Biomedical Instrumentation I

Lecture-2: Sensors for Biomedical Applications

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Lecture Outline

- Differentiate between the terms “Sensor”, “Transducer” & “Actuator”
- Active and Passive Transducers/Sensors
- Sensors used in Biomedical Instruments
- Sensor Error Sources
- Sensor Terminology
- The Wheatstone Bridge
- Displacement Transducers (Resistive, Inductive, or Capacitive type)
- Temperature Transducers (Thermocouples, Thermistors, PN Junctions)
- Piezoelectric Transducers

Definitions

Transducer

A transducer is a device which converts energy from one form to another.

Sensor

A sensor is a device which converts a physical parameter to an electrical output.

Actuator

An actuator is a device which converts an electrical energy to a mechanical or physical output.

Active Sensors

Active Sensors

- Active sensors generate electrical output directly in response to an applied stimulation or measurand.
- An active sensor doesn’t require an external voltage source to produce electrical output.

Example: Solar Cell, Piezoelectric Material, Thermocouple, etc.

Passive Sensors

Passive Sensors

- Passive sensors produce a change in some passive electrical quantity, such as capacitance, resistance, or inductance, in response to an applied stimulus or measurand.

- Therefore, a passive sensor does require an external ac or dc voltage source in order to convert passive electrical quantity such as capacitance, resistance, or inductance in to electrical output.

Example: Photo Diode, Thermistor, Strain Gauge, etc.

Examples of Sensors used in Biomedical Instruments

- Sensors are now available to measure many parameters of clinical and laboratory interest.
- Some types of sensors 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

Sensors in Medical Instruments

Example 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 Error Sources

- Sensors, like all other devices, sustain certain errors.
- The error is defined as the difference between the measured value and the true value.
- Sensor errors an be break into five basic categories:

1. **Insertion Errors**
2. **Application Errors**
3. **Characteristic Errors**
4. **Dynamic Errors**
5. **Environmental Errors**

Sensor Error Sources

1. **Insertion Errors**

   The insertion errors occur during the act of inserting the sensor into the system being measured.

2. **Application Errors**

   Application errors are caused by the operator .

3. **Characteristic Errors**

   The characteristic errors are inherent in the device itself. i.e., the difference between the ideal characteristic transfer function of the device and the actual characteristic.

   This form of error may include a dc off-set value (a false pressure head), an incorrect slope, or a slope that is not perfectly linear.

Sensor Error Sources

4. Dynamic Errors

- Many sensors are characterized and calibrated in a static condition. i.e., with an input parameter that is either static or quasi-static.
- Many sensors are heavily damped so that they will not respond to rapid changes in the input parameter.
- Dynamic errors include response time, amplitude distortion, and phase distortion.

5. Environmental Errors

- These errors are derived from the environment in which the sensor is used.
- They most often include temperature but may also include vibration. shock, altitude, chemical exposure, or other factors.
- These factor most often affect the characteristic errors of the sensor, so are often combined with that category in practical application.

Sensor Terminology

Some of the most common sensor terms are;

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**

Sensor Terminology

1. Sensitivity

- The sensitivity of the sensor is defined as the slope of the output characteristic curve ($\Delta Y/\Delta X$).
- More generally, the minimum input of physical parameter that will create a detectable output change.
- In some sensor, the sensitivity is defined as the input parameter change required to produce a standardized output change.
- In others, it is defined as an output voltage change for a given change in input parameter.

For Example: a typical blood pressure transducer may have a sensitivity rating of 10 μv/v/mm-Hg; i.e., there will be a 10 μv output voltage for each volt of excitation potential and each millimeter of mercury of applied pressure.

Sensor Terminology

2. Sensitivity Error

- The sensitivity error is a departure from the ideal slope of the characteristic curve.

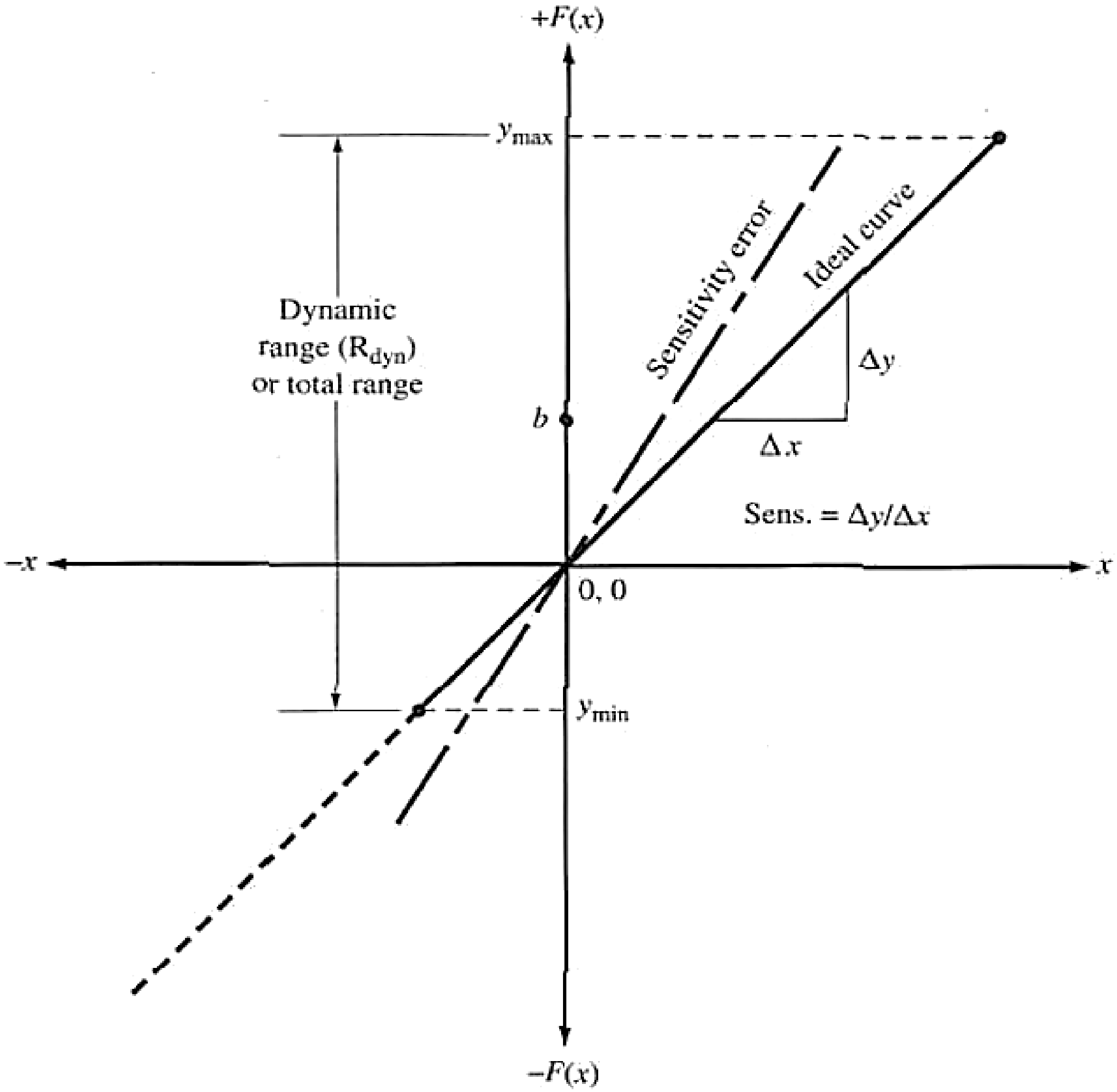
- **For Example**: the pressure transducer in the previous sensitivity example may have an actual sensitivity of 7.8 μv/v/mm-Hg instead of 10 μv/v/mm-Hg.

3. Range

- The range of the sensor is the maximum and minimum values of applied parameter that can be measured.

- **For Example:** a given pressure sensor may have a range of -400 mm-Hg to +400 mm-Hg.
- Sometimes the positive and negative ranges often are unequal.

Sensor Terminology



Sensor Terminology

4. Dynamic Range

- The dynamic range is the total range of the sensor from minimum to maximum.

5. Precision

- The precision refers to the degree of reproducibility of a measurement.

6. Resolution

- The resolution is define as the smallest detectable incremental change of input parameter that can be detected in the output signal.

7. Accuracy

- The accuracy of the sensor is the maximum difference that will exist between the actual value (which must be measured by a primary or good secondary standard) and the indicated value at the output of the sensor.

Sensor Terminology

8. Offset

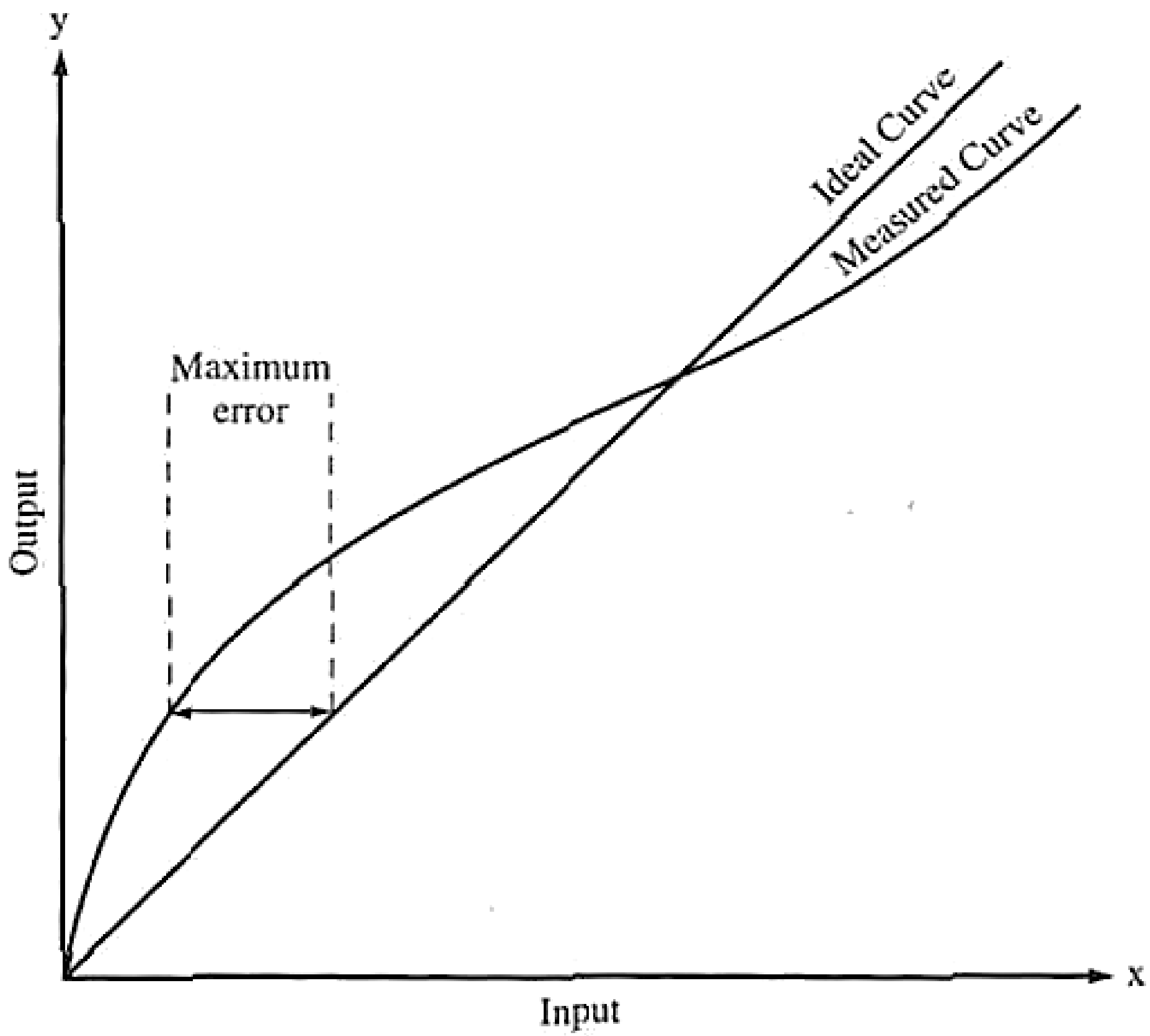
- The offset error of a transducer is defined as the output that will exist when it should be zero.
- Alternatively, the difference between the actual output value and the specified output value under some particular set of conditions.

