Basic Sensors and Principles

❑ Transducer, Sensor, and Actuator

Transducer: a device that converts energy from one form to another

Sensor: converts a physical parameter to an electrical output (a type of transducer, e.g. a microphone)

Actuator: converts an electrical signal to a physical output (opposite of a sensor, e.g. a speaker)

Examples of Sensors used in Biomedical Instruments

- Some types of sensors used in clinical and laboratory interest are summarized in the table below.

Sensor type	Sensing element	Example
Thermal	Thermocouple, thermistor	Electronic thermometer
Mechanical	Strain gauge, piezoelectric sensor	Pressure transducer
Electrical	Electrode	Electrocardiograph (ECG), electroencephalograph (EEG)
Chemical	Electrode	pH meter
Optical	Photodiode, photomultiplier	Pulse oximeter

- Examples of sensors used in typical medical instruments.

Input	Instrument	Sensor	Output	Range*
Temperature	Oral digital thermometer	Thermistor	Temperature display	32–40°C
Blood pressure	Digital sphygmomanometer	Stethoscope or strain gauge	Pressure	0–400 mmHg
Blood oxygen	Pulse oximeter	Photodiode	Percent oxygen saturation	0–100% SpO_2
Biopotentials				
Cardiac biopotentials	Electrocardiograph (ECG)	Skin electrodes	Electrocardiogram	0.5–5 mV
Neural biopotentials	Electroencephalograph (EEG)	Scalp electrodes	Electroencephalogram	5–300 mV
Retinal biopotentials	Electroretinograph (ERG)	Contact lens electrodes	Electroretinogram	0–900 mV
Muscle biopotential	Electromyograph (EMG)	Needle electrodes	Electromyograrn	0.1–5 mV

* Information on the range of measured values from Webster JG. *Bioinstrumentation*. Hoboken, NJ: John Wiley & Sons; 2003.

→Sensor Terminology

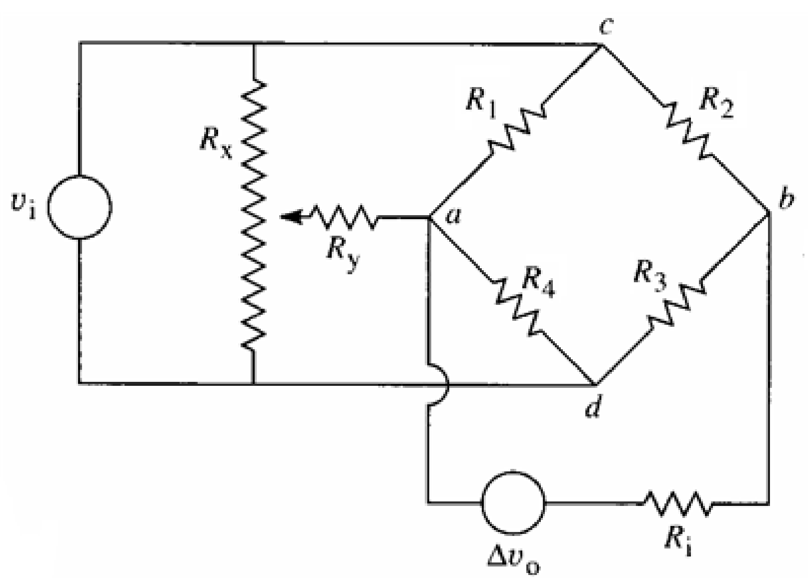
1. **Sensitivity**
2. **Sensitivity Error**
3. **Range**
4. **Dynamic Range**
5. **Precision**
6. **Resolution**
7. **Accuracy**
8. **Offset**
9. **Linearity**
10. **Hysteresis**
11. **Response time**
12. **Dynamic linearity**
13. **Transfer function**
14. **Noise**
15. **Bandwidth**

The Wheatstone Bridge

- Many biomedical passive transducers/sensors are used in a circuit configuration called a ***Wheatstone bridge***.

- The Wheatstone bridge circuit is <u>ideal for measuring small changes</u> in resistance.

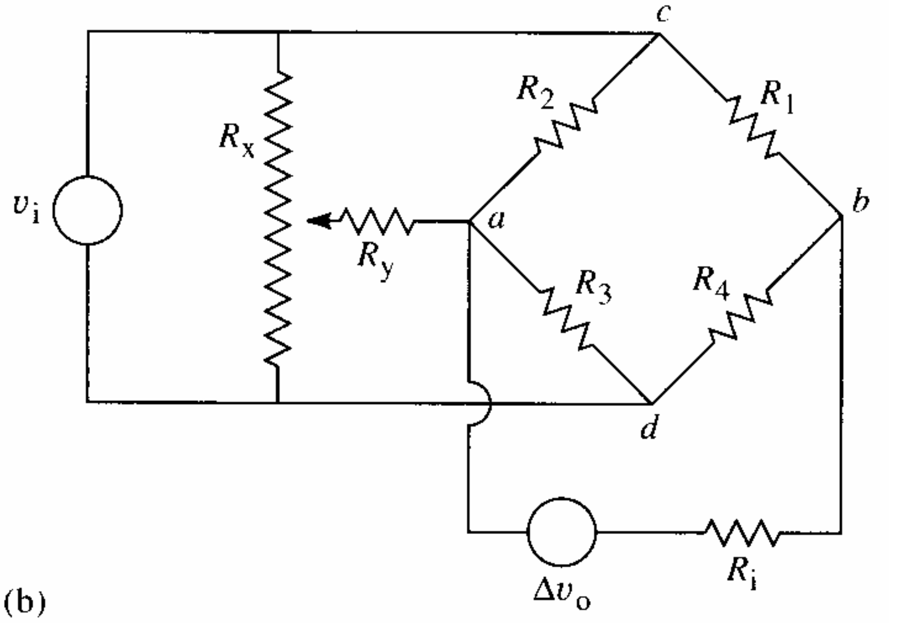
- The Wheatstone bridge can be viewed as two resistor voltage dividers connected in parallel with the voltage source V_i.



Δv_o is zero when the bridge is balanced- that is when $R_1 / R_2 = R_4 / R_3$

If all resistor has initial value R_0 then if R_1 and R_3 increase by ΔR, and R_2 and R_4 decreases by ΔR, then

$$\Delta v_0 = \frac{\Delta R}{R_0} v_i$$



(b)

Proof:

- If all resistor has initial value R_0 then if R_1 and R_3 increase by ΔR, and R_2 and R_4 decreases by ΔR, then

$$V_o = V_i\left(\frac{R_4}{R_1+R_4} - \frac{R_3}{R_2+R_3}\right)$$

$$V_o = V_i\left(\frac{R_0-\Delta R}{R_0+\Delta R+R_0-\Delta R} - \frac{R_0+\Delta R}{R_0-\Delta R+R_0+\Delta R}\right)$$

