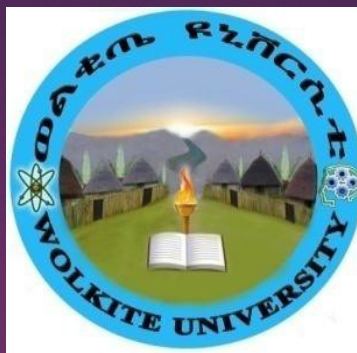




Collage of Engineering and Technology Department of Electrical and Computer Engineering

ELECTRICAL MEASUREMENT & INSTRUMENTATION

CHAPTER 3 : SENSOR AND TRANSDUCERS

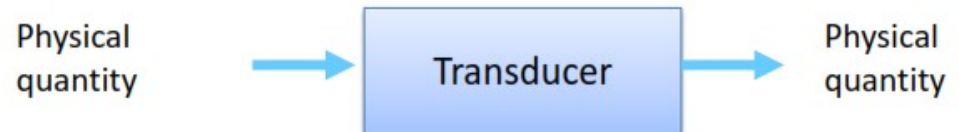
3.1 Introduction

Transducer

- ▶ A transducer is an element that converts ***one physical quantity into another physical quantity***

Example:

- ▶ Mercury thermometer (temperature – displacement)
- ▶ Accelerometer (acceleration – voltage)
- ▶ Electrode in a battery (ion – electrical charge)
- ▶ Motor (electrical current – mechanical moment)
- ▶ LED (electrical current – light)





Sensor

- ▶ A sensor is a transducer that converts ***a physical quantity into an electrical quantity.***

Example:

- ▶ Resistance thermometer (temperature - resistance)
- ▶ Photo detector (light - current)



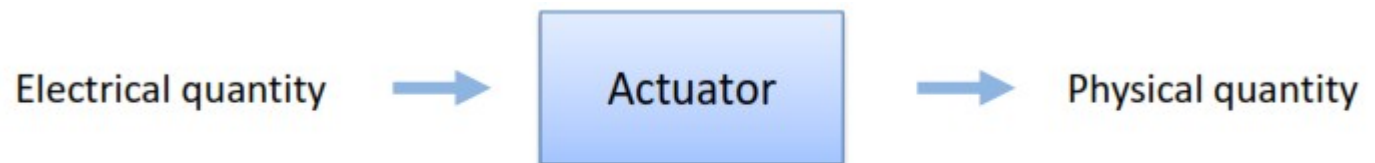


Actuator

- ▶ An actuator is a transducer that converts ***an electrical quantity into a non-electrical quantity.***

Example:

- ▶ Piezo actuator (charge - displacement)
- ▶ Resistive heater (current - heat)
- ▶ LED (current - light)



3.2 Characteristics of transducers

1. Dynamic Range

- ▶ It is defined as the **ratio between the largest and smallest amplitude signals** that can be translated by a transducer. Larger the Dynamic Range implies more sensitive and precise transducers will be.

2. Repeatability

- ▶ A transducer's **ability to produce identical output upon stimulation by the same input** is termed as repeatability.



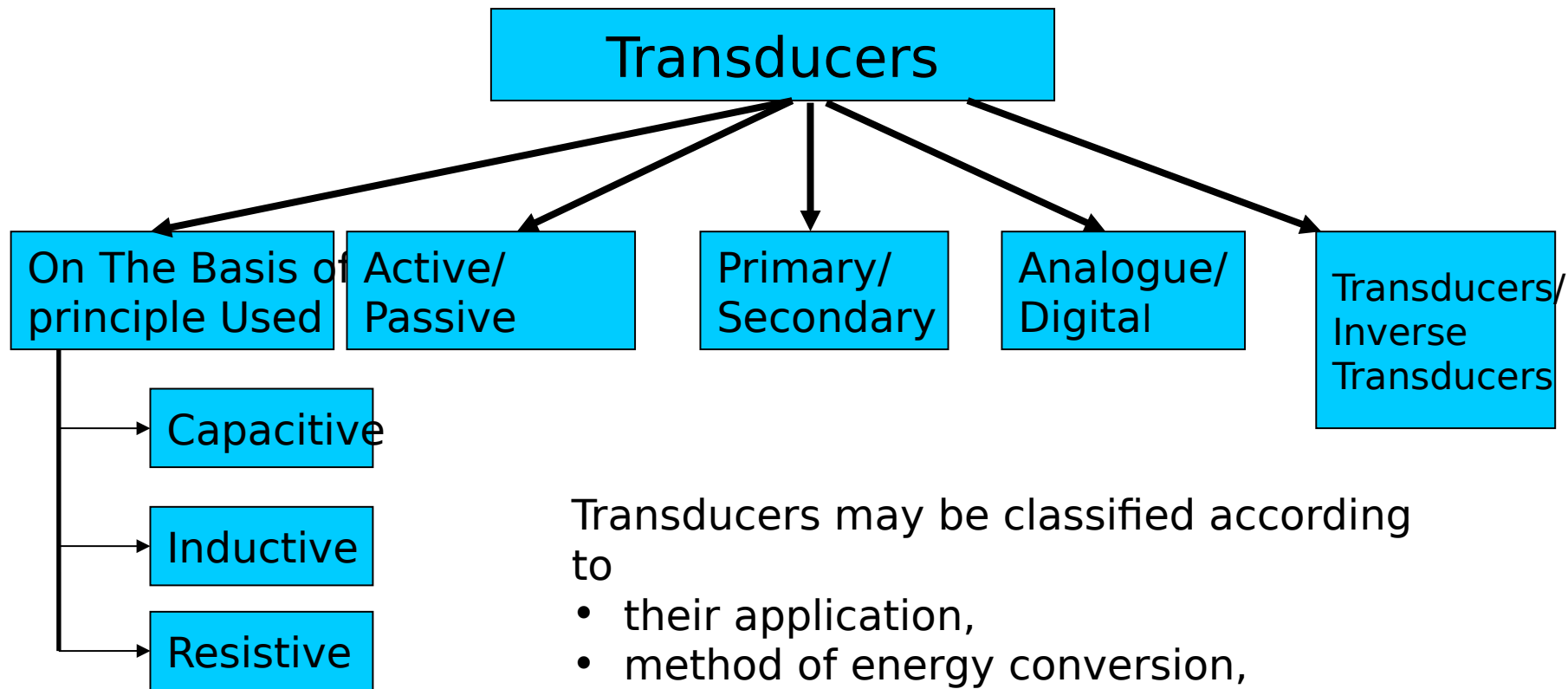
3. Noise

- ▶ All transducers ***have some random noise*** in their output. ***Small signals are largely affected*** by noise in comparison to larger signals.

4. Hysteresis

- ▶ This is property wherein a transducer's output is dependent not only on the present input, but, also on the previous inputs.

3.3 Classification of Transducers



Active and passive transducer

Active transducer

- ▶ These transducer ***do not need any external source of power*** for their operation. Therefore they are ***also called as self generating*** type transducer.
- I. The active transducer are self generating devices which ***operate under the energy conversion principle.***
- II. As the output of active transducers we get an equivalent electrical output signal e.g. temperature or strain to electric potential, without any external source of energy being used.



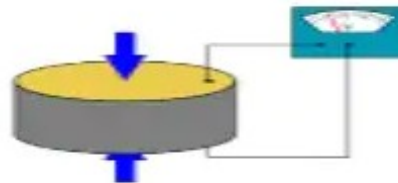
Active transducers

- ▶ Photovoltaic
- ▶ Thermoelectric
- ▶ Electromagnetic
- ▶ Piezoelectric
- ▶ Chemical
- ▶ Others

Example of active transducers

Piezoelectric transducer

- ▶ When an **external force** is applied on **to** a quartz crystal, there will be a **change in the voltage** generated across the surface.
- ▶ This change is measured by its corresponding value of sound or vibration





Passive transducer

- ▶ These transducers ***need external source of power*** for their operation. So they are not self generating type transducers.
- ▶ A DC power supply or an audio frequency generator is used as an external power source.
- ▶ These transducers ***produce the output signal in the form of variation in electrical parameter*** like resistance.
- ▶ Examples: Thermistors

Primary and secondary transducers

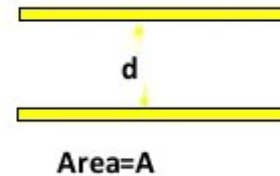
- ▶ Some transducers contain the mechanical as well as electrical device. The mechanical device converts the physical quantity to be measured into a mechanical signal.
- ▶ Such **mechanical** device are called as the **primary** transducers, because they **deal with the physical quantity to be measured**.
- ▶ The **electrical** device that **convert this mechanical signal into a corresponding electrical signal**. Such electrical device are known as **secondary** transducers.

According to transduction principle used

- ▶ Capacitive
- ▶ Electromagnetic
- ▶ Inductive
- ▶ Piezoelectric
- ▶ Photovoltaic
- ▶ Photoconductive

Capacitive transduction

- ▶ Here, the ***measurand is converted into a change in capacitance.***
- ▶ A change in capacitance occurs either ***by changing the distance between the two plates or by changing the dielectric.***



Electromagnetic transduction

- ▶ In electromagnetic transduction, the ***measurand is converted to voltage induced in conductor*** by change in the magnetic flux, in absence of excitation.
- ▶ The electromagnetic transducer are self generating active transducers.
- ▶ The motion between a piece of magnet and an electromagnet is responsible for the change in flux.





Inductance transduction

- ▶ Here the ***measurand is converted into a change in the self inductance*** of a single coil. It is achieved by displacing the core of the coil that is attached to a mechanical sensing material.

Piezoelectric transduction

- ▶ Here the ***measurand is converted into a change in electrostatic charge q or voltage V*** generated by crystals when it is mechanically stressed.



Photovoltaic transduction

- ▶ Here the ***measurand is converted to voltage generated*** when the junction between dissimilar materials is illuminated.

Photoconductive transduction

- ▶ Here the ***measurand is converted to change in resistance of semiconductor*** material by the change in light incident on the material.