9. Linearity

- The linearity of the transducer is an expression of the extent to which the actual measured curve of a sensor departs from the ideal curve.

Sensor Terminology

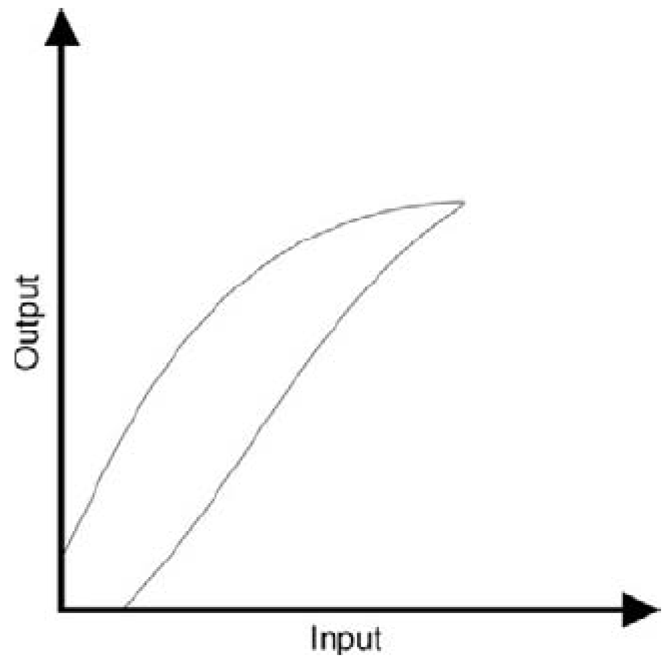
Ideal versus measured curve showing linearity error



Sensor Terminology

10. Hysteresis

- A transducer should be capable of following the changes of the input parameter regardless of in which direction the change is made, hysteresis is the measure of this property.



Input versus output response of a sensor with hysteresis.

Sensor Terminology

11. Response Time

- Sensors do not change output state immediately when an input parameter change occur. Rather, it will change to the new state over a period of time, called the response time.

- The response time can be defined as the time required for a sensor output to change from its previous state to a final settled value within a tolerance band of the correct new value.

12. Dynamic Linearity

- The dynamic linearity of the sensor is a measure of its ability to follow rapid changes in the input parameter.
- Amplitude distortion characteristics. phase distortion characteristics, and response time are important in determining dynamic linearity.

Sensor Terminology

13. Transfer Function

- The functional relationship between physical input signal and electrical output signal.

14. Noise

- Almost all type of sensors produce some output noise in addition to the output signal.
- The noise of the sensor limits the performance of the system.
- Most common types of noise are 50 Hz supply noise, and white noise which is generally distributed across the frequency spectrum.

Sensor Terminology

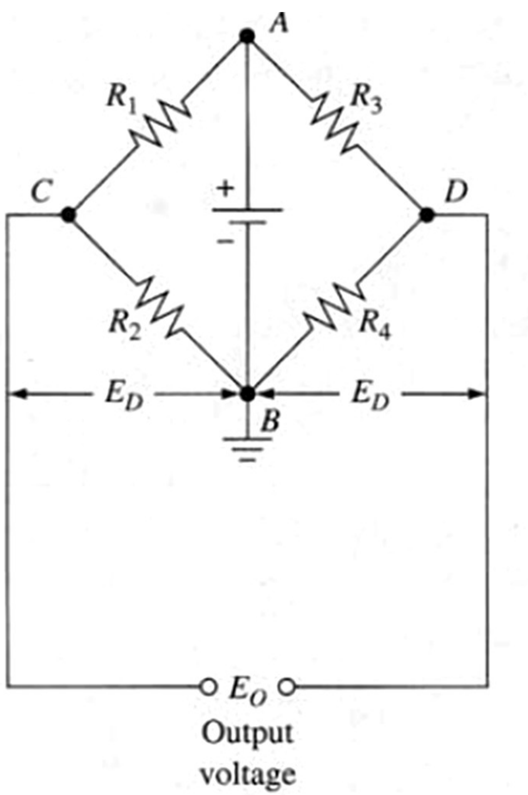
15. Bandwidth

- All sensors have ***finite response times*** to an instantaneous change in physical signal.
- In addition, many sensors have ***decay times***, which would represent the time after a step change in physical signal for the sensor output to decay to its original value.
- The reciprocal of these times correspond to the upper and lower cutoff frequencies, respectively.
- The bandwidth of a sensor is the frequency range between these two frequencies.

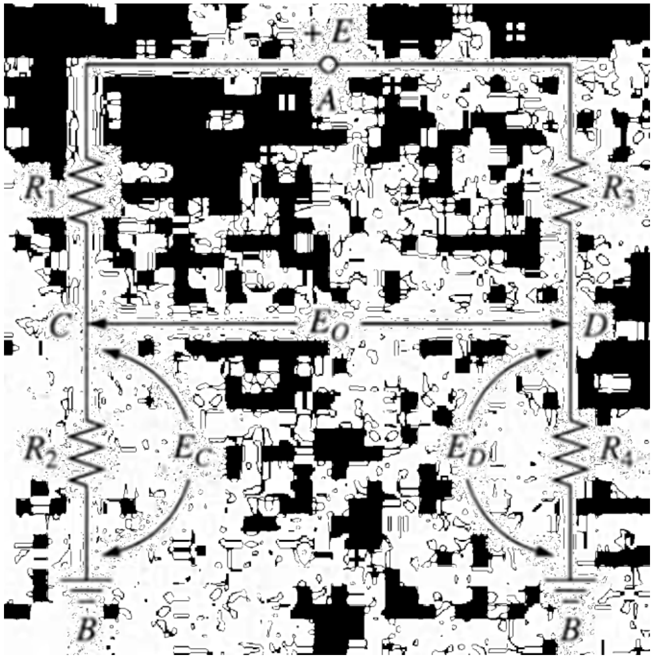
The Wheatstone Bridge

- Many biomedical passive transducers/sensors are used in a circuit configuration called a ***Wheatstone bridge***.
- The Wheatstone bridge circuit is ideal for measuring small changes in resistance.
- The Wheatstone bridge can be viewed as two resistor voltage dividers connected in parallel with the voltage source *E*.

Wheatstone Bridge Circuit



Wheatstone Bridge Circuit Redrawn for Simplify Analysis



The Wheatstone Bridge

The output voltage E_0 is the difference between the two ground referenced potentials E_C and E_D produced by the two voltage divider networks;

$$E_o = E_C - E_D$$

Where E_C and E_D *can be calculated as;*

$$E_C = E \times \frac{R_2}{R_1 + R_2}$$

$$E_D = E \times \frac{R_4}{R_3 + R_4}$$

So, the output can be calculated as;

$$E_o \frac{ER_2}{R_1 + R_2} - \frac{ER_4}{R_3 + R_4}$$

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

The Wheatstone Bridge

Example: **A Wheatstone bridge is excited by a 12 v dc source and contains the following resistances; R_1 = 1.2 kΩ, R_2 = 3 kΩ, R_3 = 2.2 kΩ, and R_4 = 5 kΩ. Find the output voltage E_0.**

Solution

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

$$E_o = 12\left(\frac{3}{1.2 + 3} - \frac{5}{2.2 + 5}\right)$$

$$E_o = 12\left(\frac{3}{4.2} - \frac{5}{7.2}\right)$$

$$E_o = 12(0.714 - 0.694) = \mathbf{0.24\ V}$$

The Wheatstone Bridge

The Null Condition:

- The null condition in a Wheatstone bridge circuit exists when the output voltage E_0 is zero.

- The equation of Wheatstone bridge is, $E_o = E\left(\frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4}\right)$

- The null condition exists when either the excitation source voltage *E* must be zero or the expression inside bracket s must be equal to zero.
- So the null condition occurs when; $E_{CB} = E_{DB}$, and $E_{AC} = E_{AD}$.

- Therefore, the ratio of two equals are, $\frac{E_{CB}}{E_{AC}} = \frac{E_{DB}}{E_{AD}}$

- Replacing voltages with the equivalent current and resistance, $\frac{I_{ACB}R_1}{I_{ACB}R_2} = \frac{I_{ADB}R_3}{I_{ADB}R_4}$

- So, the null condition in a Wheatstone bridge circuit occurs when $\frac{R_1}{R_2} = \frac{R_3}{R_4}$

The Wheatstone Bridge

Example: **Show that the null condition exists in a Wheatstone bridge consisting of the following resistances,**

R_1 = 2 kΩ, R_2 = 1 kΩ, R_3 = 10 kΩ, and R_4 = 5 kΩ.

Solution

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

$$\frac{1}{2} = \frac{5}{10}$$

$$0.5 = 0.5$$

- Note that it is not necessary for the resistances to be equal for the null condition, only that the ratios of the two half-bridge voltage dividers must be equal.

- Since both sides of the equation evaluate to the same quantity, we may conclude that the bridge is in the null condition.

- A bridge in the null condition is said to be balanced.

Displacement Transducers

- Displacement transducers are typically used to measure physical changes in the position of an object or medium.
- They are commonly employed in detecting changes in length, pressure, or force.
- Variations in these parameters can be used to quantify and diagnose abnormal physiological functions.
- Displacement transducers can be **resistive**, **inductive**, or **capacitive** type.

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.

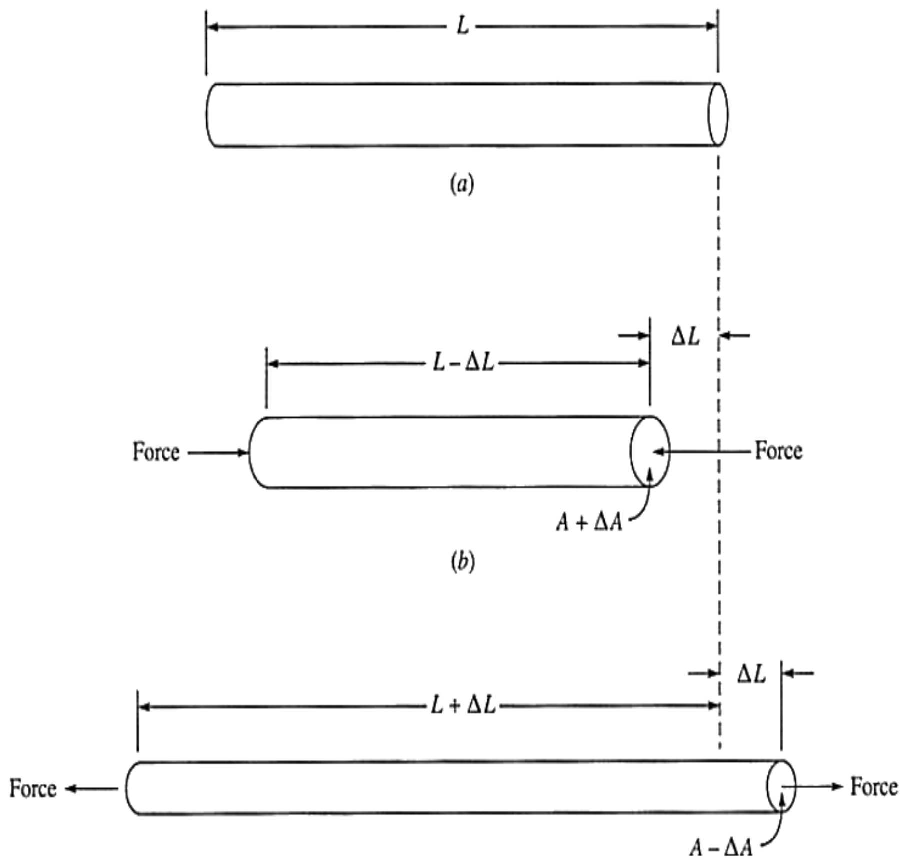
- It will have a length ***L*** and a cross-sectional area ***A***.
- Changes in length are given by ***ΔL*** and changes in area are given by ***ΔA***.