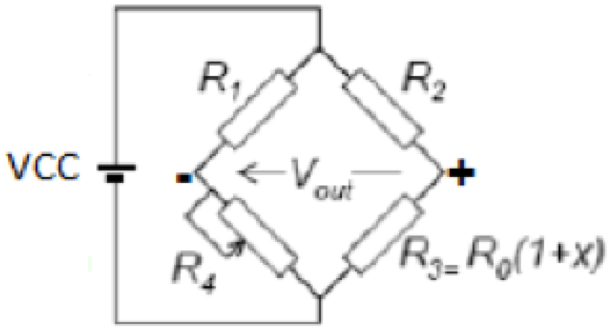
$$V_o = V_i\left(\frac{R_0-\Delta R}{2R_0} - \frac{R_0+\Delta R}{2R_0}\right)$$

$$V_o = V_i\left(\frac{2\Delta R}{2R_0}\right)$$

$$\Delta V_o = \frac{\Delta R}{R_0}V_i$$

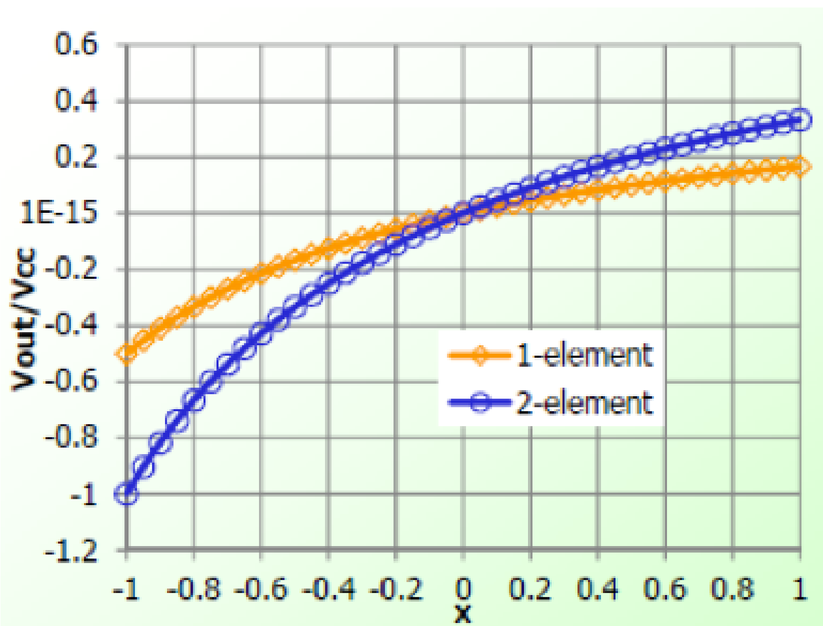
Wheatstone Bridge

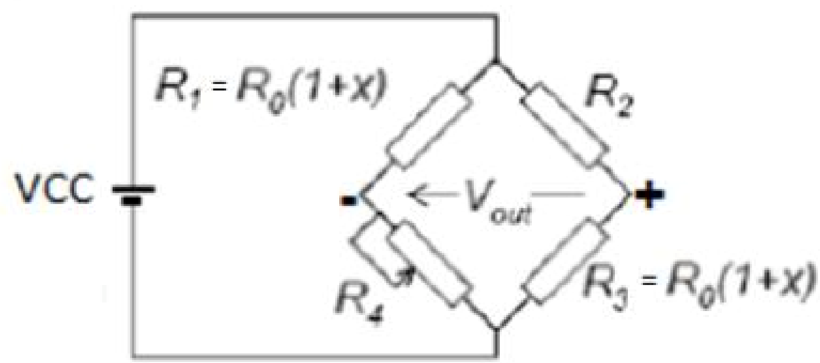
- Single sensor element bridge configuration
  - $R_3 = R_o(1+x)$, x: fractional changes in resistance sensor
  - If $R_1 = R_4$, $V_{out-} = \frac{V_{CC}}{2}$
  - If $R_2 = R_o$, $V_{out+} = V_{CC}\left(\frac{R_o(1+x)}{R_o(2+x)}\right)$
    - V_{out+} increases as x increseas
    - $V_{out+} = V_{CC}/2$ when x=0
    - $V_{out+} = V_{CC}$ when x=∞
  - V_{out-} is same only V_{out+} increases with x
    - $V_{out} = V_{CC}\left(\left(\frac{1+x}{2+x}\right) - \frac{1}{2}\right)$



Wheatstone Bridge

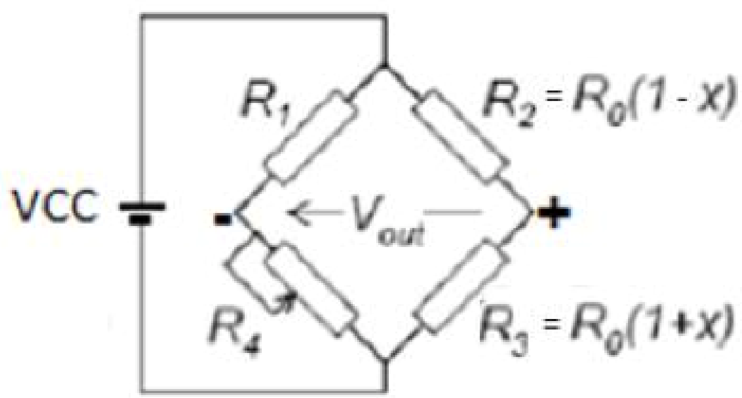
- Two sensor element bridge configuration (half bridge circuit)
  - R_1 and R_3 increases/decreases together
  - If $R_2 = R_4 = R_o$ and $R_1 = R_3 = R_o(1 + x)$
    - $V_{out-} = \frac{V_{CC}}{(2+x)}$ and $V_{out+} = V_{CC}\left(\frac{(1+x)}{(2+x)}\right) \rightarrow V_{out} = V_{CC}\left(\frac{x}{2+x}\right)$
    - Increasing positive values of a x cause V_{out} to become more positive





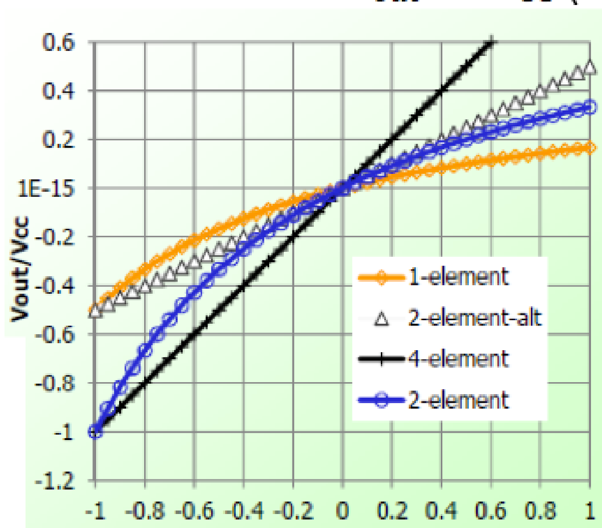
Wheatstone Bridge

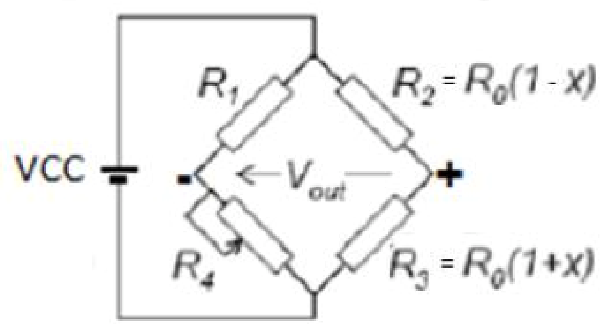
- Alternative half bridge circuit
  - $R_1 = R_4,\ \ R_3$ increases when R_2 decreases and vice versa
  - If $R_1 = R_4 = R_o, R_3 = R_o(1+x)$ and $R_2 = R_o(1-x)$
    - $V_{out-} = \frac{V_{CC}}{2}$ and $V_{out+} = V_{CC}\left(\frac{1+x}{2}\right) \rightarrow V_{out} = V_{CC}\left(\frac{1+x}{2} - \frac{1}{2}\right)$
    - Increasing positive values of a x cause V_{out} to become more positive



Wheatstone Bridge

- Four sensor elements bridge circuit (full bridge circuit)
  - R_1 & R_3 increase/decrease together
  - R_2 & R_4 decrease/increase together
    - change opposite of R_1 & R_3
  - If $R_1 = R_3 = R_o(1 + x)$ and $R_2 = R_4 = R_o(1 - x)$
    - $V_{out-} = V_{CC}\left(\frac{1-x}{2}\right)$ and $V_{out+} = V_{CC}\left(\frac{1+x}{2}\right)$ → $V_{out} = V_{CC}(1 + x)$





- Useful for temperature compensation

  - When all R's from same material, TCR (Temperature Coefficient of Resistivity) of all elements cancel → no change in output voltage

Strain Gauge

- Strain gauges are displacement-type transducers that measure changes in the length of an object as a result of an applied force.
- A strain gauge is a resistive element that produces a change in its resistance proportional to an applied mechanical strain.
- A strain is a force applied in either compression (a push along the axis to-word the center) or tension (a pull along the axis away from the center).
- **The piezoresistive effect** describes change in the electrical resistivity of a semiconductor when mechanical stress (force) is applied.