Analog and Digital transducers

Analog transducers

- ▶ These transducers convert the ***input quantity into an analog output*** which is continuous function of time.
- ▶ Thus a **strain gauge**. An **LVDT**, a **thermocouple** or a **thermistor** may be called as Analog transducers as they give an output which is a continuous function of time.

Digital transducer

- ▶ These transducers convert the ***input quantity into an electrical output*** which is in the form of pulses and its output is represented by 0 and 1.

Transducer and Inverse transducer

Transducer

- ▶ Convert non electrical quantity to electrical quantity.

Inverse transducer

- ▶ Convert electrical quantity to a non electrical quantity.

3.4 Resistive transducers

- ▶ are those transducers in which the ***resistance change due to the change in some physical phenomenon.***
- ▶ The resistance of a metal conductor is expressed by a simple equation.

$$R = \rho L/A$$

Where R= resistance of conductor in Ω

L = length of conductor in m

A = cross sectional area of conductor in m^2

ρ = resistivity of conductor material in $\Omega\cdot m$.



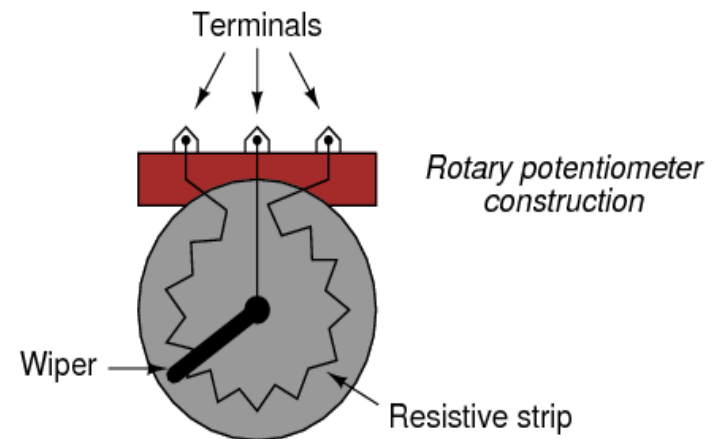
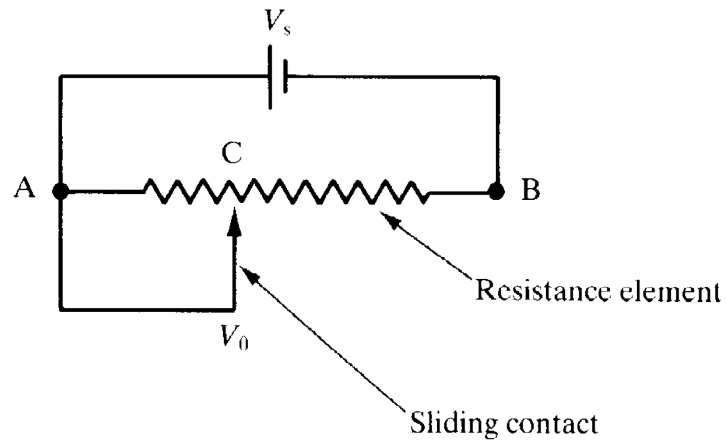
There are 4 type of resistive transducers.

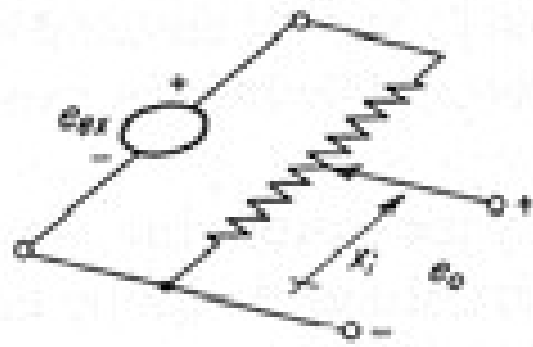
1. Potentiometers (POT)
2. Strain gauge
3. Thermistors
4. Resistance thermometer

3.4.1 POTENTIOMETER

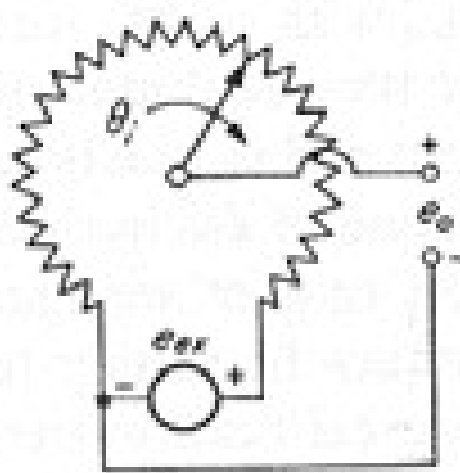
- ▶ Used for ***voltage division***.
- ▶ Consist of a ***resistive element provided with a sliding contact(wiper)***.
- ▶ The contact motion may be ***linear or rotational or combination*** of the two.
- ▶ The combinational potentiometer have their resistive element in helix form and are called helipots.

Fig shows a linear pot and a rotary pot.

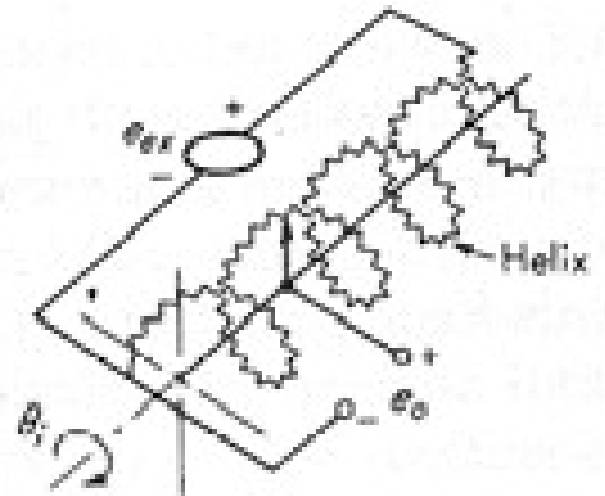




Translational

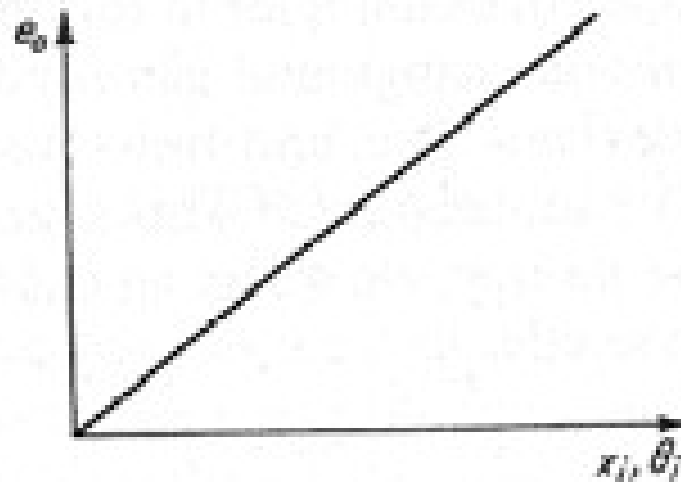


Single - turn



Multiturn

Rotational



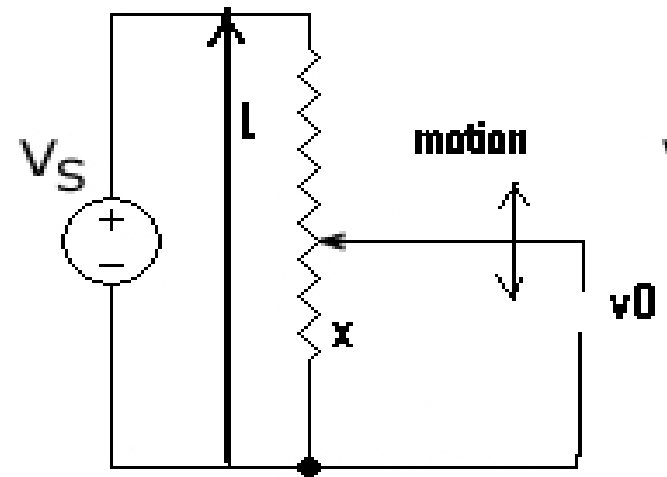
Longitudinal Displacement

Potentiometer or longitudinal displacement

Theory of Operation:

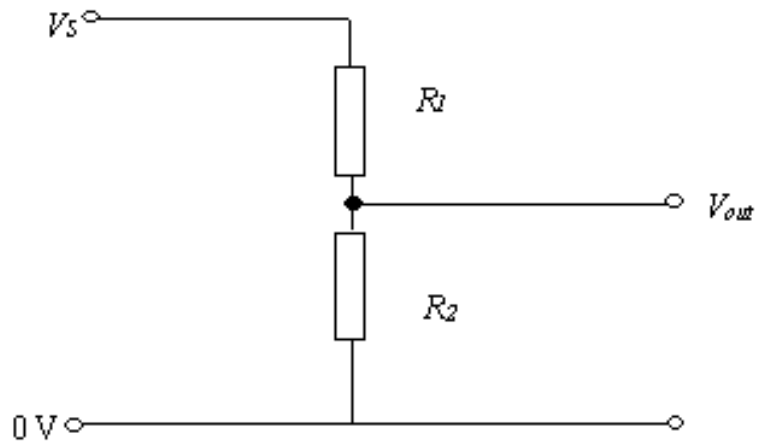
The sensor consists of a length “L” of resistance wire attached across a voltage source “ V_s ”. The wiper is pushed up or down by moving target, for which displacement “x” is required to be measured. V_o is the **output voltage representing displacement in terms of volts** and is given by:

$$V_o = \frac{x}{L} V_s$$



Applications: Potentiometer

- ▶ The **Potential divider** is the most obvious application. In its simplest form it is two resistors in series with an input voltage V_s across the ends.
- ▶ If only two terminals are used, one end and the wiper, it acts as a **variable resistor** or **rheostat**.
- ▶ Potentiometers were formerly used to **control picture brightness, contrast, and color response in Television sets**.
- ▶ Low-power potentiometers, both linear and rotary, are used **to control audio equipment, changing loudness, frequency attenuation** and other characteristics of audio signals.