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;

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

Where;

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.
- Both of these phenomena are crucial to the operation of the resistive strain gauge transducers.

Strain Gauge

Example: Find the resistance of a copper bar that has a cross-sectional area of 0.5 mm^2, length of 250 mm, and the resistivity of copper is 1.7 X 10^{-8} Ω-m.

Solution:

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

$$R = \frac{1.7 \times 10^{-8} \times 0.25}{0.0005}$$

R = 8.5 μΩ

Strain Gauge

Piezoresistivity:

- The change of resistance with changes in size and shape is some called *piezoresistivity*.
- The resistance of the bar will become ***R*** + ***h*** in tension.
- The resistance of the bar will become ***R*** - ***h*** in compression.
- Where the ***h*** is change in resistance.
- Examine the equation of strain gauge, it is found that changes in both length and cross-sectional area tend to increase the resistance in tension and decrease the resistance in compression.

- The resistances after force is applied are in tension:

$$(R + h) = \frac{L + \Delta L}{A - \Delta A}$$

- The resistances after force is applied are in compression:

$$(R - h) = \frac{L - \Delta L}{A + \Delta A}$$

Strain Gauge

Example: A thin constantan wire stretched taut has a length of 30 mm and a cross-sectional area of 0.01 mm^2. The resistance is 1.5 Ω. The force applied to the wire is increased so that the length further increases by 10 mm and the cross-sectional area decreases by 0.0027 mm^2. Find the change in resistance ***h***, where the resistivity of constantan is approximately 5 x 10^{-7} Ω-m.

Solution:

$$(R + h) = \rho\frac{L + \Delta L}{A - \Delta A}$$

$$(R + h) = (5 \times 10^{-7}\ \Omega\text{-M}) \times \frac{[(30 + 10)\text{mm} \times (1\ \text{m}/1000\ \text{mm})]}{(0.01 - 0.0027)\ \text{mm}^2 \times [(1\ \text{m}/1000\ \text{mm})]^2}$$

$$1.5 + h = \frac{(5 \times 10^{-7}\ \Omega)(40)(10^3)}{0.0073}$$

then $1.5 + h = 2.74\ \Omega$

so $h = 2.74 - 1.5 = \mathbf{1.24\ \Omega}$

Strain Gauge

Gauge Factor (GF):

- The fractional change in resistance, $(\Delta R/R)$, divided by the fractional change in length, $(\Delta L/L)$, is called the gauge factor (GF).
- The gauge factor GF is a unit less number.
- The gauge factor provides sensitivity information on the expected change in resistance for a given change in the length of a strain gauge.
- The gauge factor varies with temperature and the type of material.
- Therefore, it is important to select a material with a high gauge factor and small temperature coefficient.
- For a common metal wire strain gauge made of constantan, GF is approximately equal to 2.
- Semiconductor strain gauges made of silicon have a GF about 70 to 100 times higher and are therefore much more sensitive than metallic wire strain gauges.

Properties of Strain-Gage Materials

Material	Composition (%)	Gage Factor	Temperature Coefficient of Resistivity ($°C^{-1} - 10^{-5}$)
Constantan (advance)	Ni_{45}, Cu_{55}	2.1	±2
Isoelastic	Ni_{36}, Cr_8 $(Mn, Si, Mo)_4$ Fe_{52}	3.52 to 3.6	+17
Karma	Ni_{74}, Cr_{20}, Fe_3 Cu_3	2.1	+2
Manganin	Cu_{84}, Mn_{12}, Ni_4	0.3 to 0.47	±2
Alloy 479	Pt_{92}, W_8	3.6 to 4.4	+24
Nickel	Pure	−12 to −20	670
Nichrome V	Ni_{80}, Cr_{20}	2.1 to 2.63	10
Silicon	(*p* type)	100 to 170	70 to 700
Silicon	(*n* type)	−100 to −140	70 to 700
Germanium	(*p* type)	102	
Germanium	(*n* type)	−150	

Strain Gauge

Gauge Factor (GF):

- The gauge factor (GF) for a strain gauge transducer is a means of comparing it with other semiconductor transducers.
- The definition of gauge factor is;

$$GF = \frac{\Delta R/R}{\Delta L/L} \quad \text{or} \quad GF = \frac{\Delta R/R}{\mathscr{E}} \quad \text{where } \mathscr{E} \text{ (strain) is the factor } \Delta L/L$$

Where;

GF is the gauge factor (dimensionless)

ΔR is the change in resistance in ohms (Ω)

R is the unstrained resistance in ohms (Ω)

ΔL is the change in length in meters (m)

L is the length in meters (m)

Strain Gauge

Example: A 20 mm length of wire used as a strain gauge exhibits a resistance of 150 Ω. When a force is applied in tension, the resistance changes by 2 Ω and the length changes by 0.07 mm. Find the gauge factor GF.

Solution

$$GF = \frac{\Delta R/R}{\Delta L/L}$$

$$GF = \frac{2/150}{0.07/20}$$

$$GF = \frac{0.013}{0.0035} = \mathbf{3.71}$$

- The gauge factor gives us a means for evaluating the relative sensitivity of a strain gauge element.
- The greater the change in resistance per unit change in length the greater the sensitivity of the element and the greater the gauge factor GF.

Types of Strain Gauges

Strain gauges typically fall into two categories:

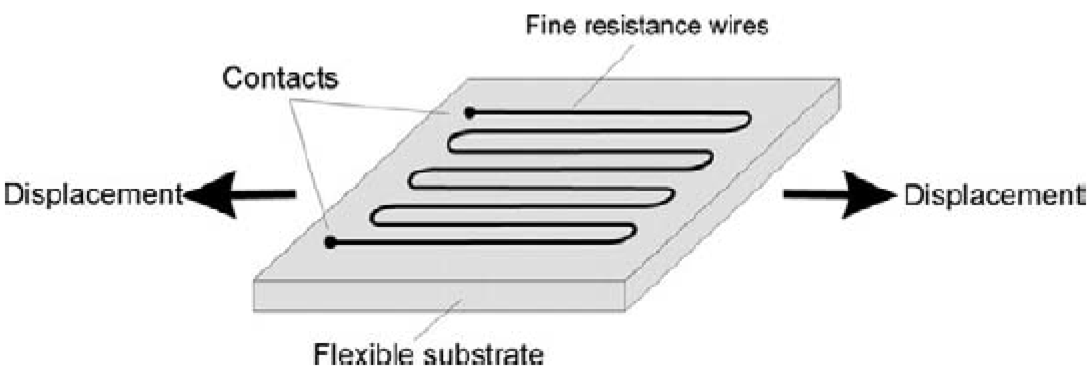
1. **Bonded Strain Gauge**

2. **Unbonded Strain Gauge**

Types of Strain Gauges

1. Bonded Strain Gauge

- A bonded strain gauge has a folded thin wire cemented to a semi flexible backing material.
- Unbonded strain gauges can he constructed so that they are linear over a wide range of applied force but are very delicate.
- The bonded strain gauge, on the other hand, is generally mare rugged but is linear over a smaller ranges of forces.



A bonded-type strain gauge transducer.

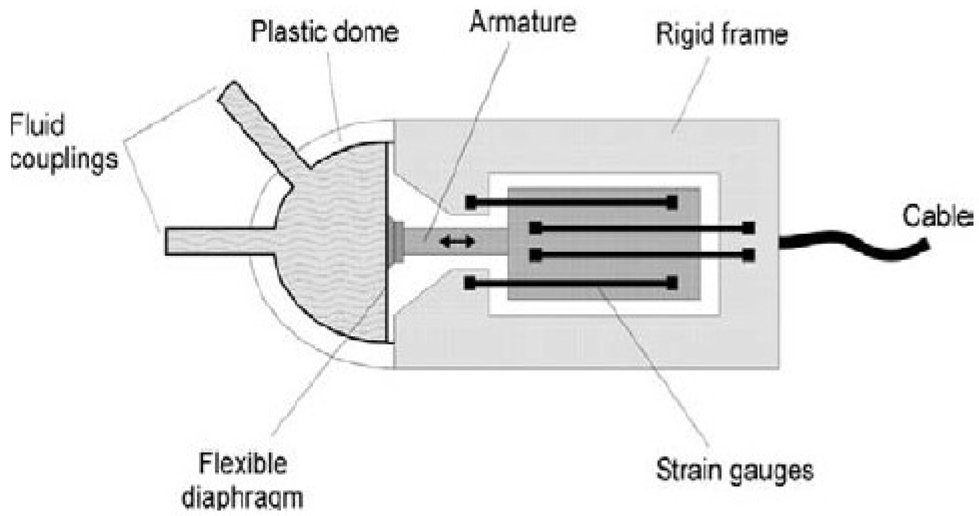
Types of Strain Gauges

2. Unbonded Strain Gauge

- An unbonded strain gauge 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.

- The unbonded strain gauge is used as a blood pressure transducers, as illustrated in the Figure.



A resistive strain gauge (unbounded-type) blood pressure transducer.

Types of Strain Gauges

2. Unbonded Strain Gauge

- In the blood pressure transducer, 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.

Strain Gauge

- Many biomedical strain gauge transducers are of bonded construction because the linear range is adequate and the extra ruggedness is a desirable feature in medical environments, where people cannot take the kind of precautions that would be required if a more delicate type were used.

- The Statham P-23 series are of the unbonded type strain gauge transducer but are made in a very rugged housing. These are among the most common cardiovascular pressure transducers used in medicine.

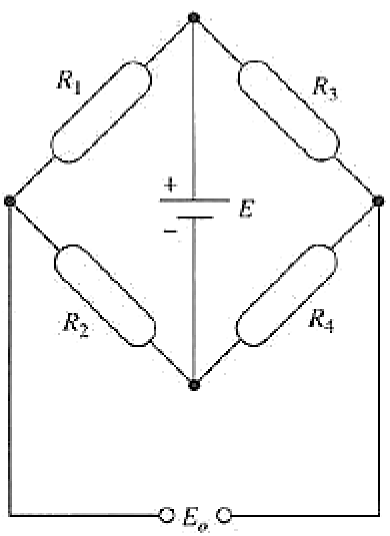
- In general, the change in resistance of a strain gauge is typically quite small.

- In addition, changes in temperature can also cause thermal expansion of the wire and thus lead to large changes in the resistance of a strain gauge.

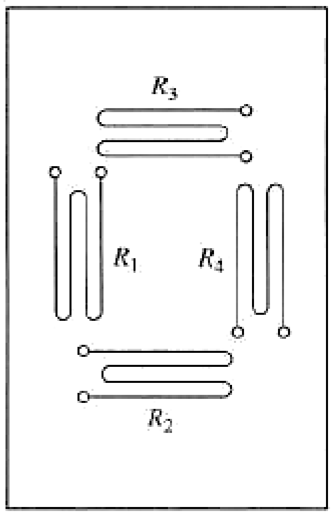
- Therefore, very sensitive electronic amplifiers with special temperature compensation circuits are typically used in applications involving strain gauge transducers.

Strain Gauge

- Most physiological strain gauge transducers use four strain gauge elements connected in a Wheatstone bridge circuit as shown in the figure.
- Both bonded and unbonded types of transducers are found with an element geometry that places two elements in tension and two elements in compression for any applied force (tension or compression).
- Such a configuration increases the output of the bridge for any applied force and so increases the sensitivity of the transducer.



Strain gauge elements in a Wheatstone bridge circuit



Mechanical configuration Using a common diaphragm

Strain Gauge

- Assume that all resistors of the Wheatstone bridge circuit are equal (***R1*** = ***R2,*** = ***R3,*** = ***R4***) when no force is applied.