→Mechanism for Piezoresistivity

Figure (a): **shows a small metallic bar with no force applied.**

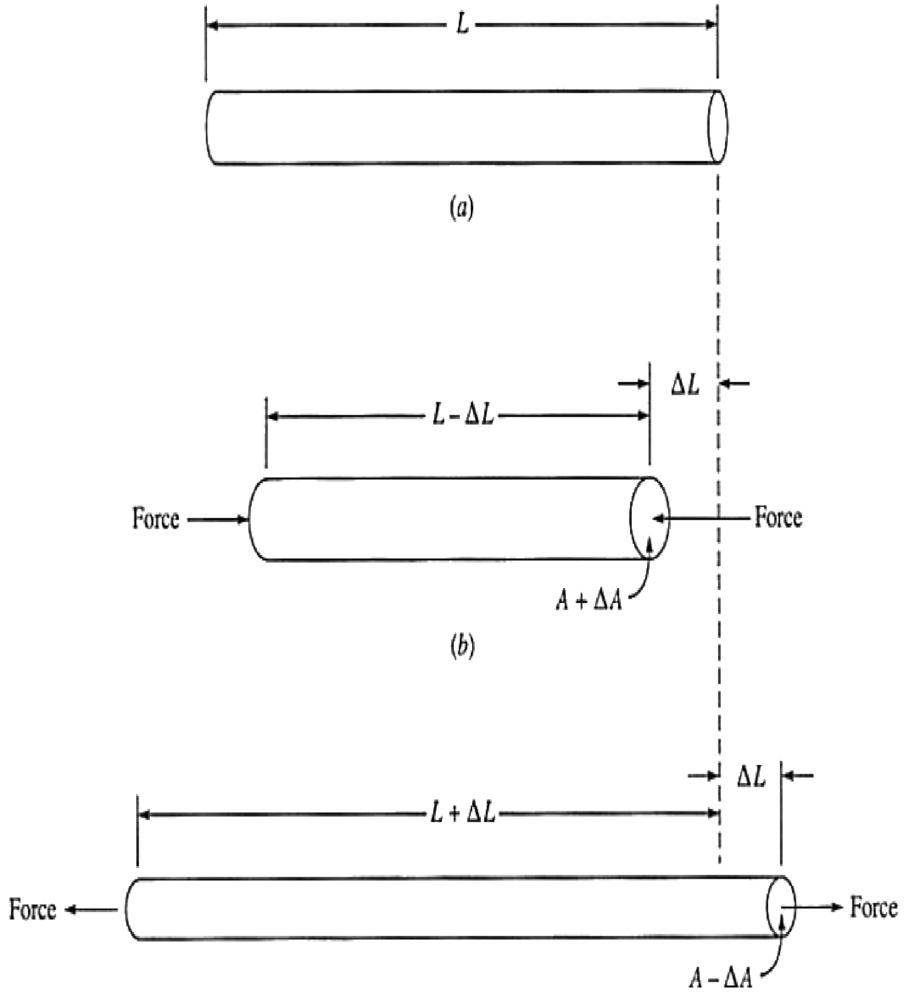
- It will have a length ***L*** and a cross-sectional area ***A***.
- Changes in length are given by ***ΔL*** and changes in area are given by ***ΔA***.

Figure (b): **shows the result of applying a compression force to the ends of the bar.**

- The length reduces to ***L – ΔL***, and the cross-sectional area increases to ***A* + *ΔA***.

Figure (c): **shows the result of applying a tension force of the same magnitude to the bar.**

- The length increases to ***L* + *ΔL***, and the cross-sectional area reduces to ***A – ΔA***.



→Strain Gauge Resistance

- The resistance of a metallic bar is given in terms of the length and cross-sectional area in the expression as;

Where;

$$R = \rho\left(\frac{L}{A}\right)$$

ρ is the resistivity constant of the material in ohm-meter (Ω-m)
L is the length in meters (m)
A is the cross-sectional area in square meters (m^2)

- The above equation shows that the resistance is directly proportional to the length and inversely proportional to the square of the cross-sectional area.

Types of Strain Gauges

- Strain gauges typically fall into two categories:

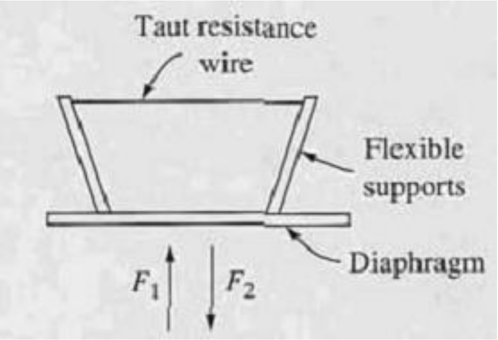
1. **Unbonded Strain Gauge**
2. **Bonded Strain Gauge**

→Unbonded Strain Gauge

- The resistance element is a thin wire of a special alloy that is stretched taut between two flexible supports, which are in turn mounted on a thin metal diaphragm.

- When a force such as F1 is applied, the diaphragm will flex in a manner that spreads the supports further apart, causing an increased tension in the resistance wire.

- This tension tends to <u>increase the resistance of the wire</u> in an amount proportional to the applied force.

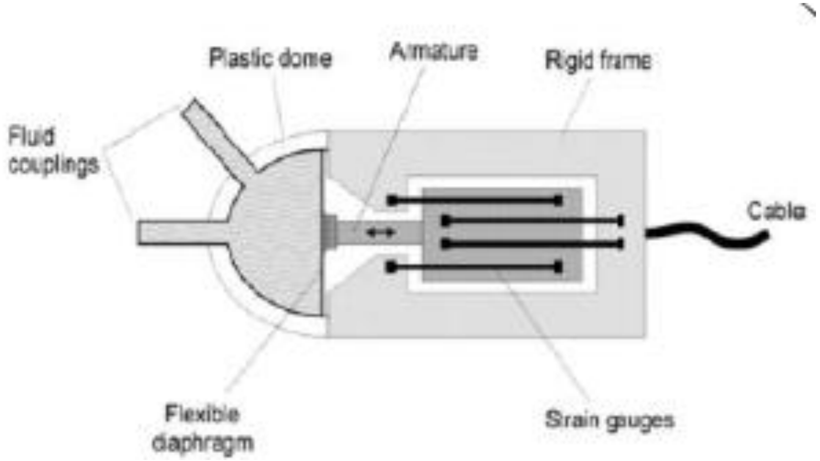


Cont…

- Similarly, if a force such as F2 is applied to the diaphragm, the ends of the supports move closer together, reducing the tension in the taut wire.

- The electrical resistance in this case will reduce in an amount proportional to the applied force

- **This configuration is used in blood pressure transducers.**

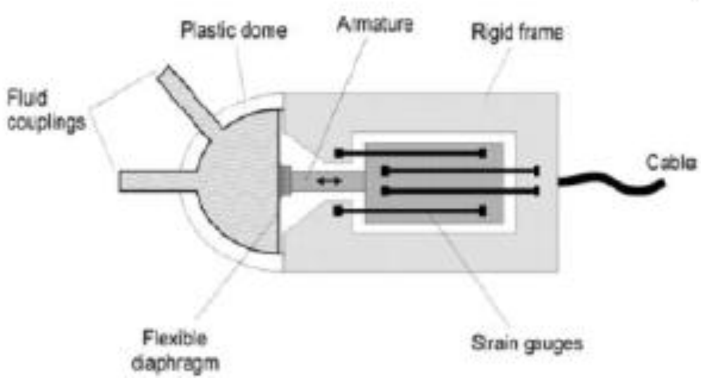


- In this arrangement, a diaphragm is coupled directly by an armature to a movable frame that is inside the transducer.