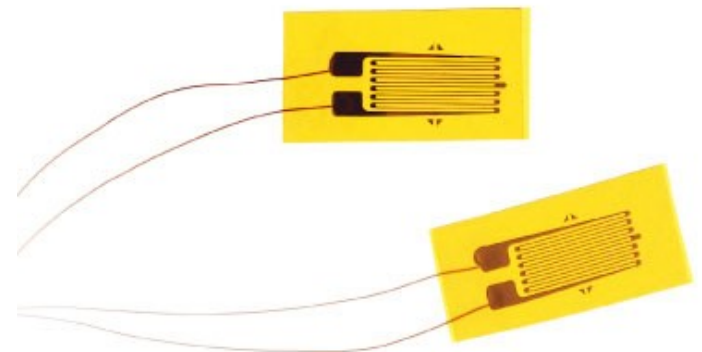
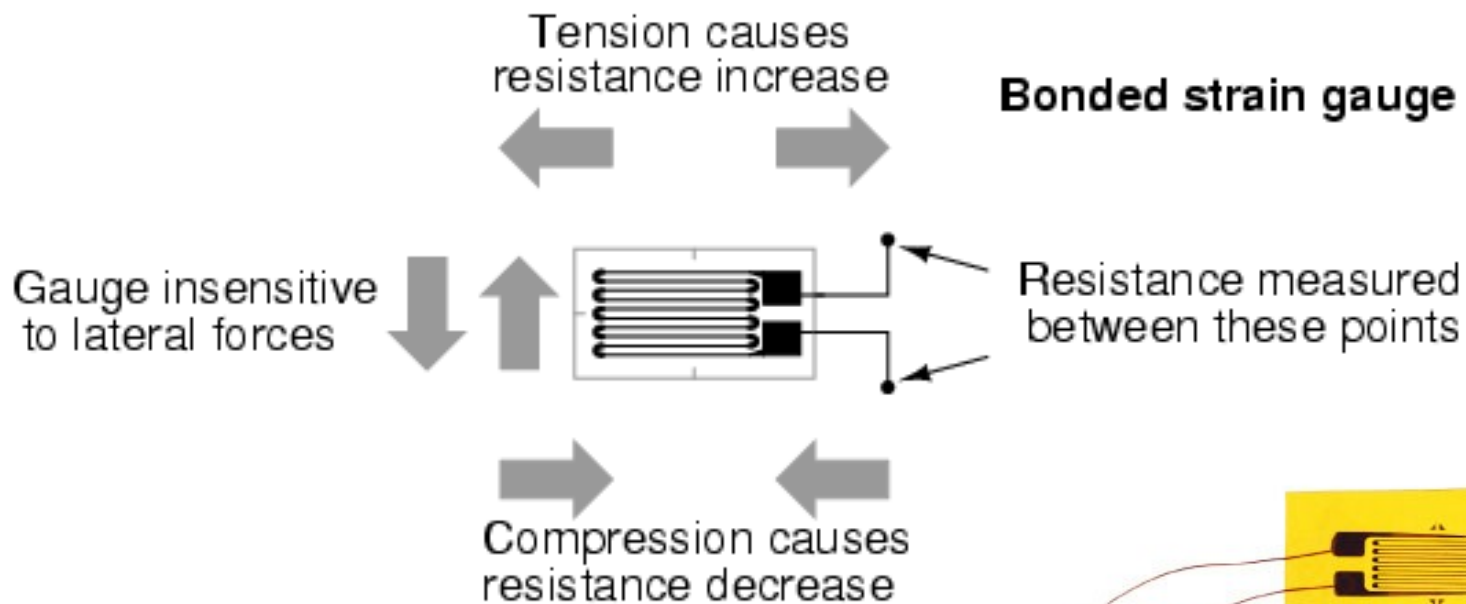
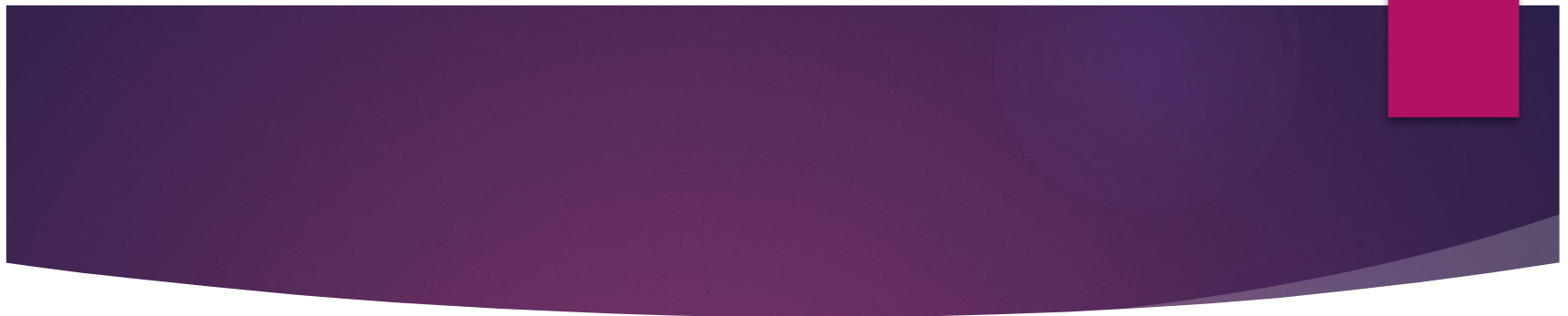
Potential Divider Circuit



Potentiometer

3.4.2 Strain Gauge

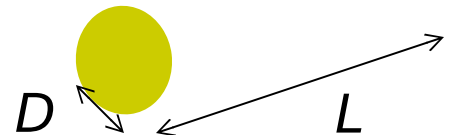
- ▶ If a strip of conductive metal is placed under compressive force , it will broaden and shorten.
- ▶ If these stresses are kept within the elastic limit of the metal strip (so that the strip does not permanently deform), the strip can be used as a measuring element for physical force, the ***amount of applied force inferred from measuring its resistance.***
- ▶ This is the principle of a Strain Gauge.



Strain Gage: Gage Factor

- ▶ Remember: for a strained thin wire
 - ▶ $\frac{DR}{R} = \frac{DL}{L} - \frac{DA}{A} + \frac{Dr}{r}$
 - ▶ $A = (D/2)^2 \pi$, for circular wire
 - ▶ **Poisson's ratio**, m : relates change in diameter D to change in length L
 - ▶ $\frac{DD}{D} = -m \frac{DL}{L}$
 - ▶ Thus
 - ▶ $\frac{DR}{R} = (1+2m) \frac{DL}{L} + \frac{Dr}{r}$
- dimensional effect piezoresistive effect
- ▶ **Gage Factor**, G , used to compare strain-gage materials

$$G = \frac{\frac{DR}{R}}{\frac{DL}{L}} = (1+2m) + \frac{Dr/r}{DL/L}$$



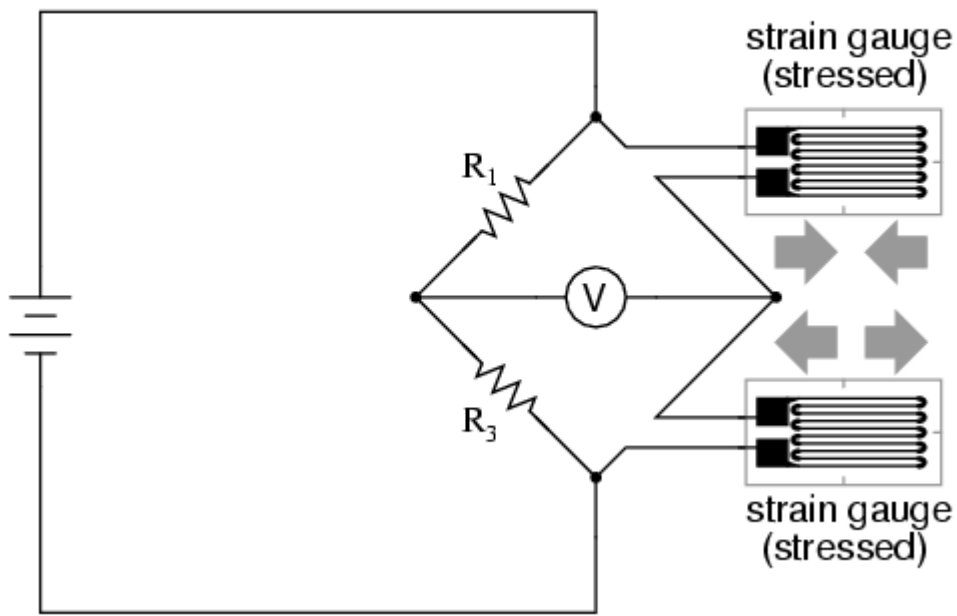
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Alloy 'Advance'; this is 54% copper, 44% nickel and 1% manganese:

- ▶ Gauge factor 2.0 to 2.2
- ▶ Unstrained resistance $120 \pm 1 \Omega$
- ▶ Linearity within $\pm 0.3\%$
- ▶ Maximum tensile strain $+2 \times 10^{-2}$
- ▶ Maximum compressive strain -1×10^{-2}
- ▶ Maximum operating temperature 150°C .
- ▶ The change in resistance at maximum tensile strain is $\Delta R = +4.8 \Omega$, and $\Delta R = -2.4 \Omega$ at maximum compressive strain.
- ▶ A maximum gauge current between 15 mA and 100 mA, depending on area, is specified in order to avoid self-heating effects.

