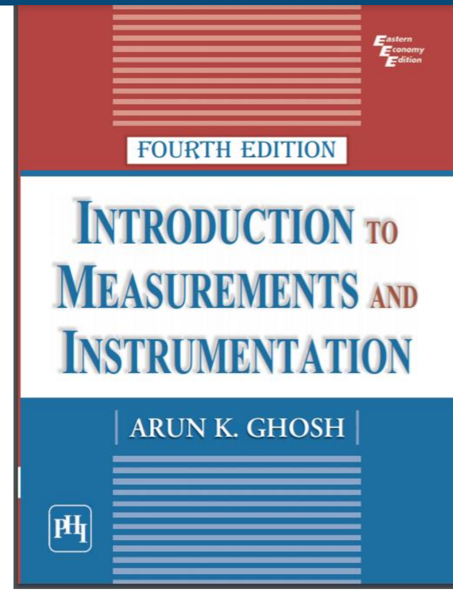
NUST
SCHOOL OF ELECTRICAL ENGINEERING
& COMPUTER SCIENCE

- Course: **EE383 Instrumentation and Measurements**
- Session: Fall 2022
- Class: BEE12
- **Lectures: Week 10**
- Course Instructor: Dr. Shahzad Younis

INSTRUMENTATION
& MEASUREMENT



Week 10

- **Chapter 6**

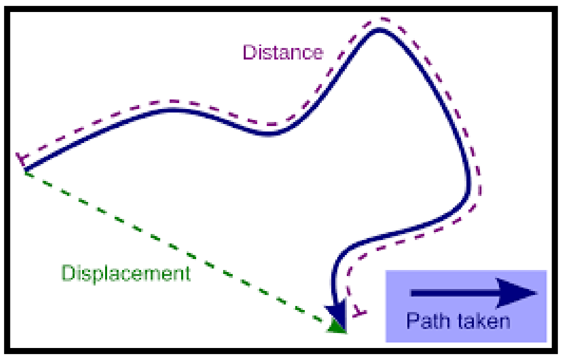
  Displacement Measurement

Book: Introduction to Measurements and Instrumentation, Arun K. Ghosh

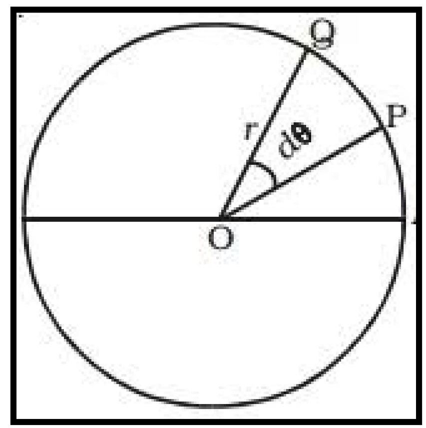
Review:
Displacement Measurement

Displacement can be of two types.

Linear Displacement



Angular Displacement



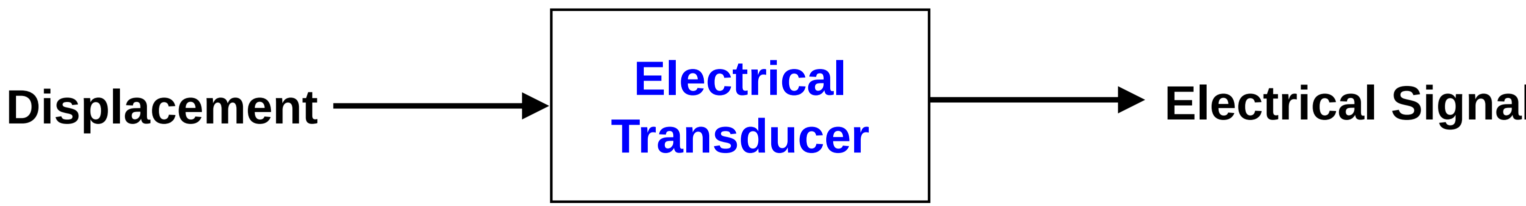
Measurement of displacement is fundamental to many measurements.

Displacement Measurement

- **Classification**
  - **Electrical**
  - **Pneumatic**
  - **Optical**
  - **Ultrasonic**
  - **Magnetostrictive**
  - **Digital**

Displacement Measurement

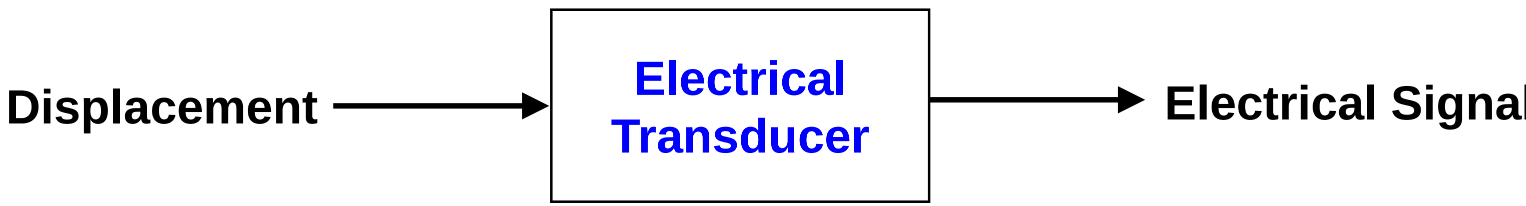
- **Electrical Transducers**
  - **Convert displacement to an electrical signal**



