperature devices* (or RTDs), rely on the principle that the resistance of a metal varies with temperature according to the relationship:

➔ FYI $$R = R_0 \left(1 + a_1 T + a_2 T^2 + a_3 T^3 + \cdots + a_n T^n\right) \quad (14.7)$$

This equation is non-linear and so is inconvenient for measurement purposes. The equation becomes linear if all the terms in $a_2 T^2$ and higher powers of T are negligible such that the resistance and temperature are related according to:

$$R \approx R_0 \left(1 + a_1 T\right)$$

This equation is approximately true over a limited temperature range for some metals, notably platinum, copper and nickel, whose characteristics are summarized in Figure 14.8. Platinum has the most linear resistance–temperature characteristic, and it also has good chemical inertness, making it the preferred type of resistance thermometer

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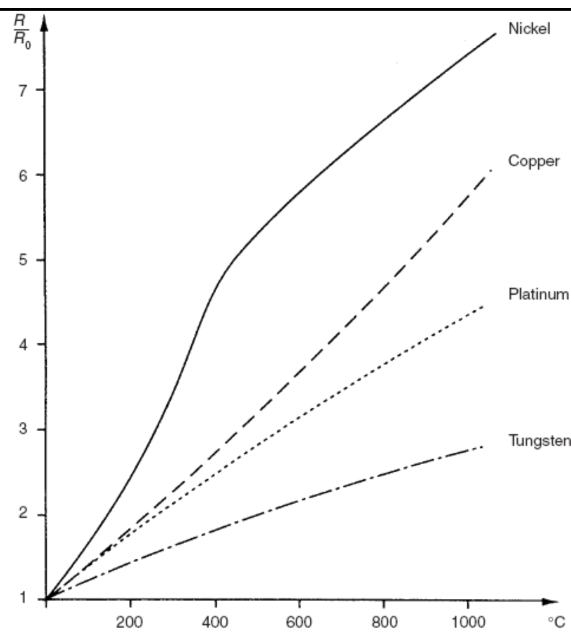
FYI



Typical resistance–temperature characteristics of metals.