Half Bridge Strain Gauge Circuit

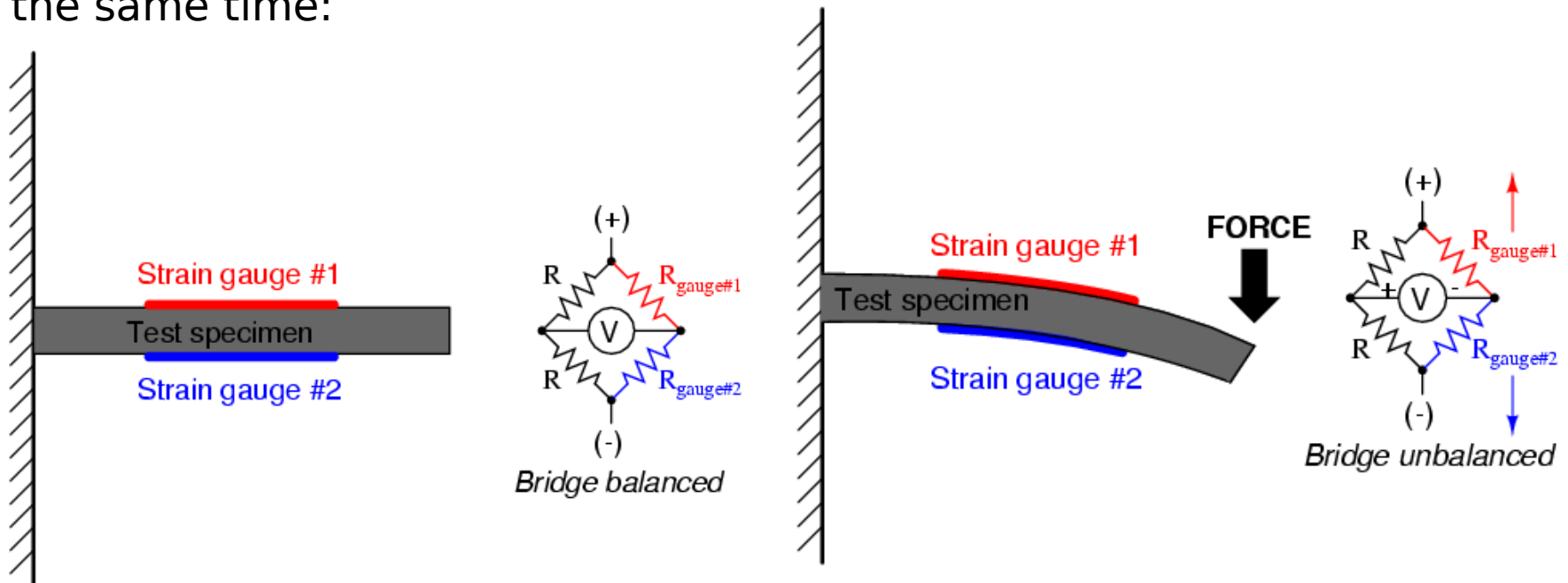
Half-bridge strain gauge circuit



- ▶ Unlike the Wheatstone bridge using a null-balance detector and a human operator to maintain a state of balance, a strain gauge bridge circuit indicates measured strain by the degree of *imbalance*, and uses a precision voltmeter in the center of the bridge to provide an accurate measurement of that imbalance.

Strain Gauge

With no force applied to the test specimen, both strain gauges have equal resistance and the bridge circuit is balanced. However, when a downward force is applied to the free end of the specimen, it will bend downward, stretching gauge #1 and compressing gauge #2 at the same time:



Applications : Strain Gauge

- ▶ to ***measure force and small displacements.***
- ▶ for ***analyzing the dynamic strain*** of complex structures.
- ▶ to ***measure tension, torque*** etc.

Types of strain gauges are:

- (a) Wire strain gauges
- (b) Foil strain gauges
- (c) Thin film
- (d) Semiconductor

3.5 Temperature Transducers

Temperature transducers can be divided into three main categories:

- 3.5.1 Resistance Temperature Detectors (RTD)

- 3.5.2 Thermocouples

- 3.5.3 Thermistor

3.5.1 Resistance Temperature Detector (RTD)

- Detectors of wire resistance temperature common employ platinum, nickel or resistance wire elements, whose resistance variation with temperature has high intrinsic accuracy.
- They are available in many configurations and size and as shielded or open units for both immersion and surface applications.

- 
- ▶ The relationship between temperature and resistance of conductors can be calculated from the equation:

$$R = R_0 (1 + \alpha \Delta T)$$

where

- ▶ R = the resistance of the conductor at temperature t ($^{\circ}\text{C}$)
- ▶ R_0 = the resistance at the reference temperature, usually 20°C
- ▶ α = the temperature coefficient of resistance
- ▶ ΔT = the difference between the operating and the reference temperature

3.5.2 Thermistor

- ❖ A thermistor is a semiconductor made by sintering mixtures of metallic oxide, such as oxides of manganese, nickel, cobalt, copper and uranium.
- ❖ Thermistors have **negative temperature coefficient (NTC)**. That is, their **resistance decreases** as their **temperature rises**.

Types of thermistor

Disc

Washer

Rod

Resistance

1 to 1M Ω

1 to 50k Ω

high resistance

thermistore resistance

$$R_t = R_0 e^{\beta(T_0 - T)/TT_0}$$

β = material constant for thermistor K

(characteristic temperature) 2000~5000K

T_0 = standard reference temperature K

Temperature coefficient $\alpha = \frac{1}{R_t} \frac{dR_t}{dT} = - \frac{\beta}{T^2} (\%/K)$

Advantages of thermistor

- Small size and low cost
- Fast response over narrow temperature range
- Good sensitivity in Negative Temperature Coefficient (NTC) region
- Cold junction compensation not required due to dependence of resistance on absolute temperature.
- Contact and lead resistance problems not encountered due to large resistance

Limitations of thermistor

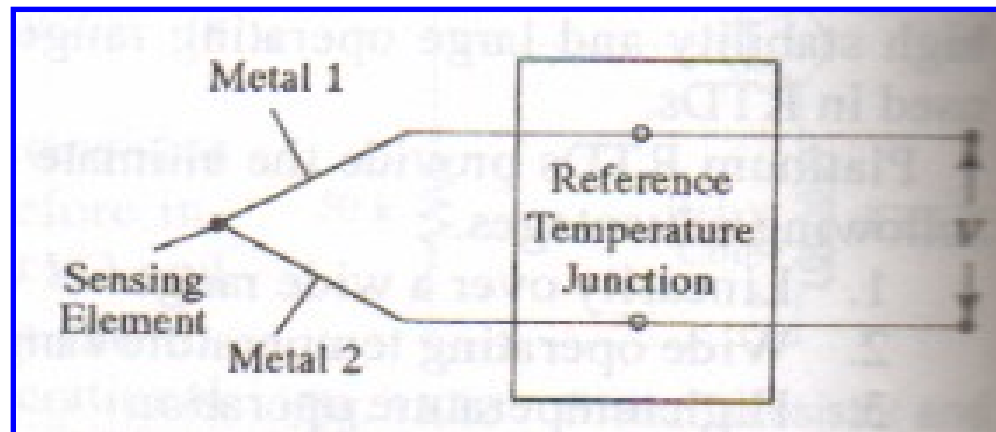
- Non linearity in resistance vs temperature characteristics
- Unsuitable for wide temperature range
- Very low excitation current to avoid self heating
- Need of shielded power lines, filters, etc due to high resistance

Applications of thermistors

- ▶ Measurement of temperature
- ▶ Measurement of Difference of two temperatures
- ▶ Control of temperature
- ▶ Temperature compensation
- ▶ Thermal conductivity measurement.
- ▶ Measurement of Gas Composition
- ▶ Measurement of Flow
- ▶ Current-limiting devices for circuit protection as replacement for fuse (PTC)

3.5.3 Thermocouple

- It consists of two wires of different metals are joined together at one end, **a temperature difference** between this end and the other end of wires **produces a voltage between the wires**.





The magnitude of this voltage depends on

- ▶ the ***materials used*** for the wires and
- ▶ the ***amount of temperature difference*** between the joined ends and the other ends.

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The emf of the thermocouple :

$$E = c(T_1 - T_2) + k(T_1^2 - T_2^2)$$

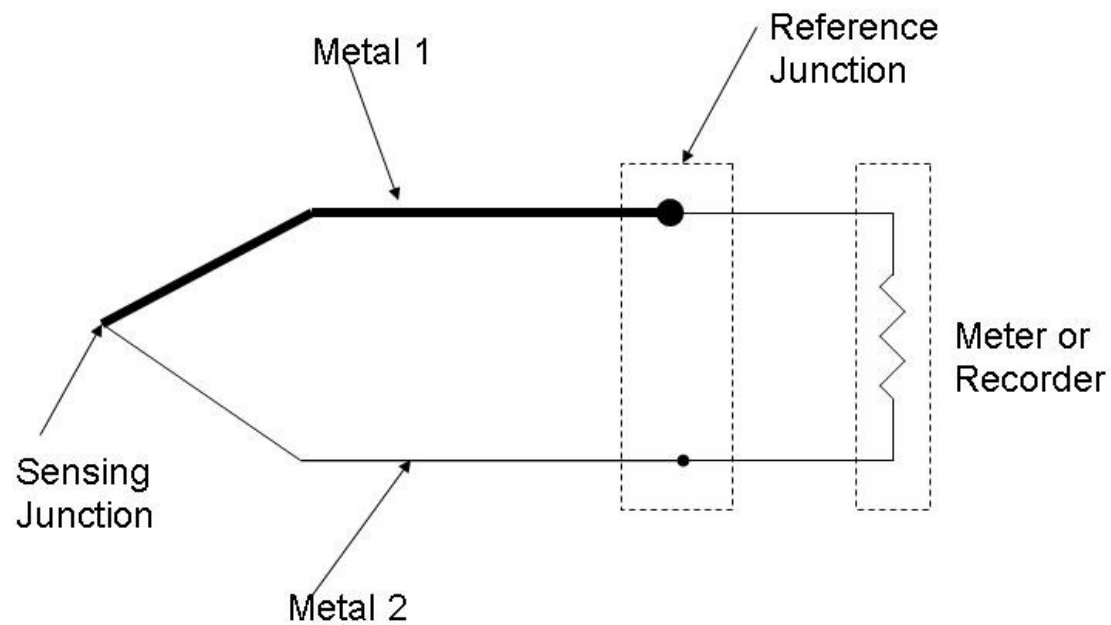
Where

c and k = constant of the thermocouple materials

T_1 = The temperature of the “hot” junction

T_2 = The temperature of the “cold” or “reference” junction

Thermocouple Internal Circuit





Cont..