- Let *ΔR* = *h*, when a force is applied, the resistance of ***R1*** and ***R4*** will be **(*R* + *h*),** and the resistance of ***R2*** and ***R3*** will be ***(R* – *h)***.

- From a rewritten version of the Wheatstone bridge circuit equation, we know that the output voltage is

$$E_o = E \times \left[\frac{(R-h)}{(R+h)+(R-h)} - \frac{(R+h)}{(R-h)+(R+h)} \right]$$

$$E_o = E \times \left[\frac{(R-h)}{2R} - \frac{(R+h)}{2R} \right]$$

$$E_o = E\left(\frac{h}{R}\right) = -E\left(\frac{\Delta R}{R}\right)$$

$$E_o = -E\left(\frac{\Delta R}{R}\right)$$

Strain Gauge

Example: A strain gauge transducer is constructed in a Wheatstone bridge circuit configuration. In the null condition, each element has a resistance of 200 Ω. When a force is applied, each resistance changes by 10 Ω. Find the output voltage if a 10-V excitation potential is applied to the bridge.

Solution

$$E_o = -E \times \frac{\Delta R}{R}$$

$$E_o = -10\text{ V} \times 10/200$$

$$E_o = -10\text{ V} \times 0.05 = \mathbf{-0.50\text{ V}}$$

Transducer Sensitivity

- The ***transducer sensitivity* (Φ)** is the rating that allows us to predict the output voltage from knowledge of the excitation voltage and the value of the applied stimulus.
- The units for sensitivity (Φ) are micro-volts per volt of excitation per unit of applied stimulus (μv/v/g).
- If the sensitivity factor (Φ) is known for a transducer, then the output voltage may be calculated as,

$$E_o = \phi \times E \times F$$

where

E_0 is the output potential in volts (V)

E is the excitation potential in volts (V)

F is the applied force in grams (g)

Φ is the sensitivity in (μv/v/g)

Transducer Sensitivity

Example: A transducer has a sensitivity of 10 µv/v/g. Predict the output voltage for an applied force of 15 g, if the excitation potential is 5 V dc.

Solution

$$E_o = \phi \times E \times F$$

$$E_o = \frac{10\ \mu\text{V}}{\text{V-}g} \times 5\ \text{V} \times 15\ g$$

$$E_o = 750\ \mu\text{V} = \mathbf{0.00075\ V}$$

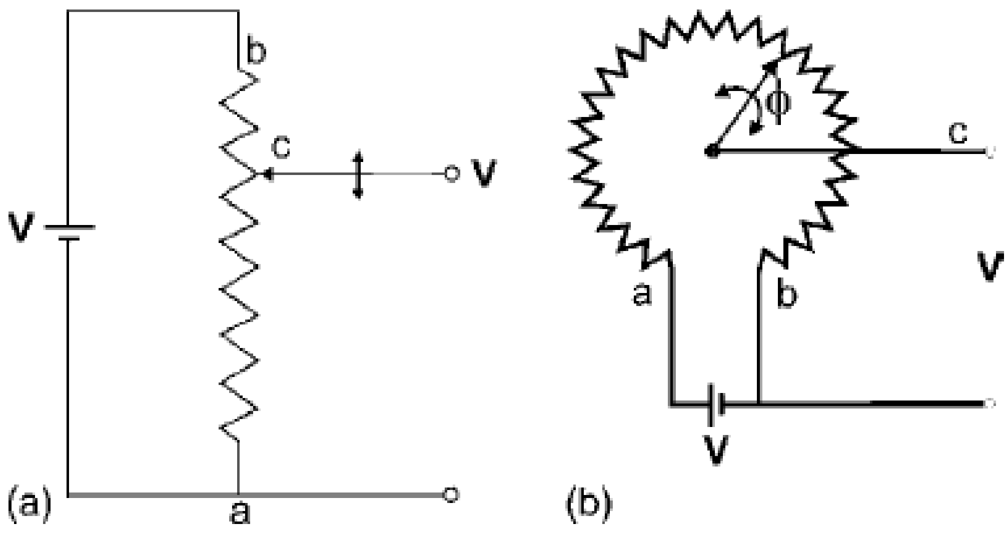
Note that the sensitivity is important in both the design and the repair of medical instruments because it allows us to predict the output voltage for a given stimulus level, and therefore the gain of the amplifier required for processing the signal.

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.

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

- 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.



Potentiometer Transducers

Example: Calculate the change in output voltage of a linear potentiometer transducer that undergoes a 20 percent change in displacement.

Solution

Assuming that the current flowing through the transducer is constant, from Ohm's law,

$$\Delta V = I \times \Delta R$$

Hence, since the resistance between the sliding contact and one terminal of the resistor is linearly proportional to the displacement, a 20 percent change in displacement will produce a 20 percent change in the output voltage of the transducer.

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 wrapping an elastic resistive transducer around the leg and measuring the rate of change in resistance of the transducer 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 a patient's breathing pattern by wrapping the elastic band around the chest.

Elastic Resistive Transducers

- 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;

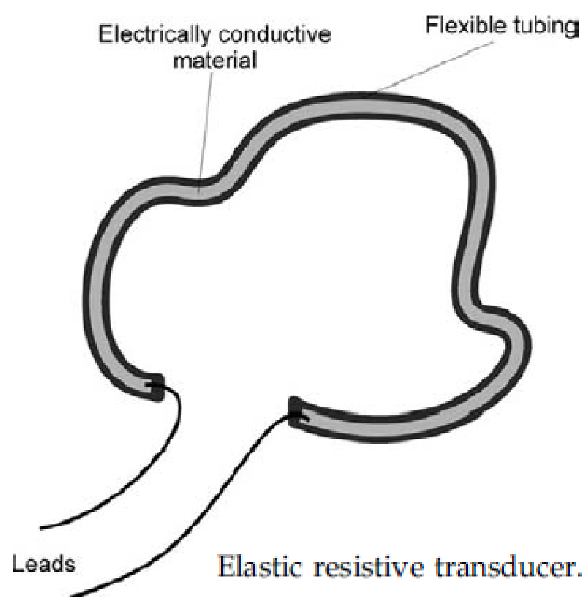
$$R = \rho \frac{I}{A}$$

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)



Elastic resistive transducer.

Elastic Resistive Transducers

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.

(2) 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 $\pi\,(0.0025)^2\ \text{m}^2 = 1.96 \cdot 10^{-5}\ \text{m}^2$.

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

2.

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

Elastic Resistive Transducers

Example: Calculate the change in voltage that is induced across the elastic transducer in the previous Example assuming that normal breathing produces a 10 percent change in chest circumference and a constant current of 0.5 mA is passed through the transducer.

Solution

From Ohm's law ($V = I \times R$)

$$V = 0.5\ \text{mA} \times 12\ \text{k}\Omega$$

$$\mathbf{V = 6\ V}$$

If R changes by 10 percent then;

$$\mathbf{\Delta V = 0.6\ V}$$

Inductive Displacement Transducers

Inductive displacement transducers are based on the inductance *L* of a coil given by:

$$L = \mu \times n^2 \times l \times A$$

where

- *n* = number of turns of coil (in turns per meter),
- *l* = the coil length (in meters),
- *A* = the cross-sectional area of the coil (in square meters),
- μ = effective permeability of the magnetically susceptible medium inside the coil (in henry per meter)

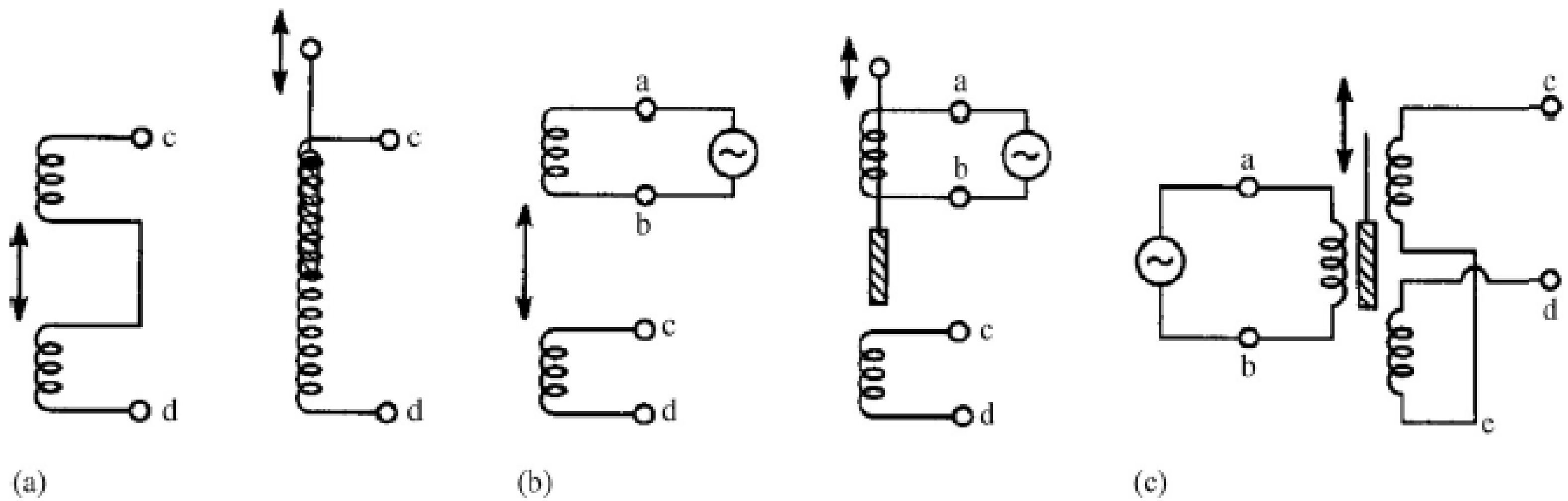
An inductance L can be used to measure displacement by varying the coil parameters.

Each of these coil parameters can be changed by mechanical means.

Inductive Displacement Transducers

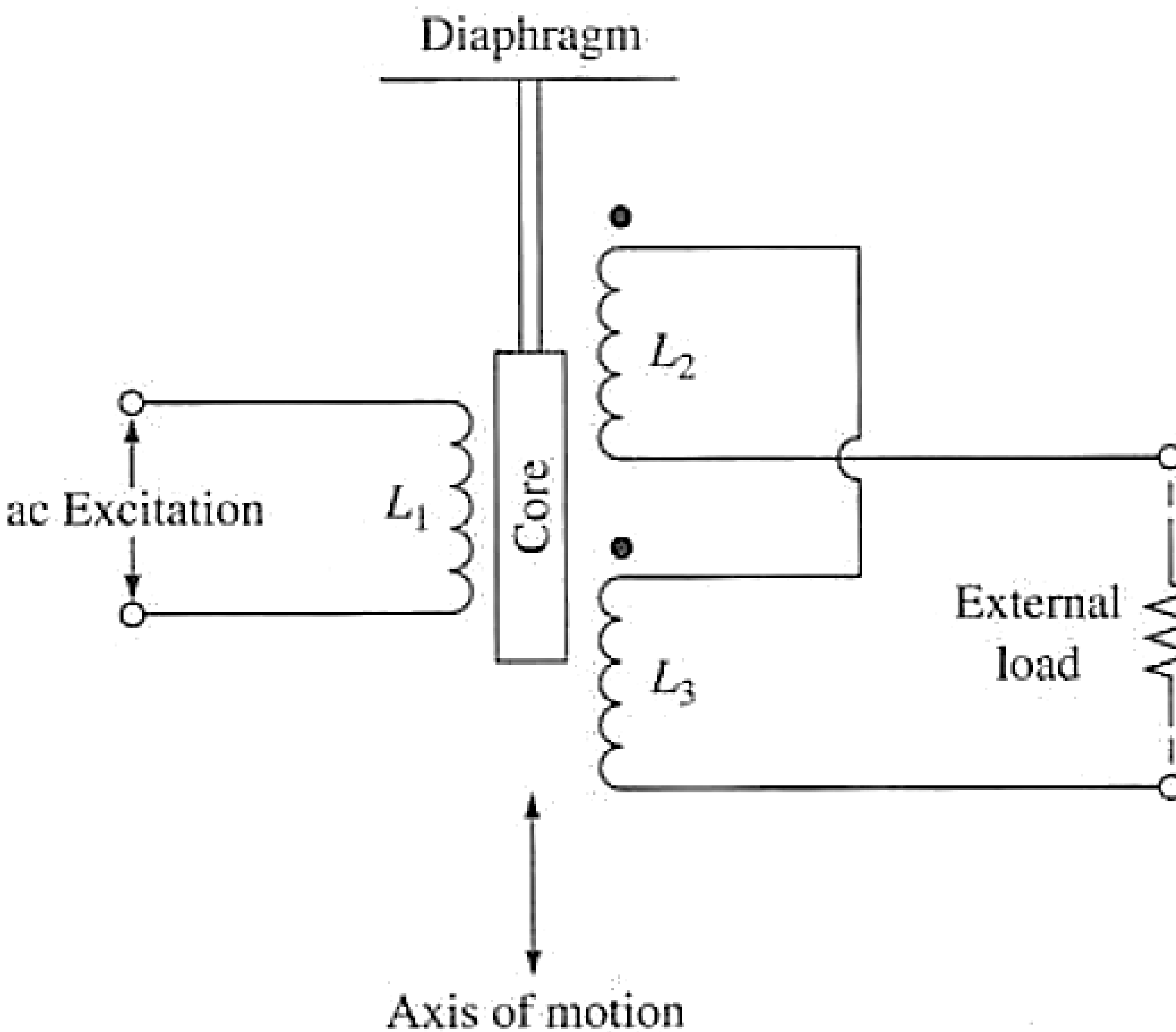
The three types of inductive displacement transducers are;