- Blood in a peripheral vessel is coupled through a thin fluid-filled (saline) catheter to a disposable dome that is sealed by the flexible diaphragm.

- Changes in blood pressure during the pumping action of the heart apply a force on the diaphragm that causes the movable frame to move from its resting position.

- This movement causes the strain gauge wires to stretch or compress and results in a cyclical change in resistance that is proportional to the pulsatile blood pressure measured by the transducer.

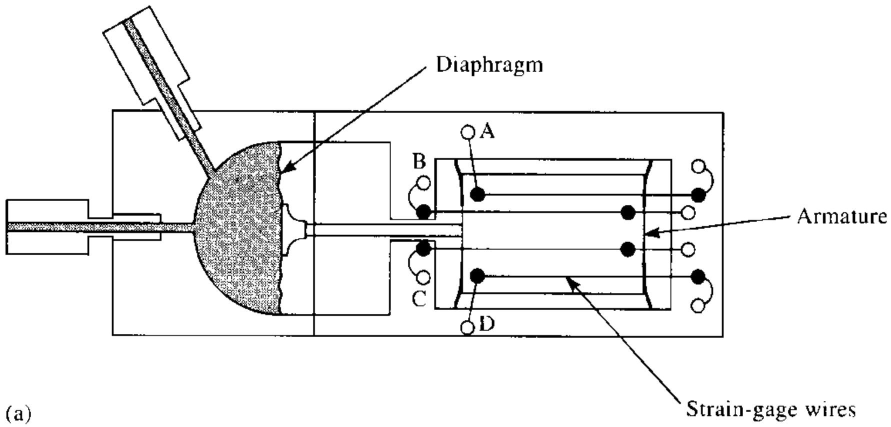


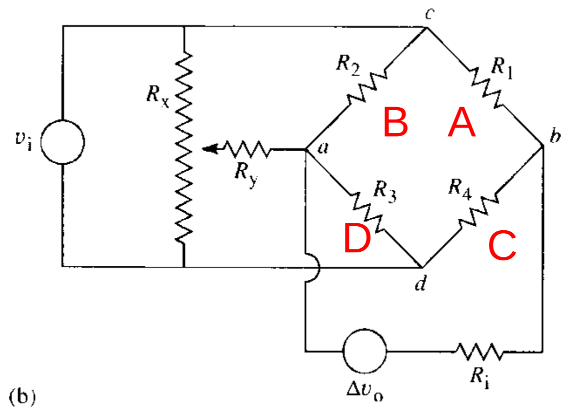
- An unbonded strain gages consists of multiple resistive wires (typically four) stretched between a fixed and a movable rigid frame.

- In this configuration, when a deforming force is applied to the structure, two of the wires are stretched, and the other two are shortened proportionally.

- With increasing pressure, the strain on gage pair B and C is increased, while that on gage pair A and D is decreased.

- Initially before any pressure $R_1 = R_4$ and $R_3 = R_2$

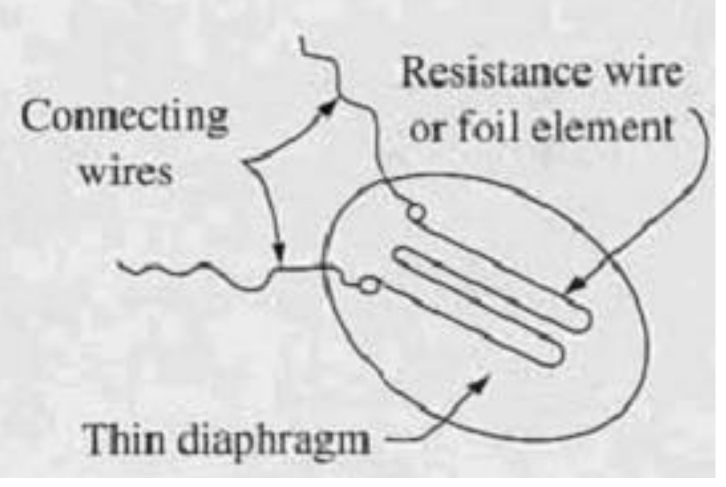




Wheatstone Bridge

→Bonded Strain Gauge

- A bonded strain gauge is made by cementing a thin wire or foil element to a diaphragm.
- Flexing the diaphragm deforms the element and led to a change in electrical resistance exactly as in the unbonded strain gauge.



Potentiometer Transducers

- A ***potentiometer*** is a resistive-type transducer that converts either linear or angular displacement into an output voltage by moving a sliding contact along the surface of a resistive element.

- A voltage $\boldsymbol{V}_i$ is applied across the resistor ***R*** (at terminal ***a*** and ***b***). The output voltage $\boldsymbol{V_o}$ between the sliding contact (terminal ***c***) and one terminal of the resistor (terminal ***a*** or ***b***) is linearly proportional to the displacement.

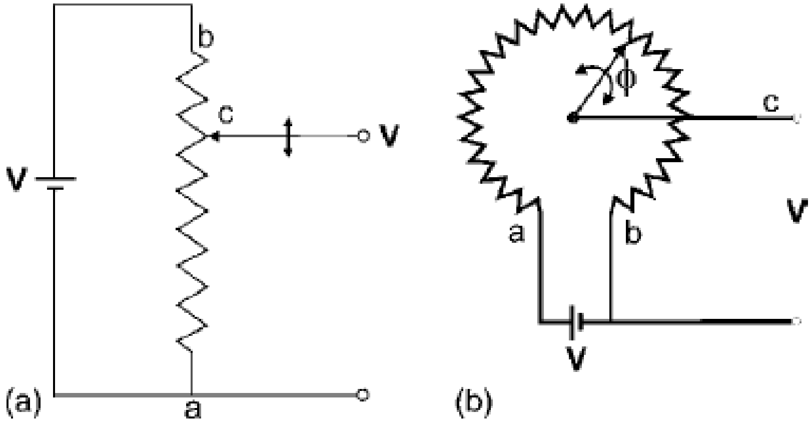


Figure illustrates linear (a) and angular (b) type potentiometric transducers.

Elastic Resistive Transducers

- In certain clinical situations, it is desirable to measure changes in the peripheral volume of a leg when the venous outflow of blood from the leg is temporarily occluded by a blood pressure cuff.

- This volume-measuring method is called *plethysmography*.

- The measurement can be performed by <u>wrapping an elastic resistive transducer</u> around the leg and <u>measuring the rate of change in resistance of the transducer</u> as a function of time.

- This change corresponds to relative changes in the blood volume of the leg.

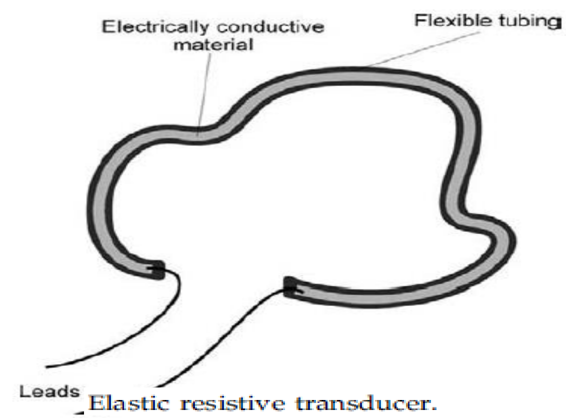
- If a clot is present, it will take more time for the blood stored in the leg to flow out through the veins after the temporary occlusion is removed.

- A similar transducer can be used to follow <u>a patient's breathing pattern</u> by wrapping the elastic band around the chest.

Cont…

- An elastic resistive transducer consists of a thin elastic tube filled with an electrically conductive material, as illustrated in the Figure below.
- The resistance of the conductor inside the flexible tubing is given by;

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



Elastic resistive transducer.