Thermocouple:

Advantages

Fast response time (T_c : 1 ms)

Small size (Diameter: 12 μm)

Long-term stability

Ease of fabrication

Disadvantages

Small output voltage

low sensitivity

Need for a reference temperature

Applications : Thermocouple

- ▶ Steel Industry
- ▶ Heating Appliance Safety
- ▶ Power Production : Thermoelectric Generation
- ▶ Thermoelectric Cooling
- ▶ Diesel Engines
- ▶ Gas Turbine Exhaust Temperature Measurement



End of Today's class!!

Inductive Transducer

- ✓ Inductive transducers may be either of the self generating or passive type.
- ✓ The self generating type utilises the basic electrical generator principle, i.e, a motion between a conductor and magnetic field induces a voltage in the conductor (generator action). This relative motion between the field and the conductor is supplied by changes in the measurand.
- ✓ An inductive electromechanical transducer is a device that converts physical motion (position change) into a change in inductance. Transducers of variable inductance type work upon one of the following principles:
 1. Variation of self inductance
 2. Variation of mutual inductance

Cont..

- ✓ Inductive transducers are mainly used for the measurement of displacement.
- ✓ The displacement to be measured is arranged to cause variation in any of three variables:
 1. Number of turns
 2. Geometric configuration
 3. Permeability of the magnetic material or magnetic circuits

$$L = n^2 G \mu$$

N: number of turns

G: geometric form factor

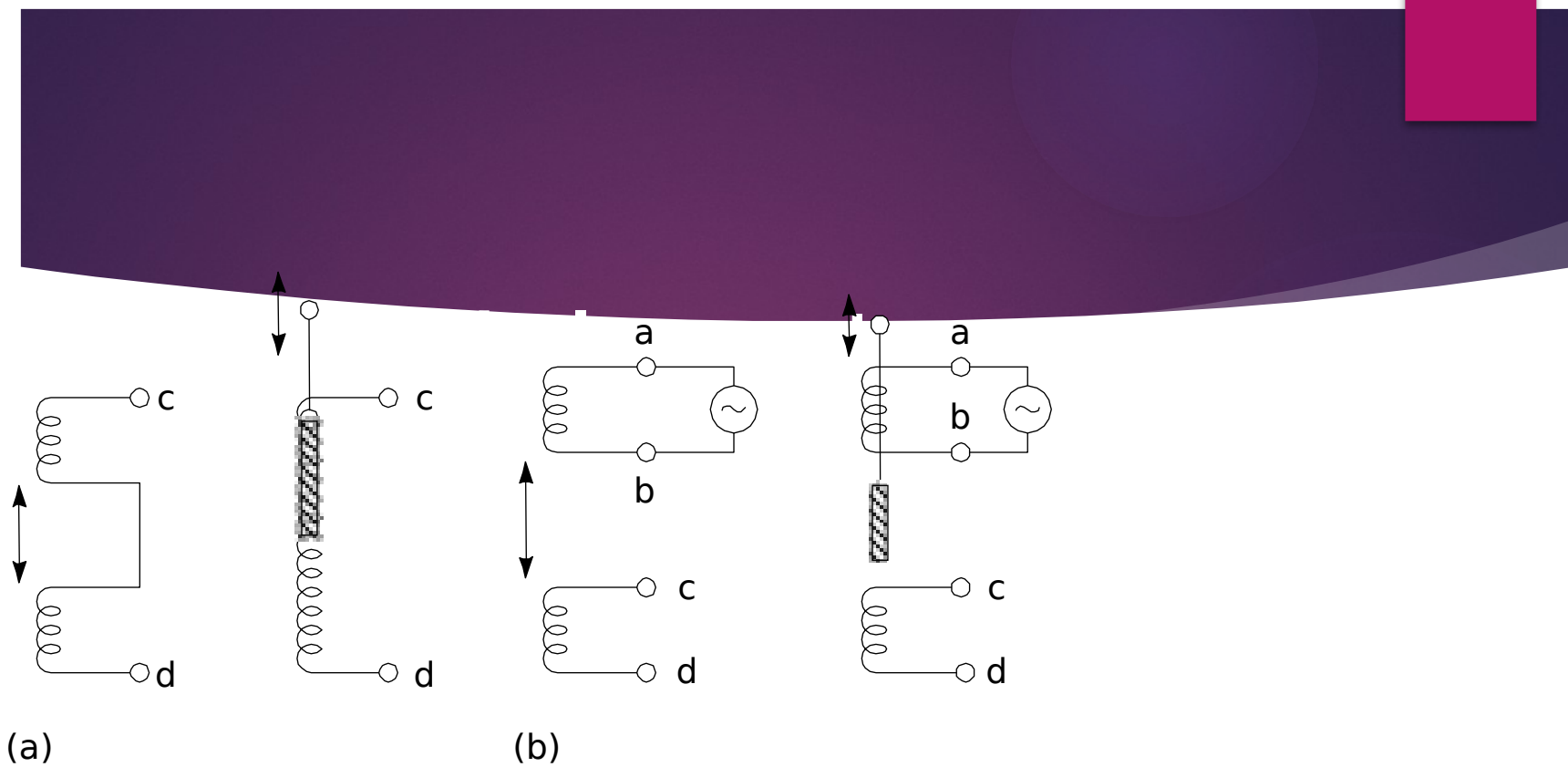
u: effective permeability

Inductive Displacement Sensors

Advantage:	not affected by the dielectric properties of the environment
Disadvantage:	affected by external magnetic field
(a) Self-inductance	
Principle	Changing the geometric form factor or moving a magnetic core within the coil $\Rightarrow$ alteration in self-inductance
Property	Change of inductance vs displacement $\Rightarrow$ not linear
Advantage:	1. Low power requirement 2. produces large variations in inductance
Applications:	radiotelemetry

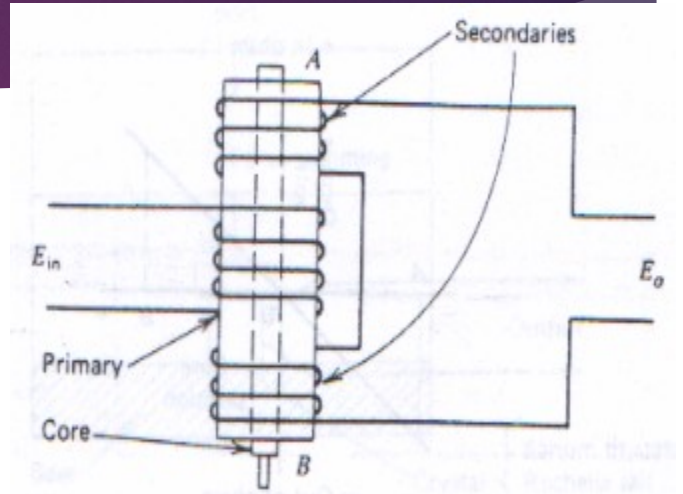
(b) Mutual-inductance

Principle □	Induced voltage in the secondary coil is a function of □ coil geometry (seperation and axial alignment), numbers of primary and secondary turns, frequency and amplitude of the excitation voltage,
Property □	Induced voltage in the 2 nd coil vs coil seperation: nonlinear
Trick □	To maximize the output signal □ choose the resonance frequency of the secondary coil
Applications:	Cardiac dimension, infant respiration, arterial diameter



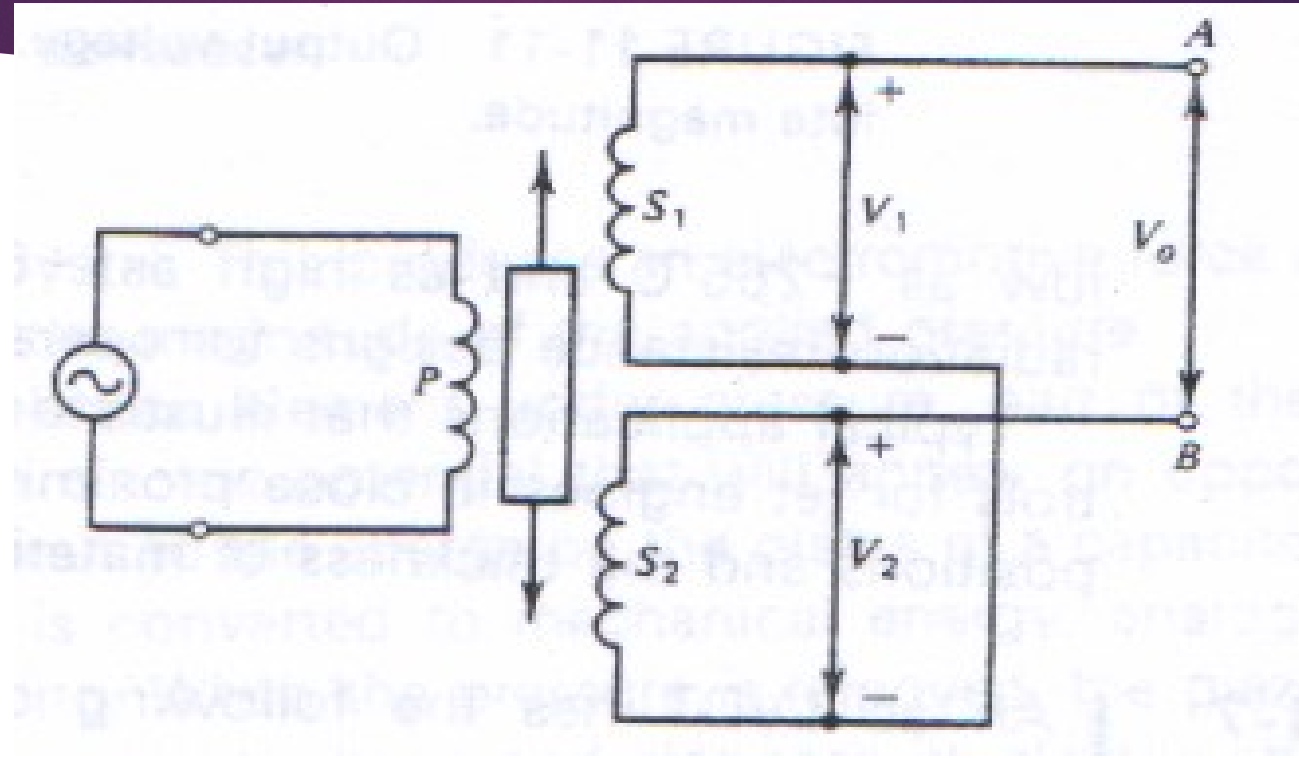
LINEAR VARIABLE DIFFERENTIAL TRANSFORMER (LVDT)