a) **Self-inductance**
b) **Mutual-inductance**
c) **Differential transformer**



Note that the mutual-inductance device (b) becomes a self-inductance device (a) when terminals b–c are connected in figure (b).

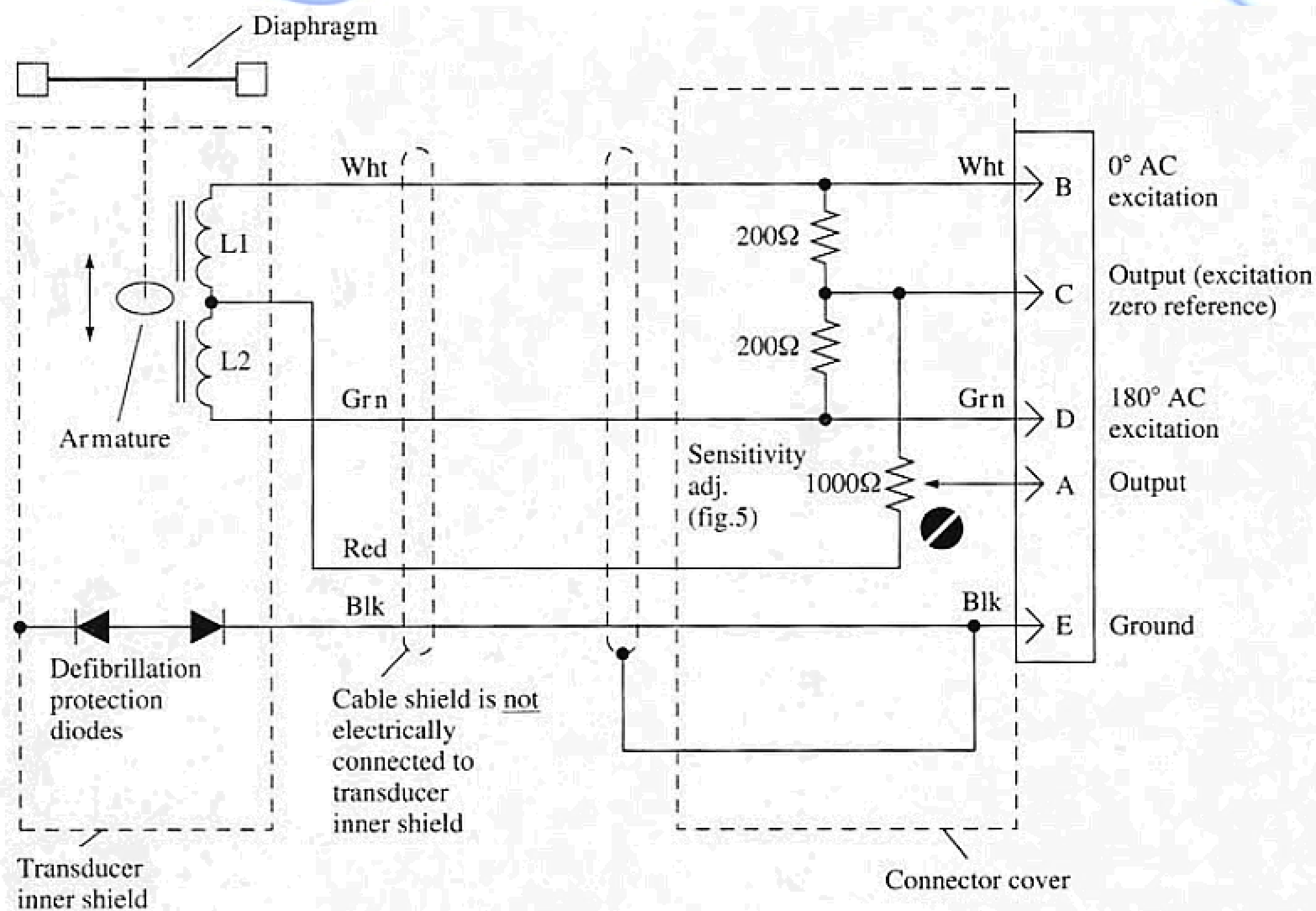
Linear Voltage Differential Transformer (LVDT)



Linear Voltage Differential Transformer (LVDT)

- The LVDT consists of one primary coil (L1) and two secondary coils (L2 & L3).
- The secondary coils are connected in opposite sense so that their respective currents tends to cancel out each other.
- When the stimulus is zero, the core affects L2 and L3, equally so the two currents cancel out each other and the output voltage is therefore zero.
- An alternating current (ac) excitation is required to the primary because the reactance of a coil is zero when dc is applied.
- When the stimulus is applied to the diaphragm, it displaces the core.
- The inductive reactances of L2 and L3, are **no** longer equal, so their respective currents are no longer equal.
- Secondary current cancellation is less than total. so a current flows in the external load, creating an output voltage signal.
- This output voltage has a magnitude proportional to the applied stimulus.
- A phase indicating the direction of the core.

Inductive Wheatstone Bridge Transducer



The Hewlett-Packard model 1280 transducer is used for measurement of arterial and venous blood pressure in mm-Hg.

Inductive Wheatstone Bridge Transducer

- Hewlett-Packard typically uses an excitation signal of 2400 Hz at 5 V (rms).

- At zero gauge pressure, the diaphragm is not distended in either direction, so the armature core is displaced equally in both L1, and L2, are equal, so the bridge is balanced. There will be no output voltage.

- When a pressure above or below atmospheric pressure is applied, the diaphragm becomes distended in one direction, and this forces the armature further into one coil than the other The respective inductive reactance of L1, and L2 are no Longer equal, so the bridge is unbalanced and an output voltage develops.

- The amplitude of the ac-output signal is proportional to the magnitude of the applied pressure.

- The phase indicates whether, the pressure in positive or negative.

- The output voltage at pin A is used to trim out normal differences between transducers (controlling the sensitivity).

Electromagnetic Flow Transducer

- Blood flow through an exposed vessel can be measured by means of an electromagnetic flow transducer.

- Consider a blood vessel of diameter, l,
- The blood vessel is filled with blood flowing with a uniform velocity, $\vec{u}$,
- The blood vessel is placed in a uniform magnetic flux, $\vec{B}$ (in weber), that is perpendicular to the direction of blood flow,
- Then the negatively charged anion and positively charged cation particles in the blood will experience a force, $\vec{F}$ (in newton), which is normal to both the magnetic field and blood flow directions and is given by;

$$\vec{F} = q(\vec{u} \times \vec{B})$$

- where q is the elementary charge (1.6×10^{-19} C).

Electromagnetic Flow Transducer

- As a result, these charged particles will be deflected in opposite directions according to the direction of the force vector, $\vec{F}$.
- This movement will produce an opposing force, $\vec{F_o}$, which is equal to;

$$\vec{F}o = q \times \vec{E} = q \times \frac{V}{l}$$

- Where $\vec{E}$ is the net electrical field produced by the displacement of the charged particles, and;
- *V*, is the potential produced across the blood vessel and is proportional to the velocity of blood through the vessel.

- The potential difference, *V*, is given by;

$$V = B \times l \times u$$

Electromagnetic Flow Transducer

Example: Calculate the voltage induced in a magnetic flow probe if the probe is applied across a blood vessel with a diameter of 5×10^{-3} m and the velocity of blood is 5×10^{-2} m/s. Assume that the magnitude of the magnetic field, B, is equal to 1.5×10^{-5} Wb/m^2. (*Note*: [Wb] = [V × S])

Solution

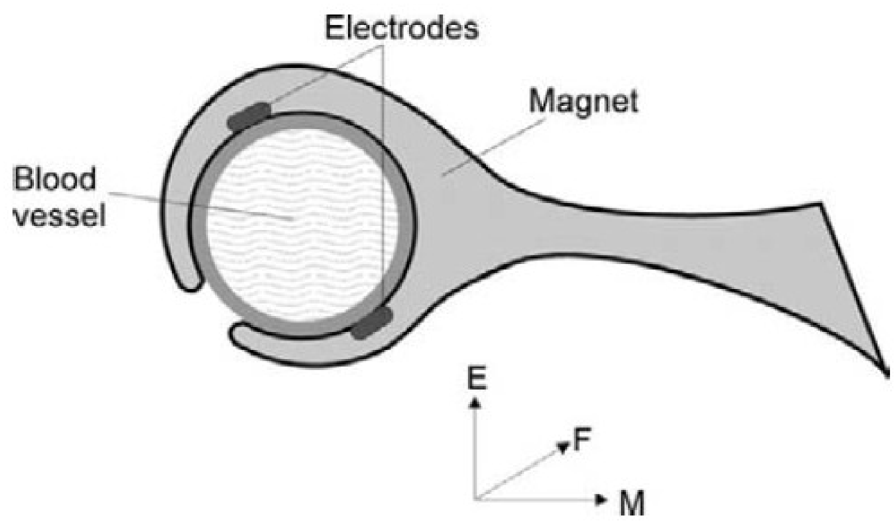
$$V = B \times l \times u$$

$$= (1.5 \times 10^{-5}\ \mathrm{Wb/m^2}) \times (5 \times 10^{-3}\ \mathrm{m}) \times (5 \times 10^{-2}\ \mathrm{m/s})$$

$$= 37.5 \times 10^{-10}\ \mathrm{V}$$

Electromagnetic Flow Transducer

- Practically, this device consists of a clip-on probe that fits closely around the blood vessel.
- The probe contains electrical coils to produce an electromagnetic field that is transverse to the direction of blood flow.
- The coil is usually excited by an AC current.
- A pair of very small biopotential electrodes are attached to the housing and rest against the wall of the blood vessel to pick up the induced potential.
- The flow induced voltage is an AC voltage at the same frequency as the excitation voltage.



Electromagnetic blood flow transducer.

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.