Where;

ρ is the resistivity of the electrically conductive material in ohm-meter (Ω-m)

L is the length in meters (m)

A is the cross-sectional area of the conductor in square meters (m^2)

Cont…

Example: **A 0.1 m long by 0.005 m diameter elastic resistive transducer has a resistance of 1 kΩ.**

(1) Calculate the resistivity of the electrically conductive material inside the transducer.

(1) Calculate the resistance of the transducer after it has been wrapped around a patient's chest having a circumference of 1.2 m. Assume that the cross-sectional area of the transducer remains unchanged.

Solution

1. The cross-sectional area of the transducer (A) is equal to $\pi\,(0.0025)^2\ \mathrm{m}^2 = 1.96\cdot 10^{-5}\ \mathrm{m}^2$.

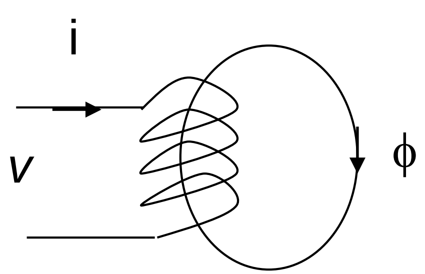
$$\rho = \frac{RA}{l} = \frac{1\cdot 10^{3}\ \Omega\cdot 1.96\cdot 10^{-5}\ \mathrm{m}^2}{0.1\ \mathrm{m}} = 0.196\ \Omega\cdot\mathrm{m}$$

2.

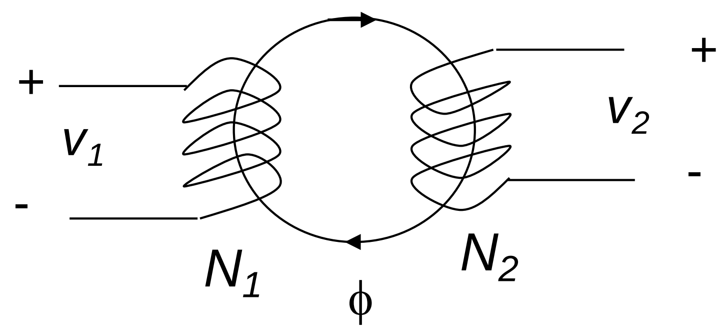
$$R_{\text{stretched}} = 0.196\ \Omega\cdot\mathrm{m}\cdot\left(\frac{1.2\ \mathrm{m}}{1.96\cdot 10^{-5}\ \mathrm{m}^2}\right) = 12\ \mathrm{k}\Omega$$

Inductive Sensors

- **Ampere's Law**: flow of electric current will create a magnetic field
- **Faraday's Law**: a magnetic field passing through an electric circuit will create a voltage

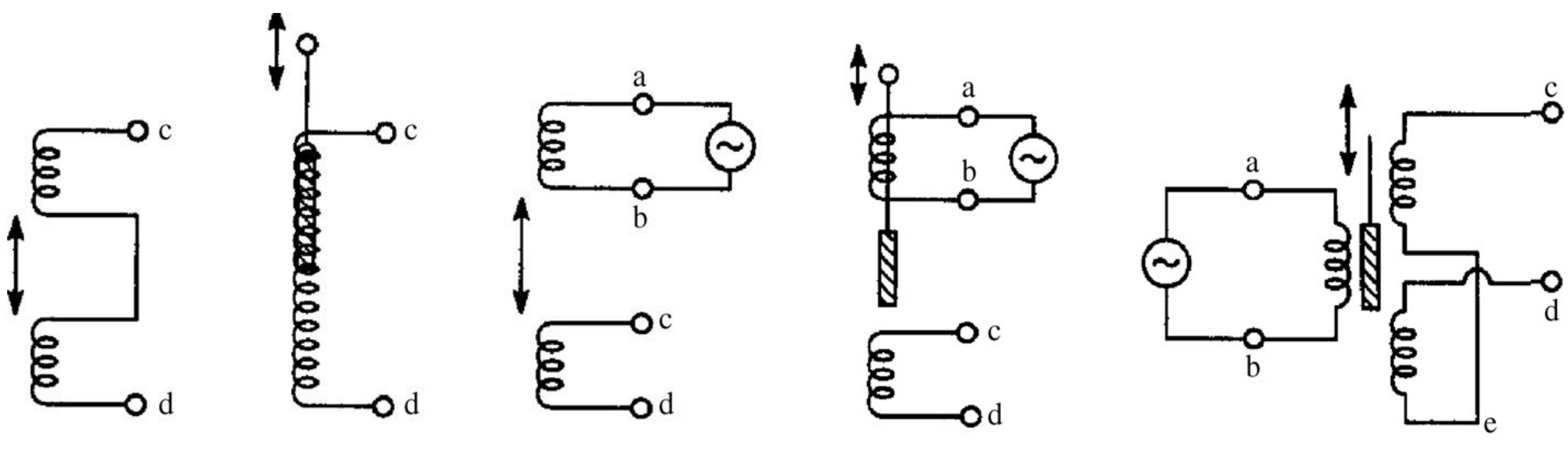


$$v = N\frac{d\Phi}{dt}$$



- An inductive sensor has an advantage in not being affected by the dielectric properties of its environment. However, it may be affected by external magnetic fields due to the proximity of magnetic materials.

- Inductive sensors are three types such as self-inductance, mutual inductance and differential transformer

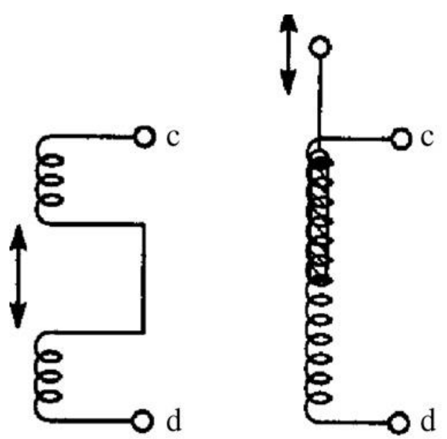


(a) (b) (c)

self-inductance mutual inductance Differential transformer

→Self Inductance

- The variable-inductance method employing a single displaceable core is shown in Figure (a).
- This device works on the principle that alterations in the self-inductance of a coil may be produced by changing the geometric form factor or the movement of a magnetic core within the coil.



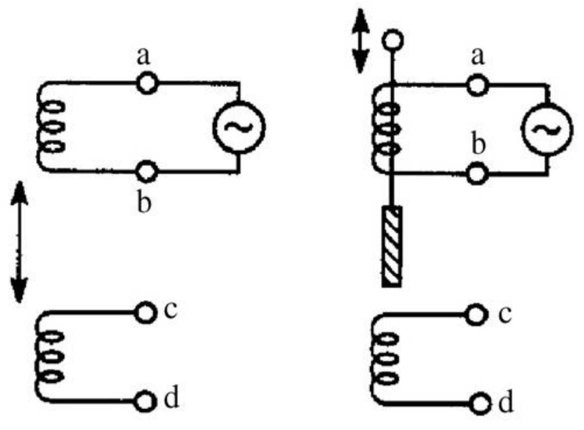
(a)

self-inductance

- The change in device is not linearly related to displacement.

→Mutual Inductance

- The mutual-inductance sensor employs two separate coils and uses the variation as shown in Figure (b).
- Cobbold (1974) describes the application of these devices in measuring cardiac dimensions, monitoring infant respiration, and ascertaining arterial diameters.