- ✓ It consists basically of a primary winding and two secondary windings, wound over a hollow tube and positioned so the primary winding is between two secondaries. In figure shows the construction of the LVDT.
- An iron core slides within the tube and therefore affects the magnet coupling between the primary and the two secondaries.
- When the core is in the center, voltage induced in the two secondaries is equal. When the core is moved in one direction from center, the voltage induced in one winding is increased and that in the other is decreased. Movement in the opposite direction reverses this effect

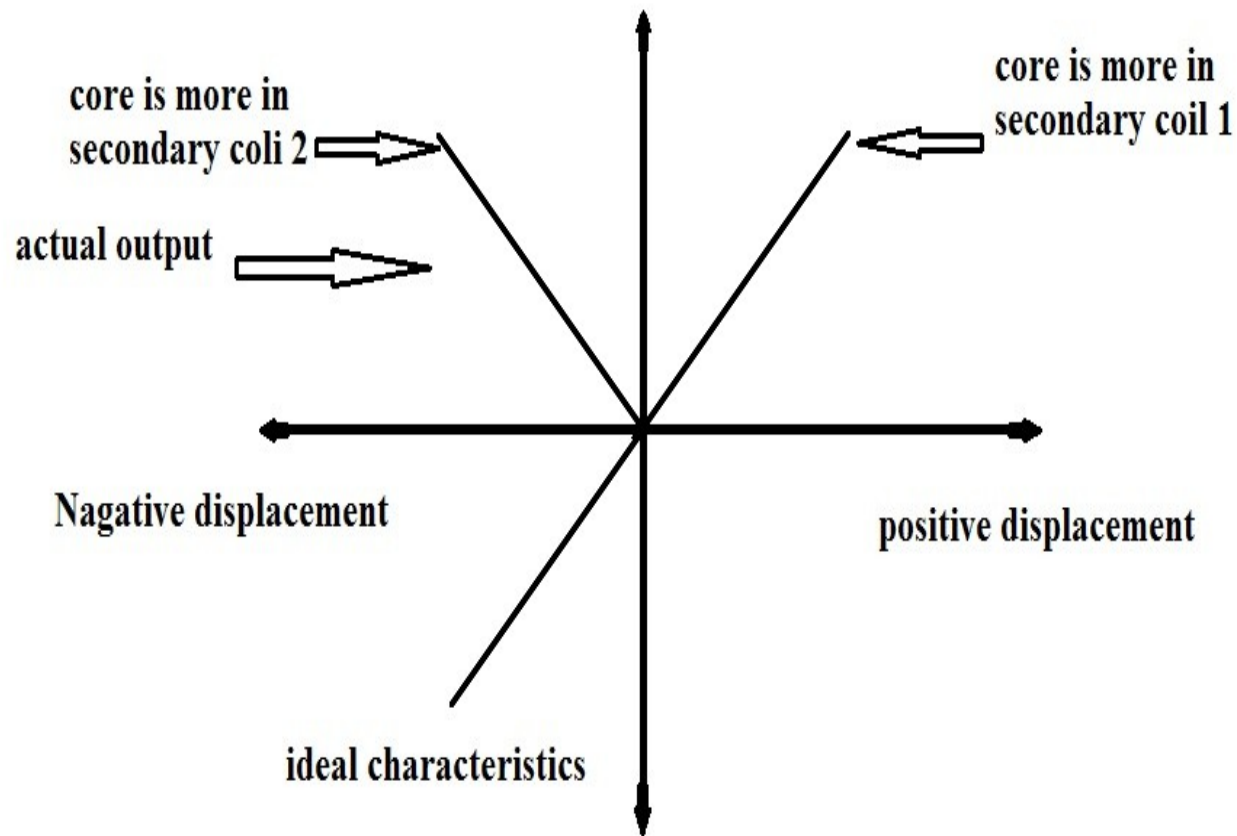


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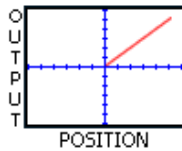
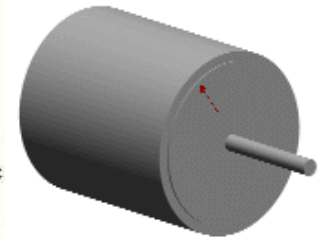
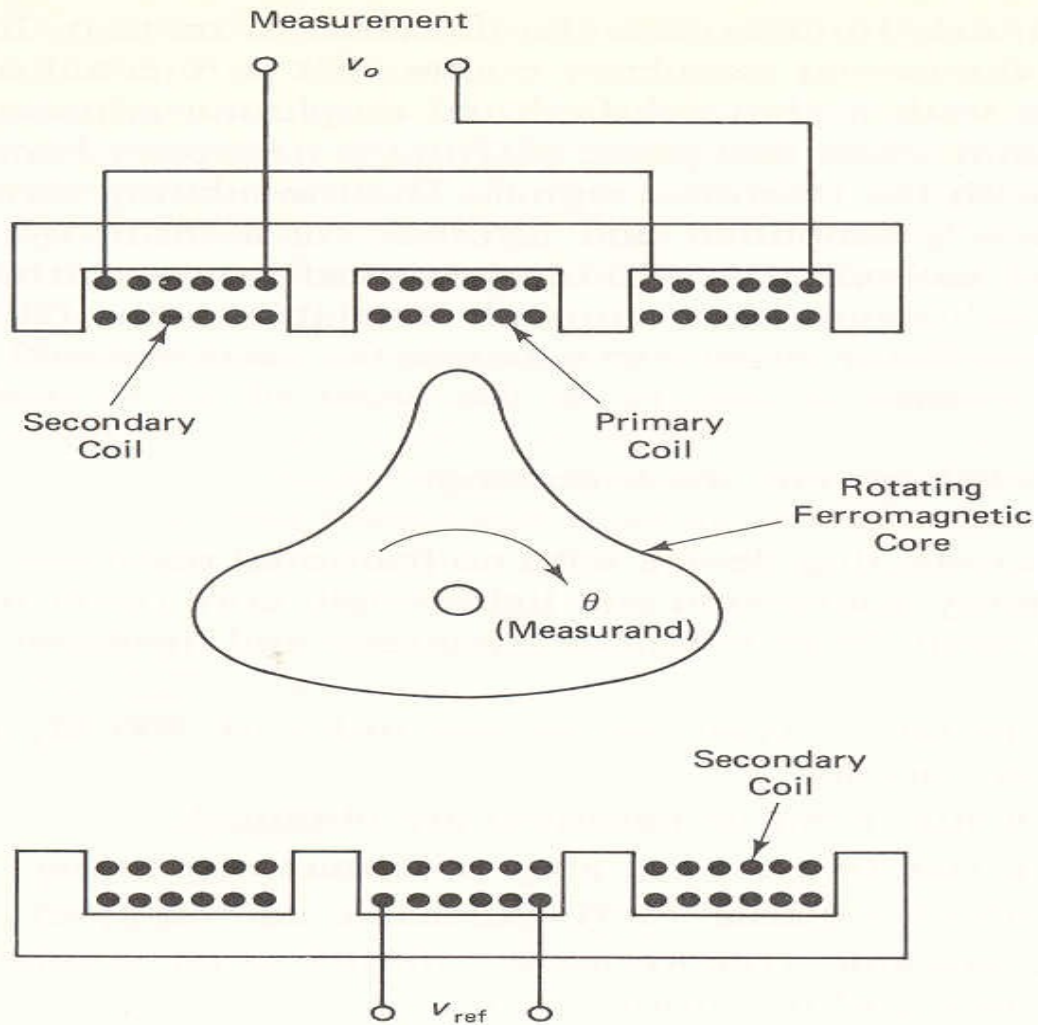
□ Graphical representation



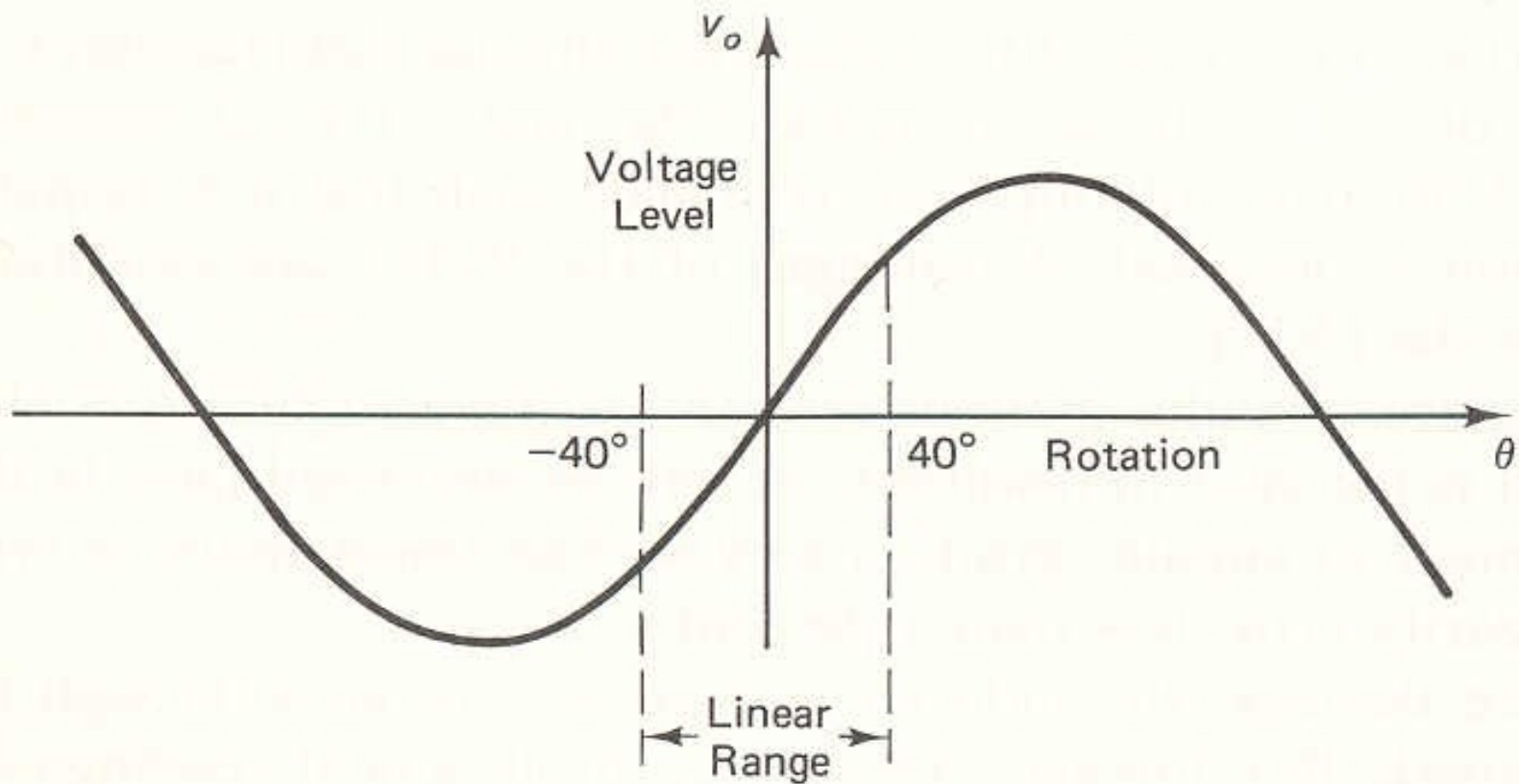
RVDT - Rotary Variable Differential Transformer