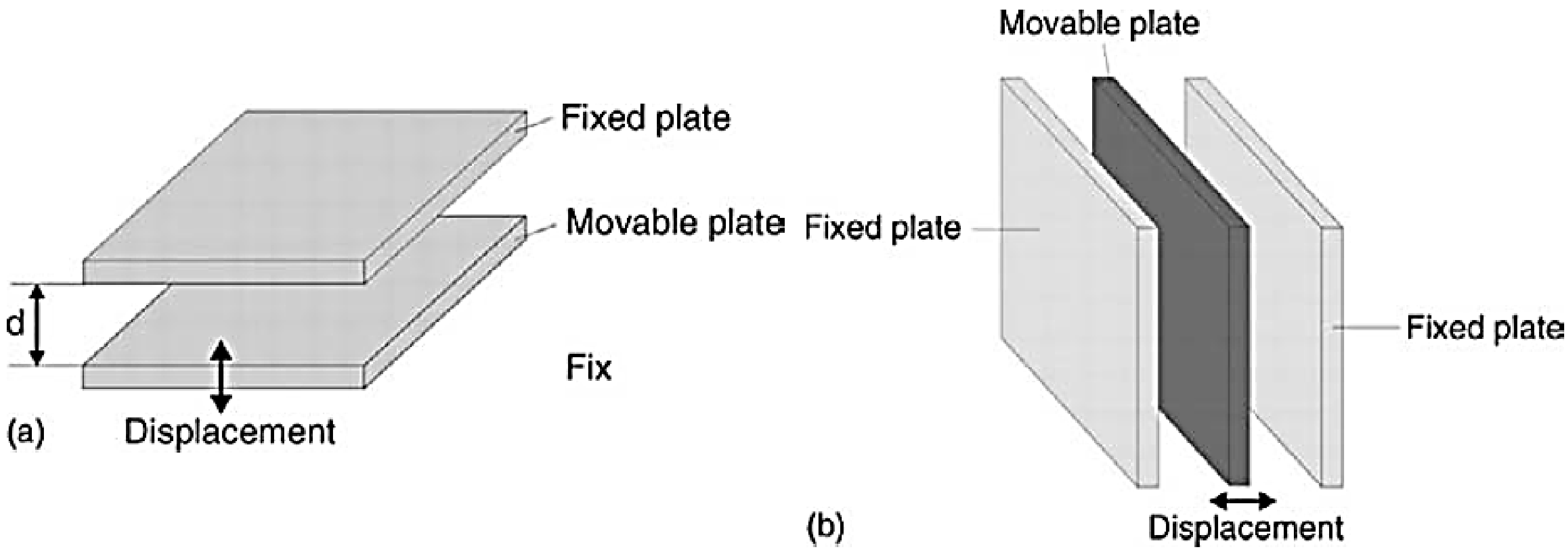
- This arrangement can be used to measure force, pressure, or acceleration.

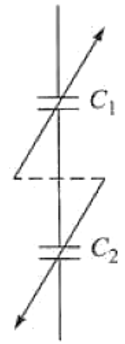
Capacitive Transducers

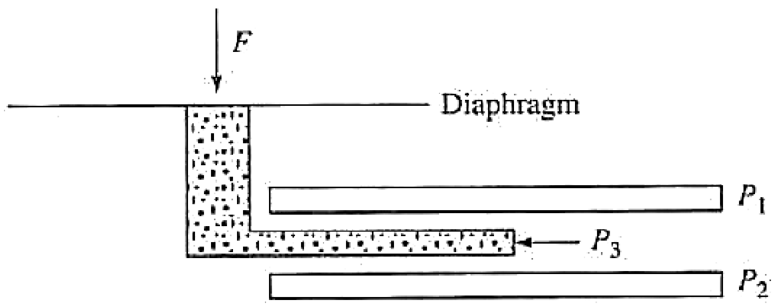
Capacitive displacement transducer:

(a) Single Capacitance

(b) Differential Capacitance.







Capacitive Transducers

Example:

Two metal plates with an area of 0.4×10^{-3} m^2 and separation distance of 1×10^{-4} m are used to form a capacitance transducer. If the material between the two plates has a dielectric constant $\varepsilon_r = 2.5$, calculate the capacitance of the transducer.

Solution

$$C = \varepsilon_o \times \varepsilon_r \frac{A}{d} = 8.85 \times 10^{-12}\ \mathrm{F/m} \times 2.5 \times 4 \times 10^{-4}\ \mathrm{m}^2/(1 \times 10^{-4}\ \mathrm{m}) = 0.885\ \mathrm{F}$$

Capacitive Transducers

Example: For a 1 cm2 capacitance sensor, R is 100 MΩ. Calculate x (or d), the plate spacing required to pass sound frequencies above 20 Hz.

Solution

Firstly, find the capacitance ***C,*** from the corner frequency;

$$C = 1/2\pi fR = 1/(2\pi 20 \times 10^8) = 80\,\text{pF}$$

We can calculate ***x*** (or ***d***) given the value of ***C***.

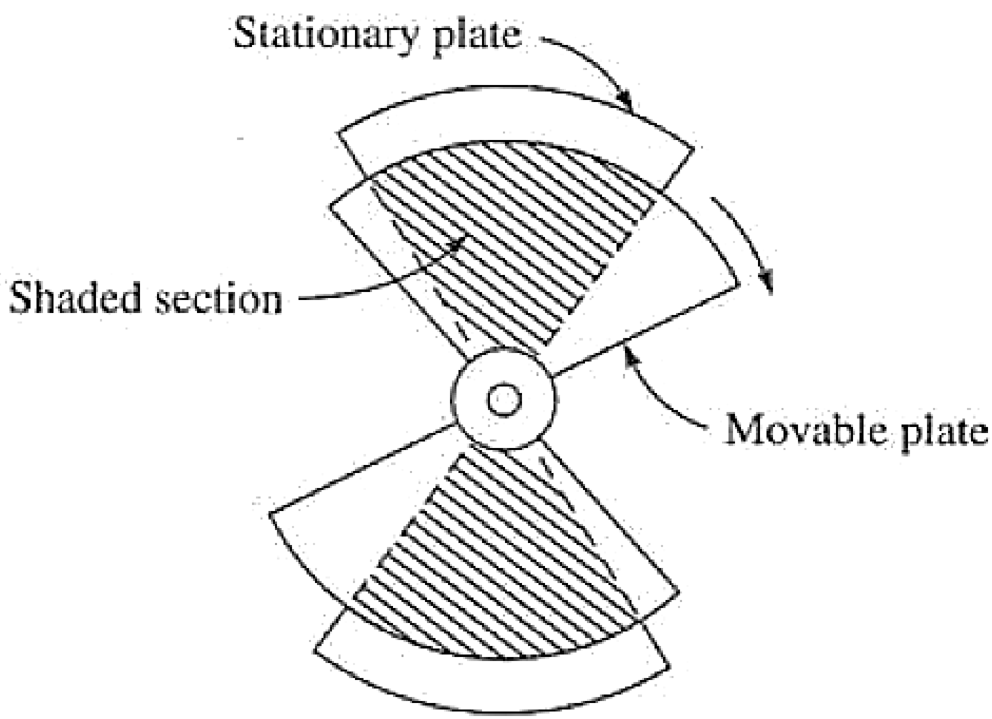
$$C = \varepsilon_o \times \varepsilon_r \times \frac{A}{d}$$

$$x = \frac{\varepsilon_0 \varepsilon_r A}{C} = \frac{(8.854 \times 10^{-12})(1 \times 10^{-4})}{80 \times 10^{-12}} = 1.11 \times 10^5\,\text{m} = 11.1\,\mu\text{m}$$

Capacitive Transducers

Butterfly Plate Transducer

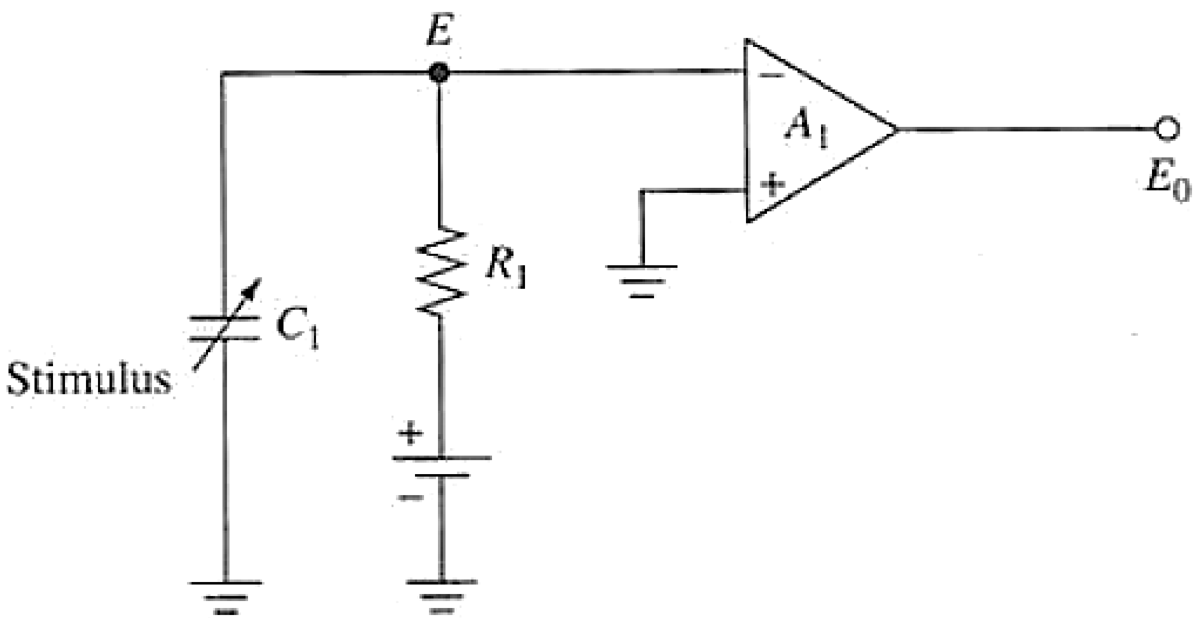
The capacitance varies because the position of the rotor determines how much of the stator plate is shaded by the rotor.



Capacitive Transducers

Electrometer Transducer

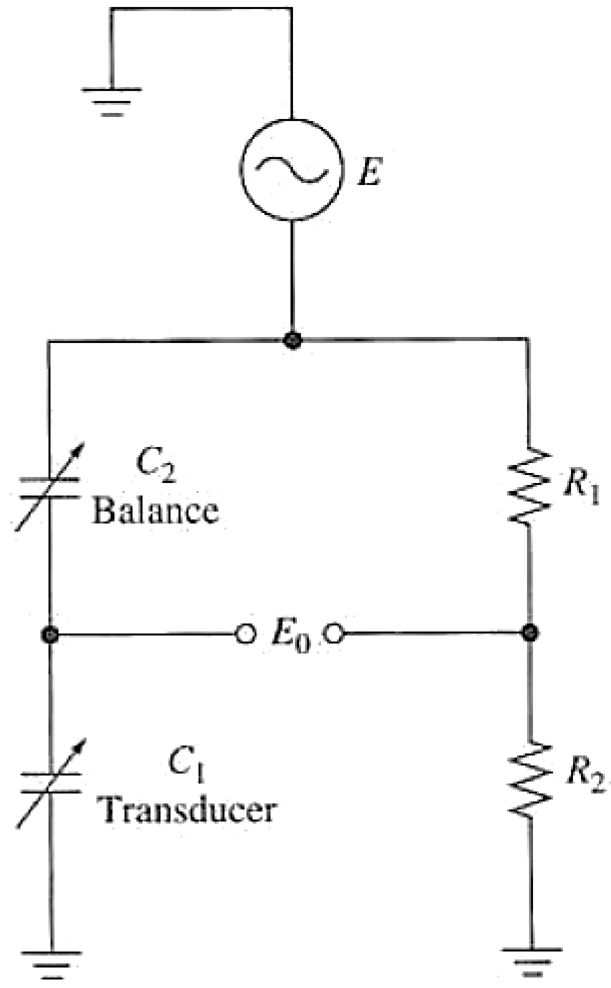
- In this circuit, the capacitance of the transducer is charged through a constant current source (R_1, and E).
- The voltage across the capacitance (the voltage applied to the input of the amplifier) depends on the capacitance, which is proportional to an applied stimulus.