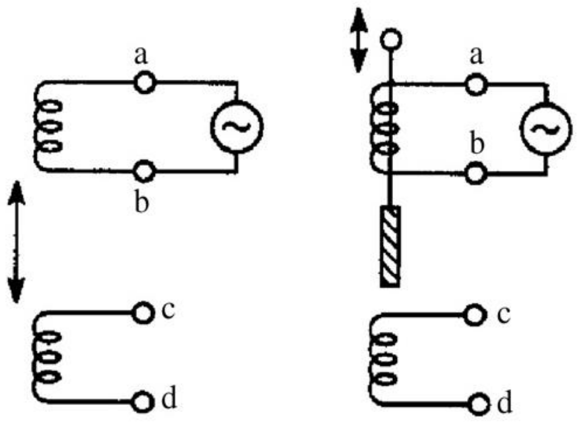
(b)

mutual-inductance

Mutual Inductance-Cont.

- Van Citters (1966) provides a good description of applications of mutual inductance transformers in measuring changes in dimension of internal organs such as kidney, major blood vessels, and left ventricle.

- The induced voltage in the secondary coil is a function of the geometry of the coils (separation and axial alignment), the number of primary and secondary turns, and the frequency and amplitude of the excitation voltage.
  - It is a nonlinear function of the separation of the coils.



(b)

mutual-inductance

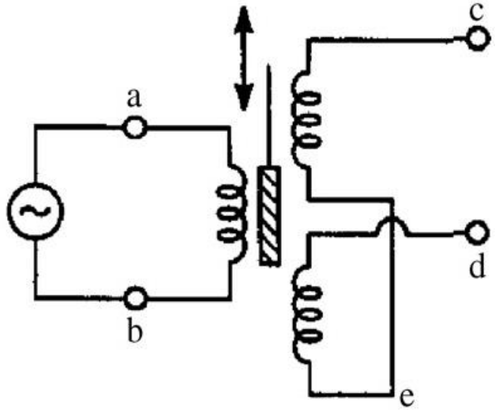
→Differential Transformers-LVDT

- The linear variable differential transformer (LVDT) is widely used in physiological research and clinical medicine to measure pressure, displacement, and force.

- As shown in Figure 2.7(c), the LVDT is composed of a primary coil (terminals a–b) and two secondary coils (c–e and d–e) connected in series.

- The coupling between these two coils is changed by the motion of a high-permeability alloy slug between them. The two secondary coils are connected in opposition in order to achieve a wider region of linearity.

Differential transformer



(c)

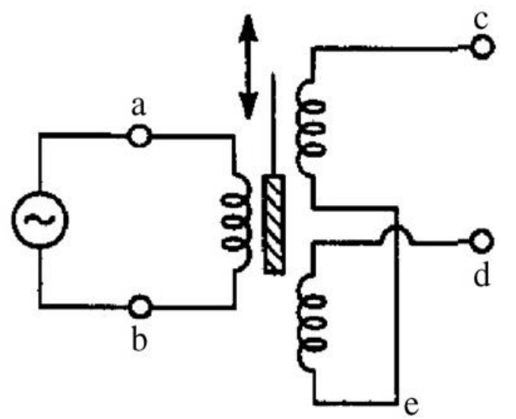
LVDT-Cont.

- The primary coil is sinusoidally excited, with a frequency between 60 Hz and 20 kHz. The alternating magnetic field induces nearly equal voltages v_{ce} and v_{de} in the secondary coils. The output voltage

$$v_{cd} = v_{ce} - v_{de}$$

- When the slug is symmetrically placed, the two secondary voltages are equal and the output signal is zero.

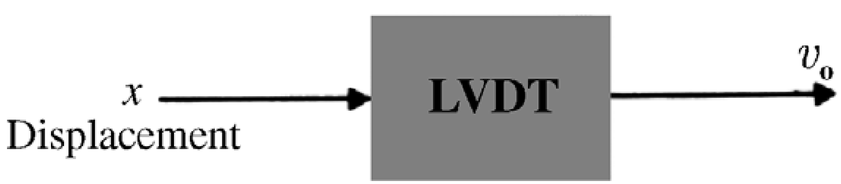
Differential transformer

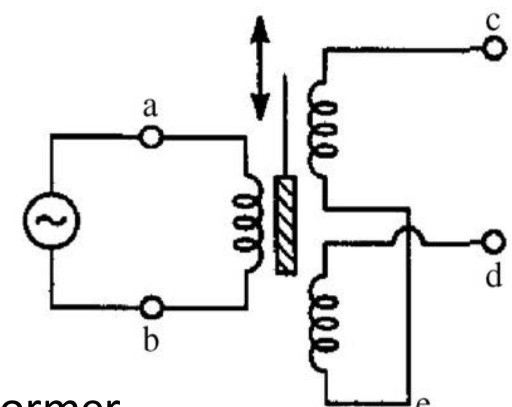


(c)

LVDT-Cont.

- Linear variable differential transformer characteristics include linearity over a large range, a change of phase by 180^{O} when the core passes through the center position, and saturation on the ends.
- Specifications of commercially available LVDTs include
  - sensitivities on the order of 0.5 to 2 mV for a displacement of 0.01 mm/V of primary voltage,
  - full-scale displacement of 0.1 to 250 mm
  - Sensitivity for LVDTs is much higher than that for strain gages.
- A disadvantage of the LVDT is that it requires more complex signal processing instrumentation.



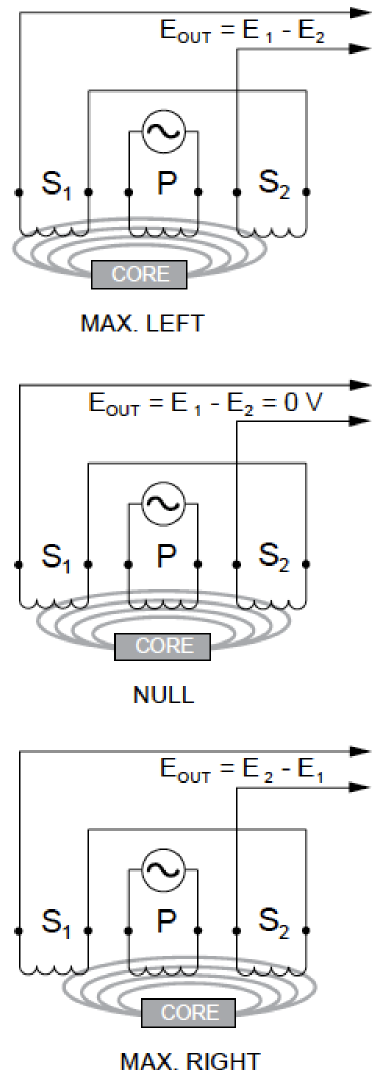


Differential transformer

(c)