- ▶ A variation of the LVDT
- ▶ Intended for angular displacement and rotary position sensing.
- ▶ In all respects it is identical in operation to the LVDT device but the rotary motion imposes certain restrictions on its construction.
- ▶ The span is given in angles and can be up to $\pm 30^\circ$ to $\pm 40^\circ$. Beyond that the output is nonlinear.

RVDT

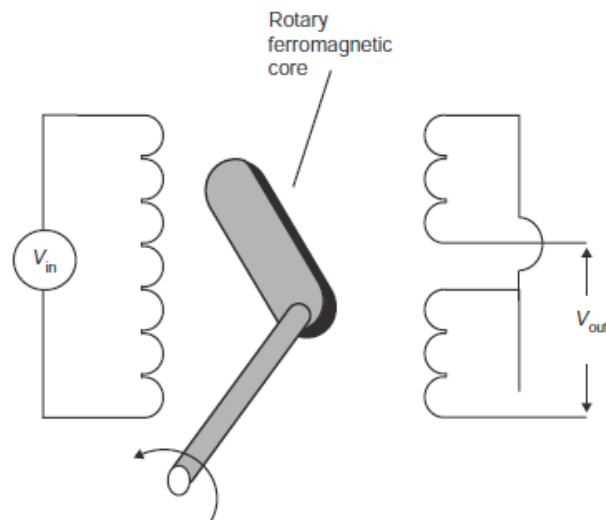


Response of an RVDT



Rotational Displacement

An *RVDT* is an electromechanical transducer that provides a variable alternating current output voltage. This output voltage is linearly proportional to the angular displacement of its input shaft. When energized with a fixed alternating current source, the output signal is linear within a specified range over the angular displacement. RVDT utilizes brushless, noncontacting technology to ensure long life, reliability, and repeatable position sensing with infinite resolution. Such reliable and repeatable performance ensures accurate position sensing under the most extreme operating conditions.



Rotational Displacement

- RVDT transducers with AC output have the basic construction with only the primary and secondary winding inside.



- RVDT transducers with DC signal output have embedded electronics responsible for powering and process the sensor internal signals, converting the detected displacement into a stable DC voltage signal.



Applications of RVDT

- o Tachometers
 - o Magnetic speed sensors
 - o Optical decoders
 - o Variable reluctance tachometers
 - o Accelerometers
 - o Eddy-current tachometers etc.

Capacitive Transducer

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The capacitance of a parallel plate capacitor is given by

$$C = \frac{kA\epsilon_0}{d} \text{ (Farads)}$$

where

- k = dielectric constant
- A = the area of the plate, in m²
- ϵ_0 = 8.854×10^{-12} F/m
- d = the plate spacing in m

CLASSIFICATION OF TRANSDUCERS

According to Transduction Principle

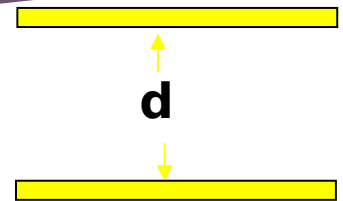
CAPACITIVE TRANSDUCER:

- In capacitive transduction transducers the measurand is converted to a change in the capacitance.
- A typical capacitor is comprised of two parallel plates of conducting material separated by an electrical insulating material called a dielectric. The plates and the dielectric may be either flattened or rolled.
- The purpose of the dielectric is to help the two parallel plates maintain their stored electrical charges.
- The relationship between the capacitance, size of capacitor plate, amount of plate separation and the dielectric is given by

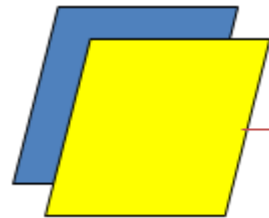
$$C = \epsilon_0 \epsilon_r A / d$$

d is the separation distance of plates (m)

C is the capacitance (F, Farad)



Area=A



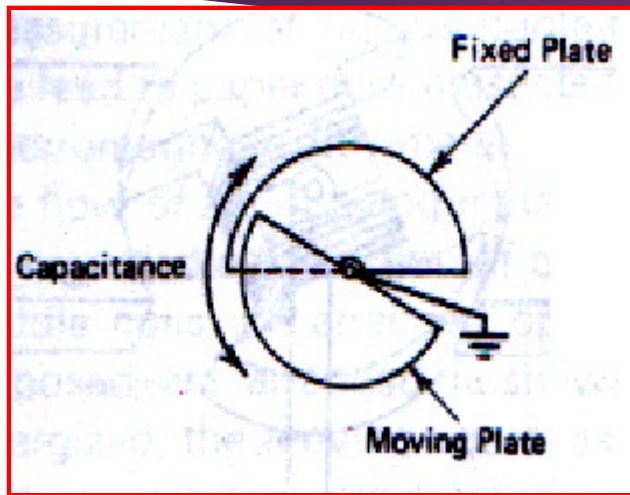
Either A , d or ϵ can be varied.



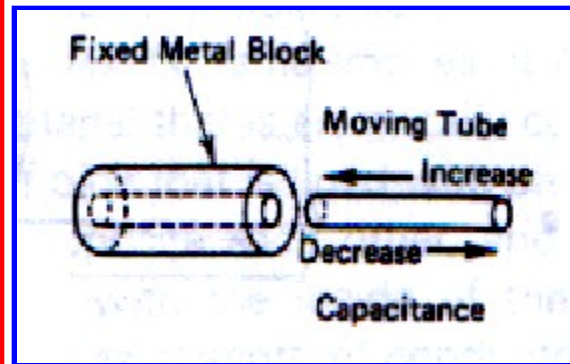
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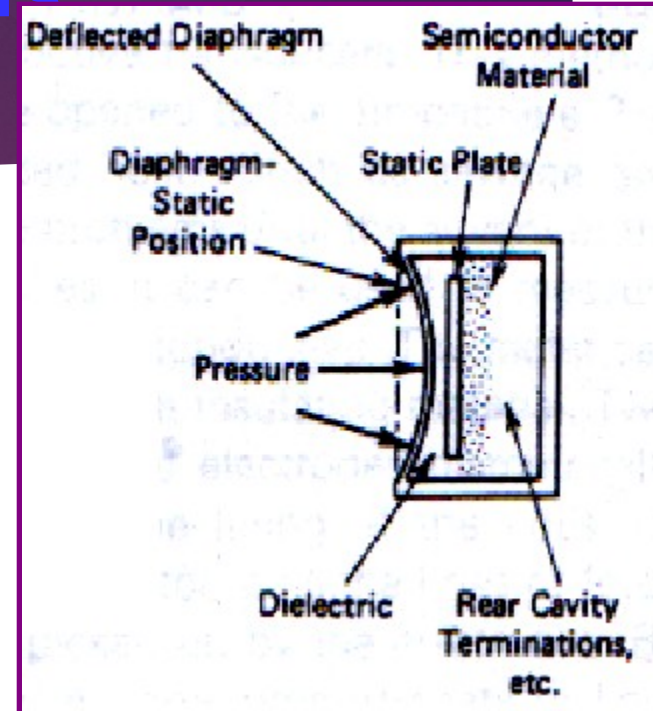
Forms of Capacitance Transducers



Rotary plate capacitor

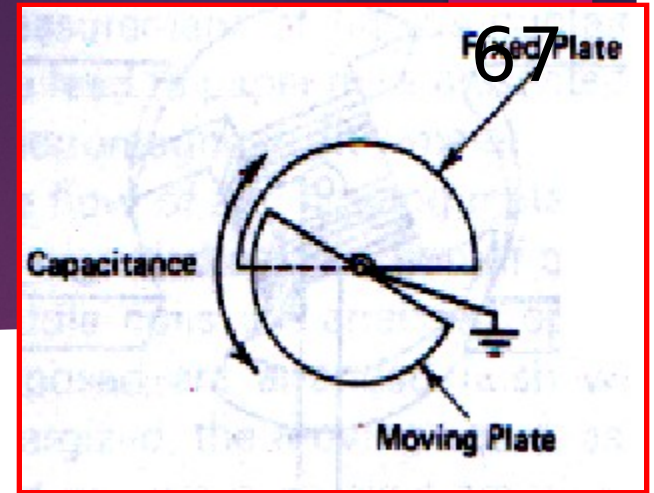


Rectilinear Capacitance Transducer



Thin diaphragm

Cont'd



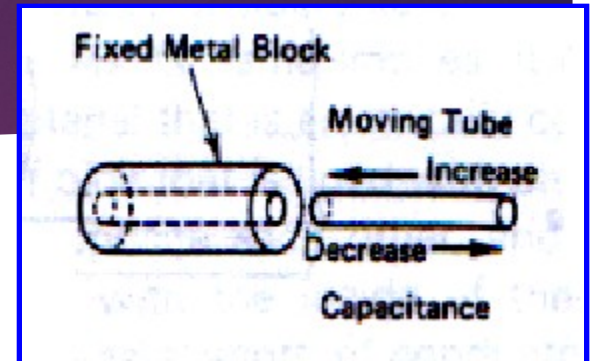
Rotary plate capacitor:

The capacitance of this unit proportional to the amount of the fixed plate that is covered, that shaded by moving plate. This type of transducer will give sign proportional to curvilinear displacement or angular velocity.