Capacitive Transducers

Capacitive Wheatstone Bridge

- One arm of the bridge consists of resistances R_1 & R_2.
- Second arm consists of capacitive reactances C_1 & C_2.
- Capacitor C_1, represents the capacitance of the transducer.
- Capacitor C_2, is the capacitance of a variable trimmer capacitor used to balance the bridge under zero stimulus conditions.



Capacitive Transducers

- Capacitive displacement transducers can be used to measure respiration or movement by attaching multiple transducers to a mat that is placed on a bed.

- A capacitive displacement transducer can also be used as a pressure transducer by attaching the movable plate to a thin diaphragm that is in contact with a fluid or air.

- By applying a voltage across the capacitor and amplifying the small AC signal generated by the movement of the diaphragm, it is possible to obtain a signal that is proportional to the applied external pressure source.

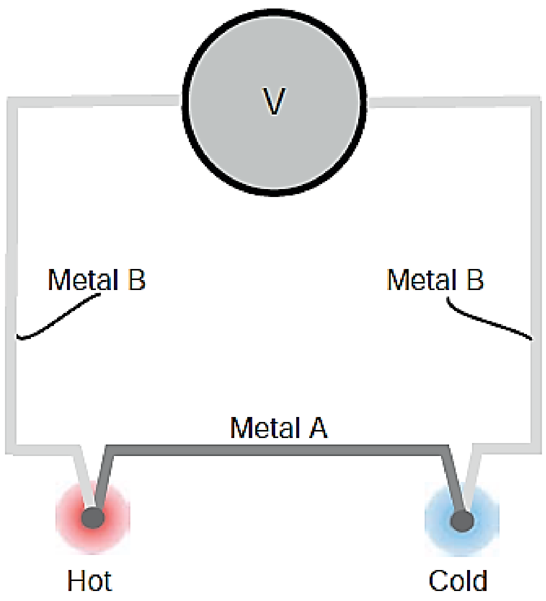
Temperature Transducers

There are three types of common temperature transducers:

1. **Thermocouples**
2. **Thermistors**
3. **Solid-state PN Junctions**

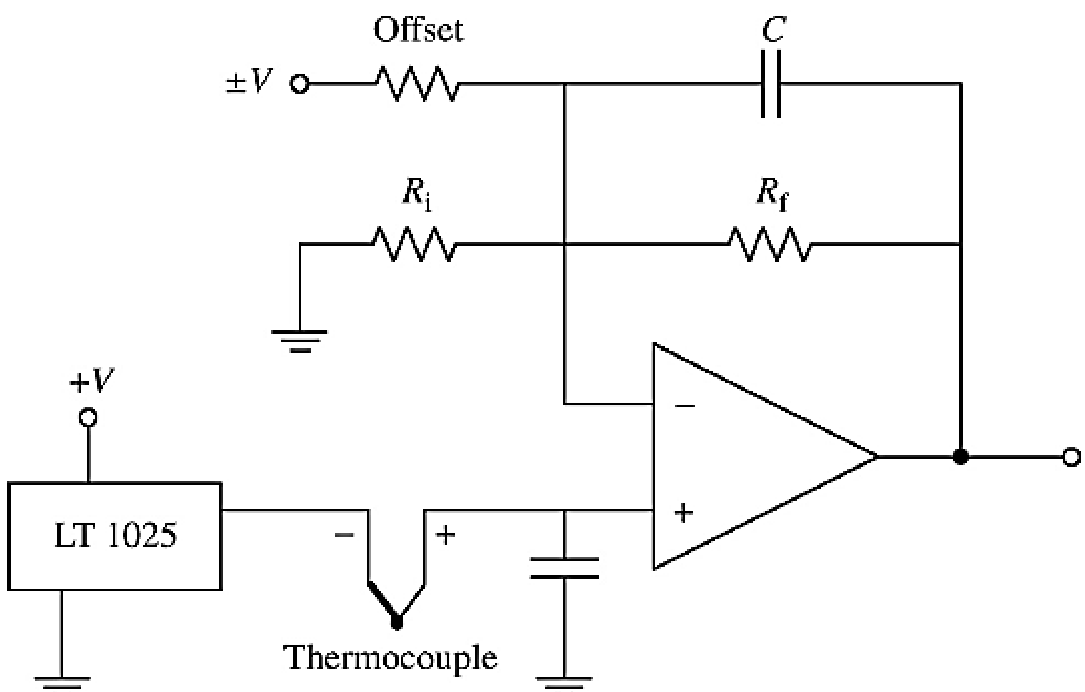
Thermocouples

- Thermocouples are temperature transducers formed by joining together two dissimilar metals, based on the discovery by Seebeck in 1821.
- When the two junctions of these dissimilar materials are maintained at different temperatures, an electromotive force (EMF) is generated.
- The magnitude of the EMF is dependent on the temperature at the junctions and the properties of the materials.
- This means that the thermocouple is only capable of recognizing a temperature difference between two points and it cannot measure absolute temperature directly.



Thermocouples

- Figure shows the modern thermocouple signal conditioners contain an electronic cold junction.
- The LT1025 electronic cold junction and the hot junction of the thermocouple yield a voltage that is amplified by an inverting amplifier.



Thermocouples

- Increased sensitivity may be achieved by connecting a number of thermocouples in series, all of them measuring the same temperature and using the same reference junction.
- An arrangement of multiple-junction thermocouples is referred to as a thermopile.
- Parallel combinations may be used to measure average temperature.
- Thermocouples can be made small in size, so they can be inserted into catheters and hypodermic needles.

Thermocouples

Thermocouples have the following advantages:

- Fast response time (time constant as small as 1 ms),
- Small size (down to 12 mm diameter),
- Ease of fabrication, and
- Long-term stability.

The disadvantages of thermocouples are:

- Small output voltage,
- Low sensitivity, and
- The need for a reference temperature.

Thermocouples

The relationship between the EMF across a junction of two dissimilar metals, ***E***, and the temperature of the measurement junction, ***T***, can be approximated using the following truncated power series expansion:

$$E = c_0 + c_1 T + c_2 T^2 + \cdots$$

where c_i are empirically derived calibration coefficients, ***T*** is given in degrees centigrade, and ***E*** is in mV.

The Seebeck coefficient **α**, which describes the temperature sensitivity of the thermocouple, can be derived by differentiating the above Eq with respect to T:

$$\alpha = \frac{dE}{dT} = c_1 + 2c_2 T + \cdots$$

Thermocouples

Table: Properties of Selected Thermocouple Materials.

Thermocouple	Sensitivity μV/°C (@25°C)	Operating Range (°C)
Chromel/Alumel	40.6	−270 to 1,300
Copper/Constantan	40.9	−270 to 600
Iron/Constantan	51.7	−270 to 1,000
Chromel/Constantan	60.9	−200 to 1,000

Thermocouples

Example: A Chromel/Alumel thermocouple has the following empirical coefficients;

$$C_0 = -1.76004 \times 10^{-2}$$

$$C_1 = 3.89212 \times 10^{-2}$$

$$C_2 = 1.85587 \times 10^{-5}$$

Find the EMF generated by this thermocouple at a temperature of 500^{o}C.

Solution

Substituting the calibration coefficients in the equation we get;

$$E = c_o + c_1 T + c_2 T^2 + \cdots$$

$$\mathrm{E} \cong 24.1\ \mathrm{mV}.$$

Thermocouples

Example: Find the Seebeck coefficient α for the Chromel/Alumel thermocouple at a temperature of 500°C, with the help of following coefficients.

$$C_0 = -1.76004 \times 10^{-2}$$

$$C_1 = 3.89212 \times 10^{-2}$$

$$C_2 = 1.85587 \times 10^{-5}$$

Solution

$$\alpha = \frac{dE}{dT} = c_1 + 2c_2T + \cdots$$

$$\alpha \cong 57\ \mu V/^\circ C.$$

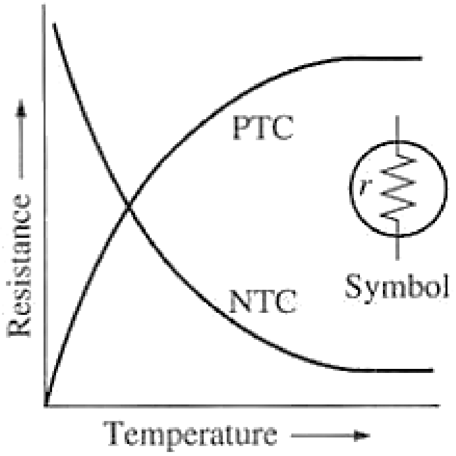
Thermistors

- Thermistors are temperature-sensitive transducers made of compressed sintered metal oxides (such as nickel, manganese, or cobalt) that change their resistance with temperature.

- There are two types of thermistors: positive temperature coefficient (PTC) and negative temperature coefficient (NTC).

- The resistance of thermistors with a PTC is increases as temperature increases.

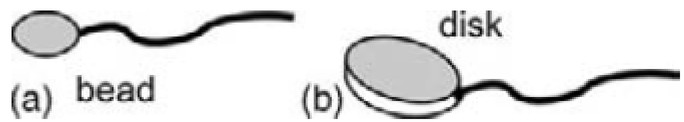
- The resistance of thermistors with a NTC is decreases as temperature increases.



Thermistors

- 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 (-3 to -5%/^{o}C), and have long-term stability characteristics (0.2% of nominal resistance value per year).

Thermistors

- The empirical relationship between the thermistor resistance R_t and absolute temperature *T* in kelvin (K) (the SI unit kelvin does not use a degree sign) is;

$$R_T = R_0 \times \exp\left[\beta \times \left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

where

$$\beta = \text{material constant for thermistor, K}$$
$$T_0 = \text{standard reference temperature, K}$$

- The β, also known as the characteristic temperature, is in the range of 2500 to 5000 K. It is usually about 4000 K.
- The temperature coefficient α can be found by differentiating the above equation with respect to *T* and dividing by R_t. Thus;

$$\alpha = \frac{1}{R_t}\frac{dR_1}{dT} = -\frac{\beta}{T^2}(\%/\text{K})$$

- Note that α is a nonlinear function of temperature.

Thermistors

Example: A thermistor with a material constant β of 4,500 K is used as a thermometer. Calculate the resistance of this thermistor at 25°C. Assume that the resistance of this thermistor at body temperature (37°C) is equal to 85 Ω.

Solution

Using the resistance-temperature characteristic of a thermistor gives;

$$R_T = R_0 \times \exp\left[\beta \times \left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

$$R_T = 85 \times \exp\left[4500 \times \left(\frac{1}{298} - \frac{1}{310}\right)\right] = 152.5\ \Omega$$

Thermistors

Example: For a thermistor assume self-heating < 0.1°C, voltage = 5V, dissipation coefficient (DC) = 2.0mW/°C. Calculate minimum thermistor resistance.