Inductive Sensors-LVDT

Watch video



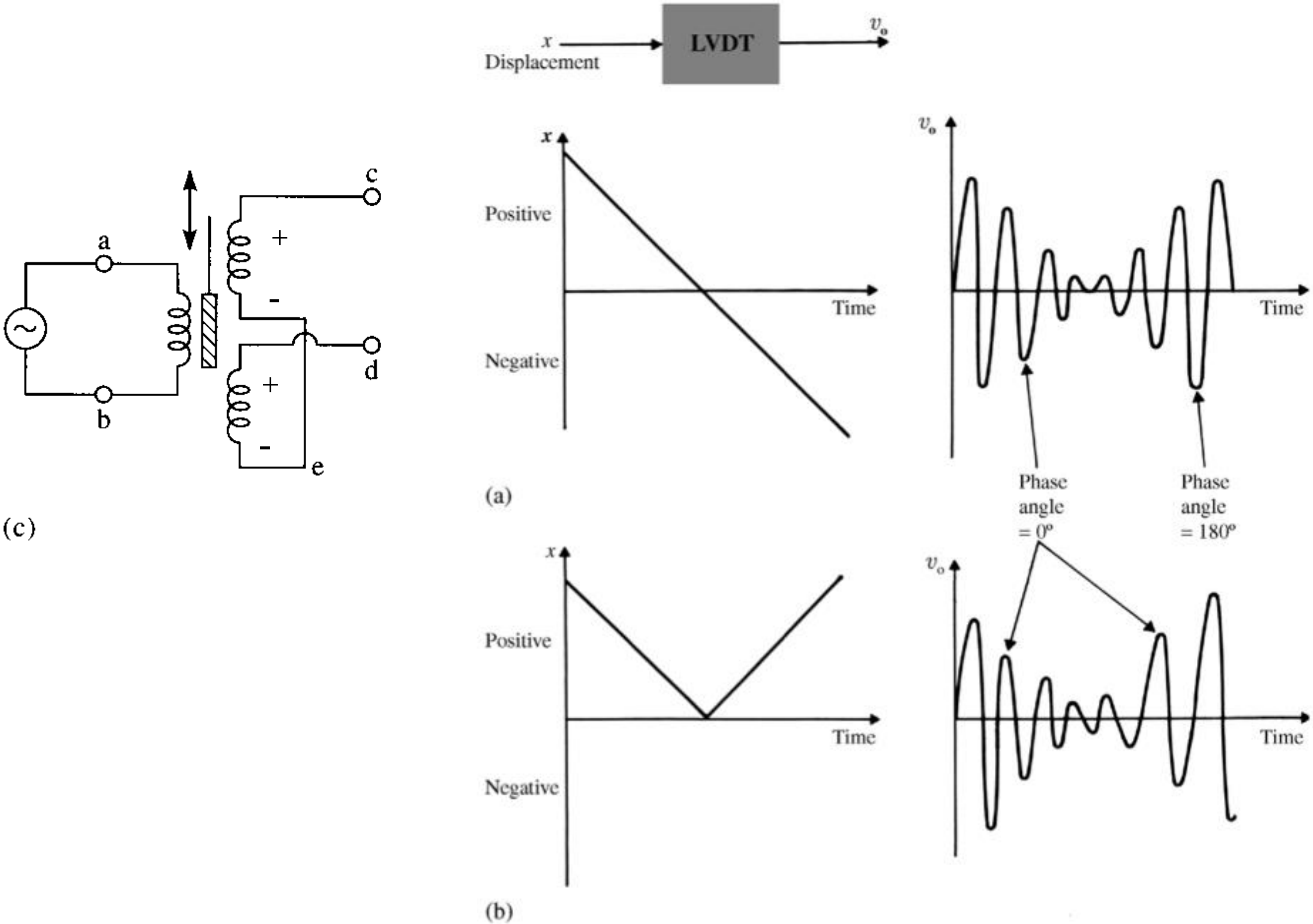


Figure 2.8 (a) As x moves through the null position, the phase changes 180°, while the magnitude of v_o is proportional to the magnitude of x. (b) An ordinary rectifier demodulator cannot distinguish between (a) and (b), so a phase-sensitive demodulator is required.

Capacitive Transducers

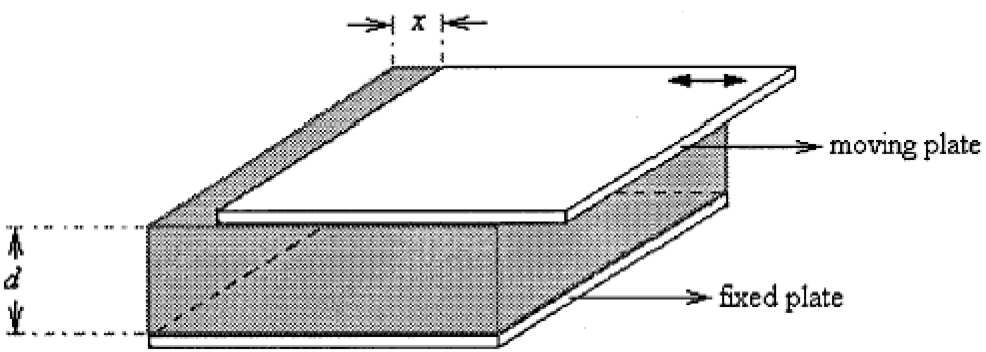
The capacitance, ***C*** (in farad), between two equal-size parallel plates of cross-sectional area, ***A***, separated by a distance, ***d***, is given by;

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

where

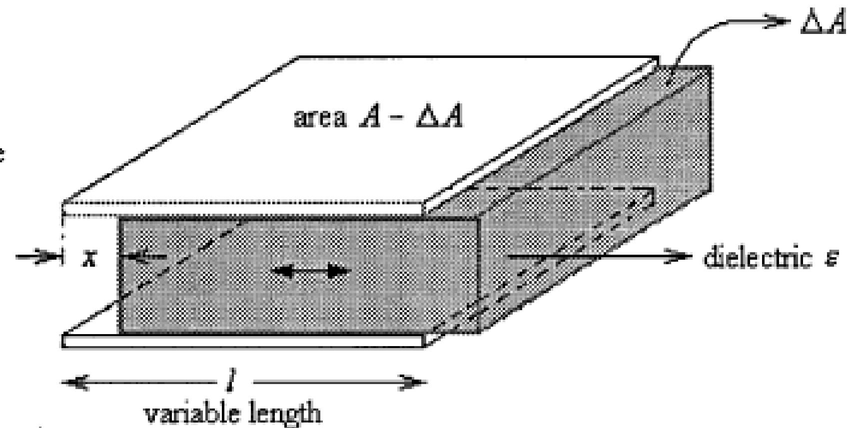
- ϵ_o is the dielectric constant of free space (8.85×10^{-12} F/m),
- ϵ_r is the relative dielectric constant of the insulating material placed between the two plates.

- The method that is most commonly employed to measure displacement is to change the separation distance, ***d***, between a fixed and a movable plate.
- This arrangement can be used to measure force, pressure, or acceleration.



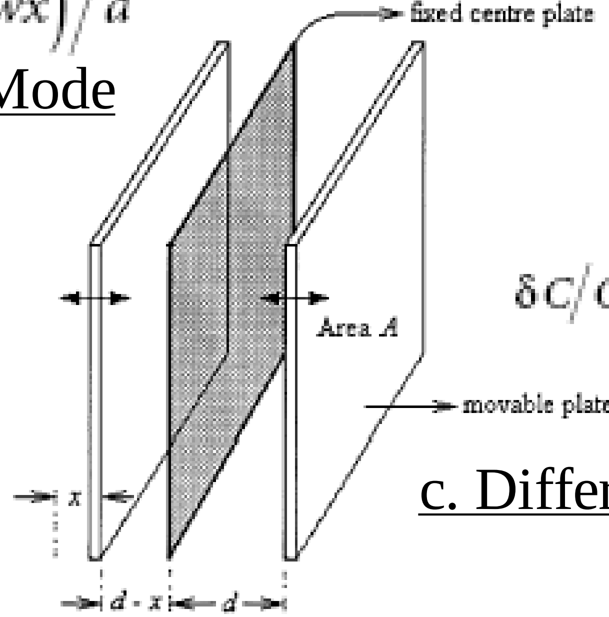
$$C = \varepsilon_r \varepsilon_0 \left(A - wx\right) / d$$

a. Variable Area Mode



$$C = \varepsilon_0 \; w \left[\varepsilon_2 l - \left(\varepsilon_2 - \varepsilon_1\right) x\right]$$

b. Variable Dielectric Mode



$$\delta C / C = \delta d / d$$

c. Differential Mode

Piezoelectric Sensors

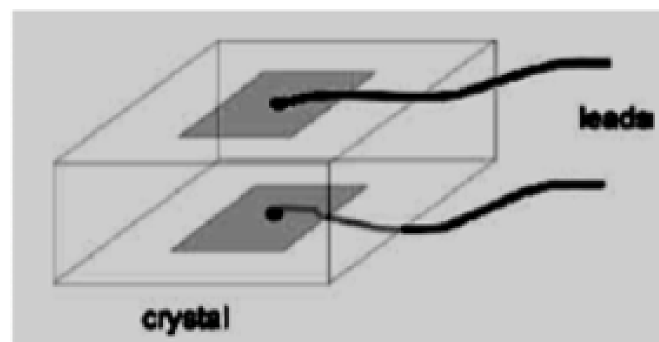
- Piezoelectric sensors are used to measure physiological displacements and record heart sounds.
- Piezoelectric materials generate an electric potential when mechanically strained, and conversely an electric potential can cause physical deformation of the material.
- The principle of operation is that
  - When an asymmetrical crystal lattice is distorted, a charge reorientation takes place, causing a relative displacement of negative and positive charges.
  - The displaced internal charges induce surface charges of opposite polarity on opposite sides of the crystal.
  - Surface charge can be determined by measuring the difference in voltage between electrodes attached to the surfaces.