Cont'd

Rectilinear capacitance transducer:

It consists of a fixed cylinder and a moving cylinder. These pieces are configured so the moving piece fits inside the fixed piece but insulated from it.

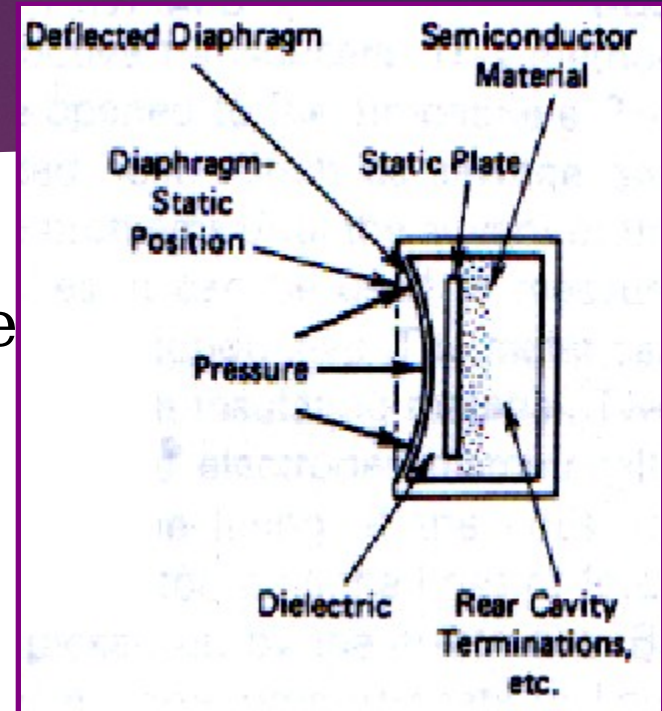


Cont'd

Thin diaphragm:

A transducer that varies the spacing between surfaces. The dielectric is either air or vacuum.

Often used as Capacitance microphones.



Advantages:

1. Has excellent frequency response
2. Can measure both static and dynamic phenomena.

Disadvantages:

3. Sensitivity to temperature variations
4. the possibility of erratic or distortion signals owing to long lead length

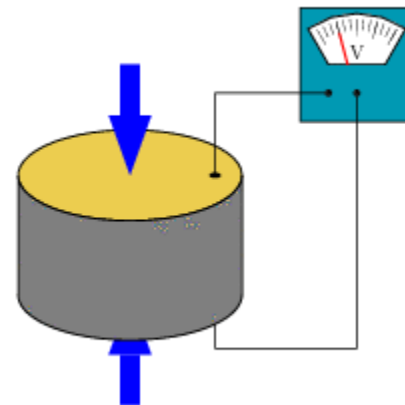
Applications:

5. As frequency modulator in RF oscillator
6. In capacitance microphone
7. Use the capacitance transducer in an ac bridge circuit

Piezoele ctric transduc er

PIEZO ELECTRIC INDUCTION :

- In piezoelectric induction the measurand is converted into a change in electrostatic charge q or voltage V generated by crystals when mechanically it is stressed as shown in fig.



Piezoelectric Effect

- ▶ Appearance of an electric potential across certain faces of a crystal when it is subjected to mechanical pressure
- ▶ The word originates from the Greek word “piezein”, which means “to press”
- ▶ Discovered in 1880 by Pierre Curie in quartz crystals.
- ▶ Conversely, when an electric field is applied to one of the faces of the crystal it undergoes mechanical distortion.
- ▶ Examples --- Quartz, Barium titanate, tourmaline

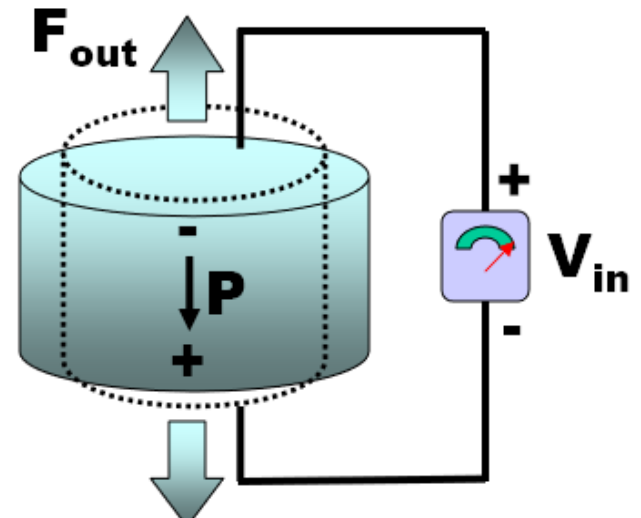
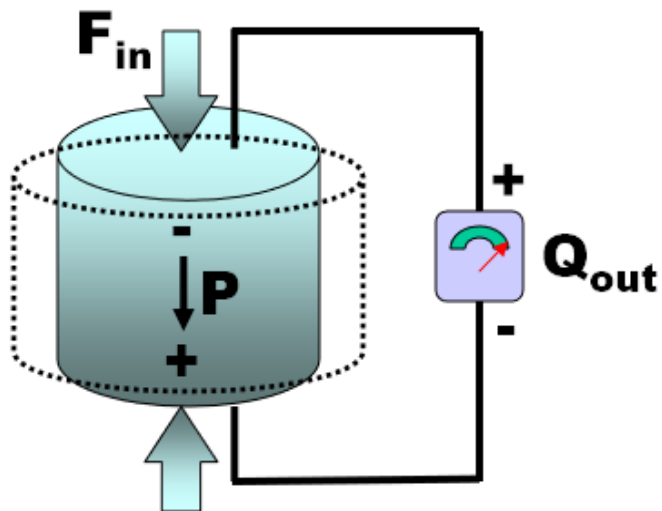
Jacques & Pierre Curie (1880)

Lippmann (1881)

**Electrical
Energy**



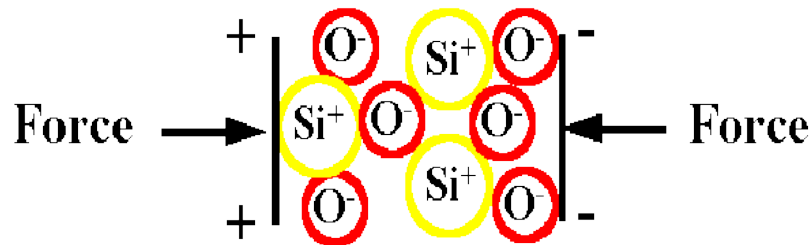
**Mechanical
Energy**



Internal working

- ▶ The effect is explained by the displacement of ions in crystals that have a nonsymmetrical unit cell
- ▶ When the crystal is compressed, the ions in each unit cell are displaced, causing the electric polarization of the unit cell.
- ▶ Because of the regularity of crystalline structure, these effects accumulate, causing the appearance of an electric potential difference between certain faces of the crystal.
- ▶ When an external electric field is applied to the crystal, the ions in each unit cell are displaced by electrostatic forces, resulting in the mechanical deformation of the whole crystal.

Piezoelectricity

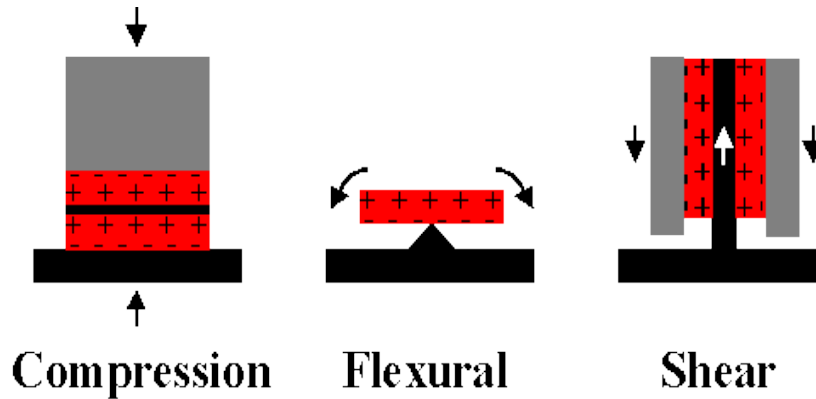


- ▶ displacement of electrical charge due to the deflection of the lattice in a naturally piezoelectric quartz crystal
- ▶ The larger circles represent silicon atoms, while the smaller ones represent oxygen.
- ▶ Quartz crystals is one of the most stable piezoelectric

Artificial materials

- ▶ polycrystalline, piezoceramics are man made materials which are forced to become piezoelectric by applying large electric field.
- ▶ high charge sensitivity
- ▶ materials available which operate at 1000 F (540 C)
- ▶ characteristics vary with temperature

Configurations



- Red indicates the crystal
- Arrows indicate the direction of applied force
- the compression design features high rigidity, making it useful for implementation in high frequency pressure and force sensors

Pros

- ▶ Have a high Stiffness value and produce a high output with very little strain.
- ▶ Ideal for rugged use.
- ▶ Excellent linearity over a wide amplitude.
- ▶ Ideal for continuous online condition monitoring smart systems.

Cons

- ▶ Can be used only for dynamic pressure sensing as in case of static sensing the signals will decay away.
- ▶ Operation over long cables may affect frequency response and introduce noise and distortion, the cables need to be protected.



Thank you