Solution

$$\Delta T = \frac{P}{\text{D.C.}} = \frac{V^2/R}{\text{D.C.}}$$

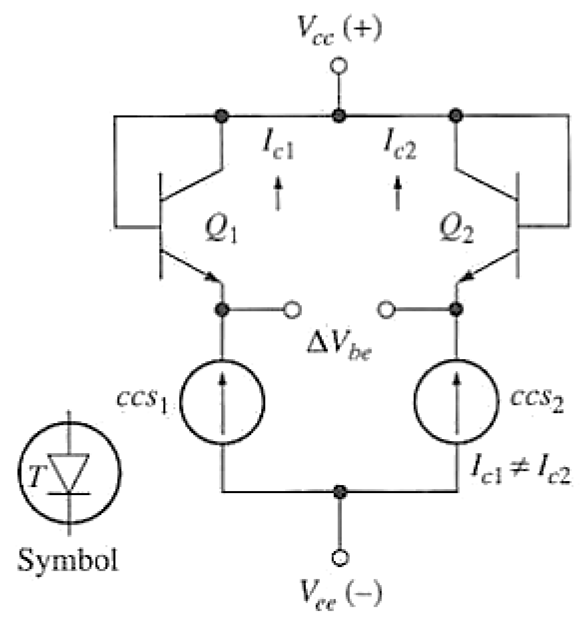
$$R = \frac{V^2}{\Delta T(\text{D.C.})} = \frac{5^2}{0.1\,^\circ\text{C}(0.002\,\text{W}/^\circ\text{C})} = 125,000\ \Omega$$

Choose next larger available size $= 500,000\,\Omega$

Solid-State PN Junctions

- Most temperature transducers, however, use a diode-connected bipolar transistor such as the one in the figure.
- We know that the base-emitter voltage of a transistor is proportional to temperature.
- For the differential pair in the figure the transducer output voltage is

$$\Delta V_{be} = \frac{KT \ln(I_{c1}/I_{c2})}{q}$$



where

K is Boltzmann's constant

T is the temperature in degrees kelvin

q is the electronic charge, in coulombs per electron

I_{c1} and I_{c2}, are the collector currents of Q_1, and Q_2

Solid-State PN Junctions

In the equation;

- The quantity ***K/q*** is a ratio of constants and is constant under all circumstances.
- The current ratio I_{c1}/I_{c2} is held constant by using constant current sources in the emitter circuits of ***Q1***, and ***Q2.***
- Of course, the logarithm of a constant is also a constant.
- So the only variable in Equation is the temperature.

$$\Delta V_{be} = \frac{KT \ln(I_{c1}/I_{c2})}{q}$$

Solid-State PN Junctions

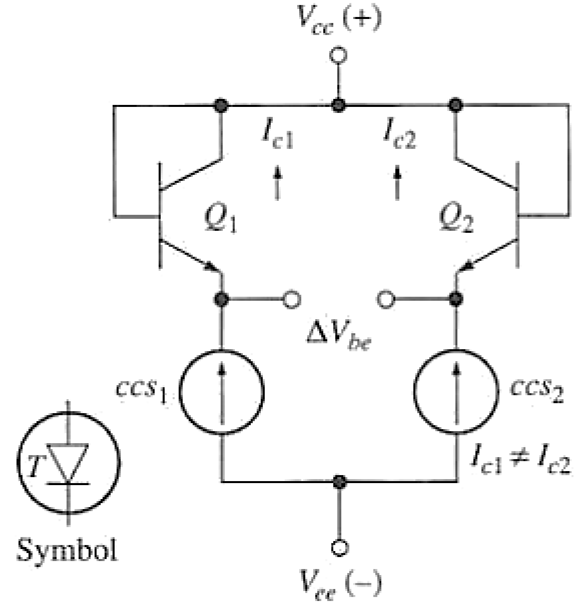
Example: Find the output voltage of a temperature transducer constructed as shown in the figure, if I_{c1} is 2 mA, and I_{c2} is 1 mA and the temperature is 37°C. (Hint 37°C is (37 + 273) °K, or 310 °K).

Solution

K is Boltzmann's constant (1.38×10^{-23} J/°K)

T is the temperature in degrees kelvin (*Note:* 0°C = 273°K)

q is the electronic charge, 1.6×10^{-19} coulombs per electron



$$\Delta V_{be} = (KT \ln(I_{c1}/I_{c2})/q$$

$$\Delta V_{be} = \frac{(1.38 \times 10^{-23} \text{J/°K})(310 \text{ K°}) [\ln (2 \text{ mA}/1 \text{ mA})]}{1.6 \times 10^{-19} \text{ °C}}$$

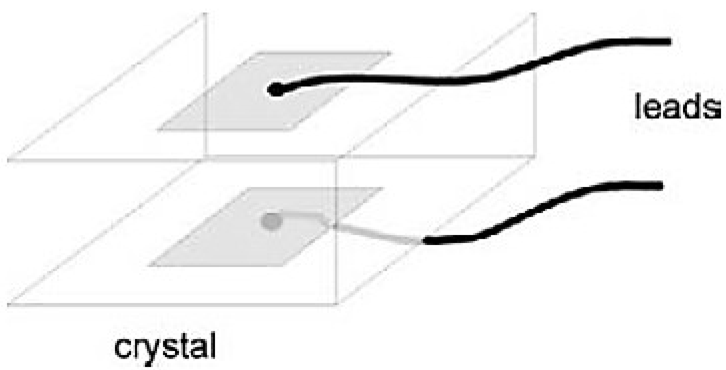
$$\Delta V_{be} = 1.85 \times 10^{-2} \text{ J/°C} = \mathbf{0.0185 \ V}$$

Piezoelectric Transducers

- A piezoelectric transducer consists of a small crystal (e.g., quartz) that contracts if an electric field is applied across its plates.

- Conversely, if the crystal is mechanically strained, it will generate a small electric potential.

- Besides quartz, several other ceramic materials, such as barium titanate and lead zirconate titanate, are also known to produce a piezoelectric effect.



Piezoelectric Transducers

Piezoelectric transducers are used in

- cardiology to listen to heart sounds (phonocardiography),
- automated blood pressure measurements, and
- for measurement of physiological forces and accelerations.

They are also commonly employed in generating ultrasonic waves (high-frequency sound waves typically above 20 kHz) that are used for measuring blood flow or imaging internal soft structures in the body.

Piezoelectric Transducers

- Piezoelectric transducers are commonly used in biomedical applications to measure the thickness of an object or in noninvasive blood pressure monitors.

For instance,

- if two similar crystals are placed across an object (e.g., a blood vessel), one crystal can be excited to produce a short burst of ultrasound.
- The time it takes for this sound to reach the other transducer can be measured.
- Assuming that the velocity of sound propagation in soft tissue, c_t, is known (typically 1500 m/s), the time, t, it takes the ultrasonic pulse to propagate across the object can be measured and used to calculate the separation distance, d, of the two transducers from the following relationship:

$$d = c_t \times t$$

Piezoelectric Transducers

- The piezoelectric principle is based on the phenomenon that when a crystal lattice is distorted by an applied force, F, the internal negative and positive charges are reoriented. This causes an induced surface charge, Q, on the opposite sides of the crystal.

- The induced charge is directly proportional to the applied force and is given by

$$Q = k \times F$$

where k is a proportionality constant for the specific piezoelectric material.

- By assuming that the piezoelectric crystal acts like a parallel plate capacitor, the voltage across the crystal, V, is given by

$$\Delta V = \frac{\Delta Q}{C}$$

where C is the equivalent capacitance of the crystal.

Piezoelectric Transducers

Example: Derive a relationship for calculating the output voltage across a piezoelectric transducer that has a thickness, ***d***, and area, ***A***, in terms of an applied force, ***F***.

Solution

The capacitance of a piezoelectric transducer can be approximated by;

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

Combine equation $\Delta V = \frac{\Delta Q}{C}$ with the relationship given by $Q = k \times F$ to give

$$\Delta V = \frac{\Delta Q}{C} = \frac{k \times F}{C} = \frac{k \times F \times d}{\varepsilon_0 \times \varepsilon_r \times A}$$

Piezoelectric Transducers

Figure (a) Equivalent circuit of piezoelectric sensor,

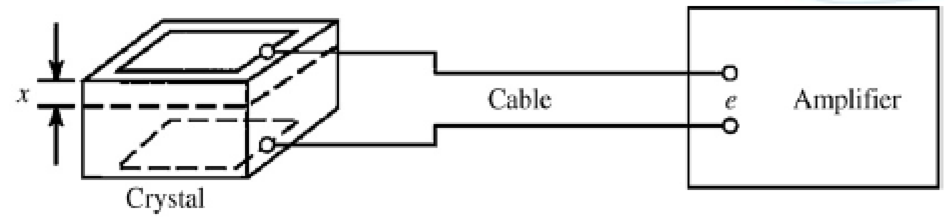
where

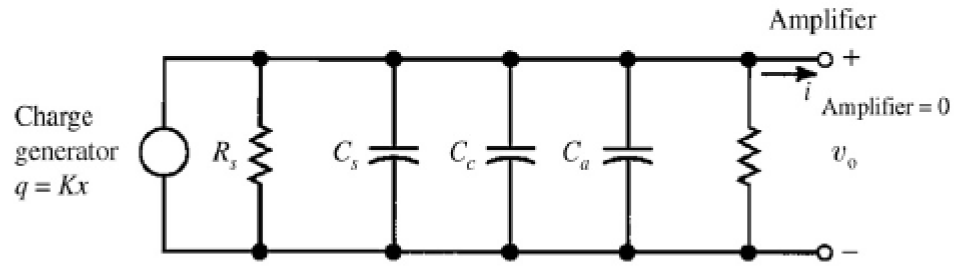
R_s = sensor leakage resistance,
C_s = sensor capacitance,

C_c = cable capacitance,

C_a = amplifier input capacitance,
R_a = amplifier input resistance,

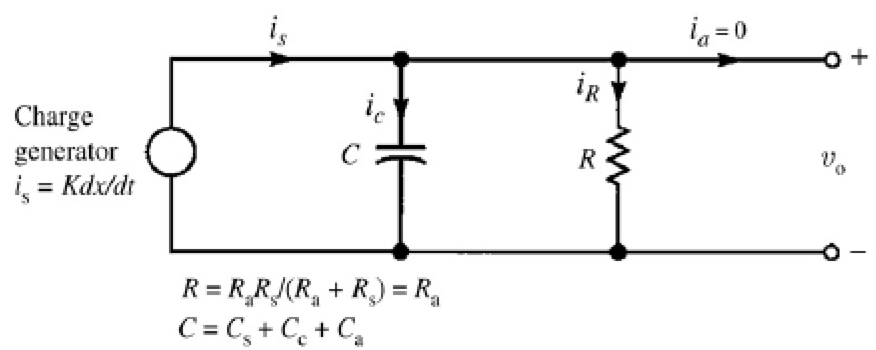
q = charge generator.





(a)

Figure (b) Modified equivalent circuit with current generator replacing charge generator.



(b)

A charge generator q defined by

$$q = Kx$$

K = proportionality constant, C/m

x = deflection

Piezoelectric Transducers

Example: A piezoelectric sensor has C = 500 pF. The sensor leakage resistance is 10 GΩ. The amplifier input impedance is 5 MΩ. What is the low corner frequency?

Solution

- We may use the modified equivalent circuit of the piezoelectric sensor given in the previous slide for this calculation.

$$f_c = 1/(2\pi RC) = 1/[2\pi(5 \times 10^6)(500 \times 10^{-12})] = 64 \text{ Hz}$$

- Note that by increasing the input impedance of the amplifier by a factor of 100, we can lower the low-corner frequency to 0.64 Hz.

Piezoelectric Transducers

Example: For a piezoelectric sensor plus cable that has 1 nF capacitance, design a voltage amplifier by using only one non-inverting amplifier that has a gain of 10. It should handle a charge of 1μC generated by the carotid pulse without saturation. It should not drift into saturation because of bias currents. It should have a frequency response from 0.05 to 100 Hz. Add the minimal number of extra components to achieve the design specifications.

Solution

Calculate the voltage from $V = Q/C = 1\,\mu\text{C}/1\,\text{nF} = 1\,\text{kV}.$

- Because this is too high, add a shunt capacitor C_s = 1μF to achieve 1.0 V. Allow for a gain of 10.

Continue on next slide

Piezoelectric Transducers

- To achieve low-corner frequency, add shunt

$$R_s = 1/2\pi f_c C = 1/2\pi(0.05)(1\ \mu F) = 3.2\ M\Omega.$$

- In order to achieve a gain of +10 in a noninverting amplifier, then select R_f = 10 kΩ and R_i = 11.1kΩ.

- To achieve high-corner frequency,

$$C_f = 1/2\pi f_c R_f = 1/2\pi(100)(10\,k\Omega) = 160\,nF.$$

Questions?