- Total induced charge q is directly proportional to the applied force F

$$q = kF$$

- k is the piezoelectric constant for the specific piezoelectric material (C/N)
- The change in voltage can be found by assuming that the system acts like a parallel-plate capacitor where the voltage v across the capacitor is charge q divided by capacitance C.

$$v = \frac{kf}{C} = \frac{kfx}{\varepsilon_0 \varepsilon_\tau A}$$



- k for Quartz = 2.3 pC/N
- k for barium titanate = 140 pC/N

Applications:

- Used extensively in cardiology to listen to heart sounds (phonocardiography)
- For measurement of physiological forces and accelerations
- Detection of Korotkoff sounds in blood-pressure measurements
- Commonly employed in generating ultrasonic waves (high-frequency sound waves typically above 20 kHz) used to measure blood flow or collect images of internal soft structures inside the body

Temperature Measurement

- Body temperature is one of the vital signs that provide the physiological state of the individual (others are pulse, respiration and blood pressure).
- Body temperature will vary in different parts of the body depending on perfusion, exposure, metabolic activity, local heat gain, or local heat loss.
- The physiologically important temperature is the ‘‘core temperature’’, which represents the temperature of the body’s vital organs (brain, heart, lungs, gut).

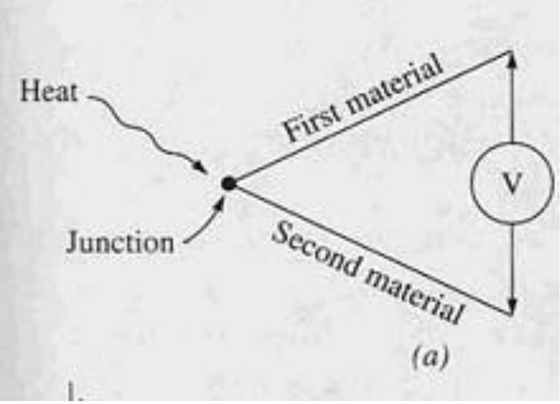
- There are four types of common temperature transducers
  1. Thermocouple
  2. Thermistors
  3. Resistance Temperature Detectors (RTDs)
  4. Infrared Thermometer

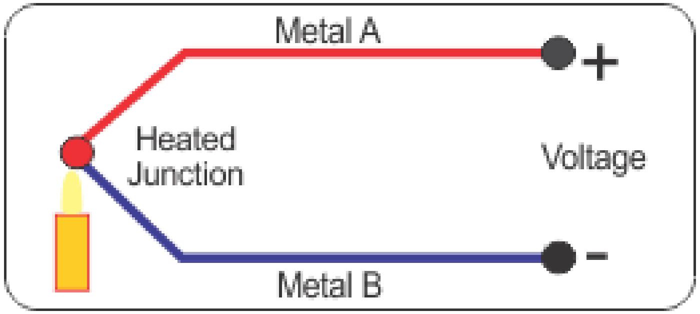
→Thermocouple

- A thermocouple consists of two dissimilar conductors or semiconductors joined together at one end.

- Because the work functions of the two material are different, a potential will be generated when this junction is heated (seebeck voltage).

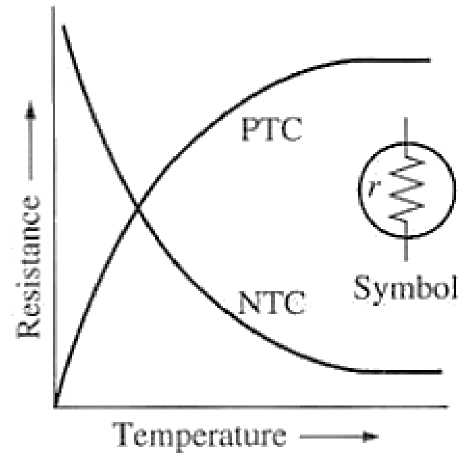
- Thermocouples can be made small in size, so they can be inserted into catheters and hypodermic needles





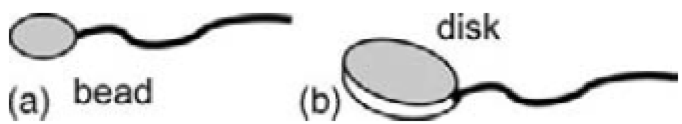
→Thermistors

- Thermistors (Thermal resistors) are resistors that are designed to change value in predictable manner with changes in temperature.
- A positive temperature coefficient (PTC) device increases resistance with increase in temperature
- A negative temperature coefficient (NTC) device decreases resistance with increases in temperature



- The resistivity of thermistor semiconductors used for biomedical applications is between 0.1 and 100 Ω-m.

- Commercially available thermistors range in shape from small beads, chips, rods to large disks as shown in the figure.

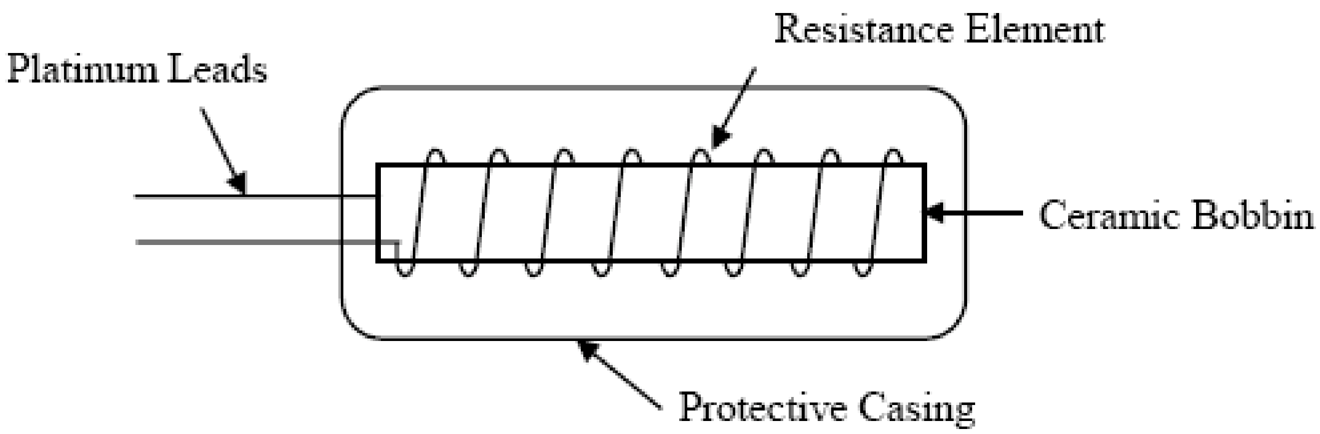


- Thermistors are small in size (typically less than 0.5 mm in diameter), have a relatively large sensitivity to temperature changes, and have long-term stability characteristics.

→Resistance Temperature Detectors (RTDs)

- A simple RTD system is comprised of a metal resistor (e.g., platinum wire fashioned into a coil), a source of electrical potential and an ammeter calibrated to indicate temperature

- The RTDs are the most stable of the electrical methods for temperature measurement and are nearly linear over a relatively wide range of temperatures. They are, however, slow and expensive compared to thermocouples and thermistors



→Infrared Thermometer

- An infrared thermometer is a thermometer which infers temperature from a portion of the thermal radiation sometimes called blackbody radiation emitted by the object being measured.