- Passive electrical components**: resistance, inductance and capacitance**
  - Resistive, inductive and capacitive transduction of displacement

Displacement Measurement

- ❑ **Electrical Transducers**
  - ❑ **Convert displacement to an electrical signal**



- ❑ Passive electrical components**:** resistance, inductance and **capacitance**
  - ❑ Resistive, inductive and capacitive transduction of displacement

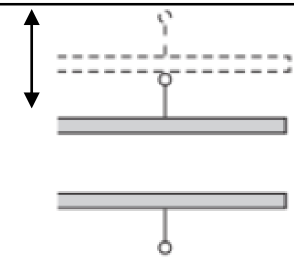
Capacitive Displacement Transducer

Capacitive Transducers

Change in capacitance is used to measure displacement.

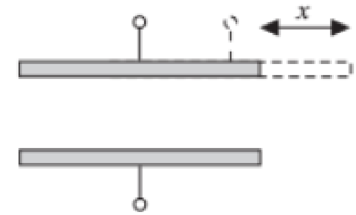
$$\boxed{C = \frac{\varepsilon A}{x} \text{ farad}}$$

- $\epsilon = \epsilon_o \epsilon_r$ is the permittivity of intervening medium (farad/meters)
  - *The absolute permittivity, often simply called permittivity and denoted by the Greek letter ε (epsilon), is a measure of the electric polarizability. he ability of a substance to store electrical energy in an electric field.*
- x is the distance between plates (meters)
- A is the overlapping area of plates (meters^2)



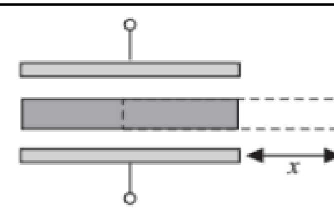
(a)

<change in the gap>



(b)

<change in the area>



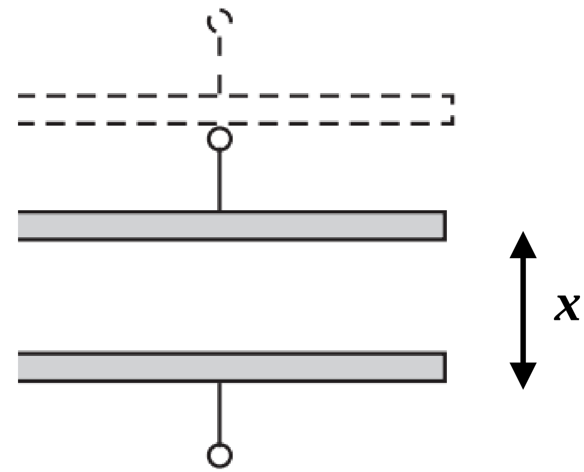
(c)

<change in the permittivity>

1. Change in the gap *x* between the plates

$$\boxed{C = \frac{\varepsilon A}{x} \text{ farad}}$$

$$\Rightarrow \boxed{\text{Sensitivity} = S = \frac{dC}{dx} = -\frac{\text{constant}}{x^2}}$$



- **Linearization Techniques:**

  1. By measuring the per cent change in capacitance
  2. Using a charge amplifier
  3. Measuring impedance
  4. Differential arrangement

Linearization Techniques

1. Measuring percent change in capacitance

$$\boxed{C = \frac{\varepsilon A}{x}}$$

$$\frac{dC}{dx} = -\frac{\epsilon A}{x^2} = -\frac{1}{x} * \left(\frac{\epsilon A}{x}\right)$$

$$\frac{dC}{dx} = -\frac{1}{x} * C$$

$$\boxed{\frac{dC}{C} = -\frac{dx}{x}}$$

Percent change in 'C' is linearly related to percent change in 'x'.

2. Measuring Impedance

$$\boxed{C = \frac{\varepsilon A}{x}}$$

$$X_c = \frac{1}{2\pi f C}$$

$$X_c = \frac{1}{2\pi f} * \left(\frac{x}{\epsilon A}\right)$$

$$\boxed{X_c \propto x}$$

Where 'f' is the frequency of exciting voltage.

Linearization Techniques

3. By using a charge amplifier

$$e_i = \frac{\int i\,dt}{C}$$

$$e_o = \frac{\int i_x\,dt}{C_x}$$

$$i = -i_x$$

$$e_o = \frac{\int i_x\,dt}{C_x} = -\frac{\int i\,dt}{C_x}$$

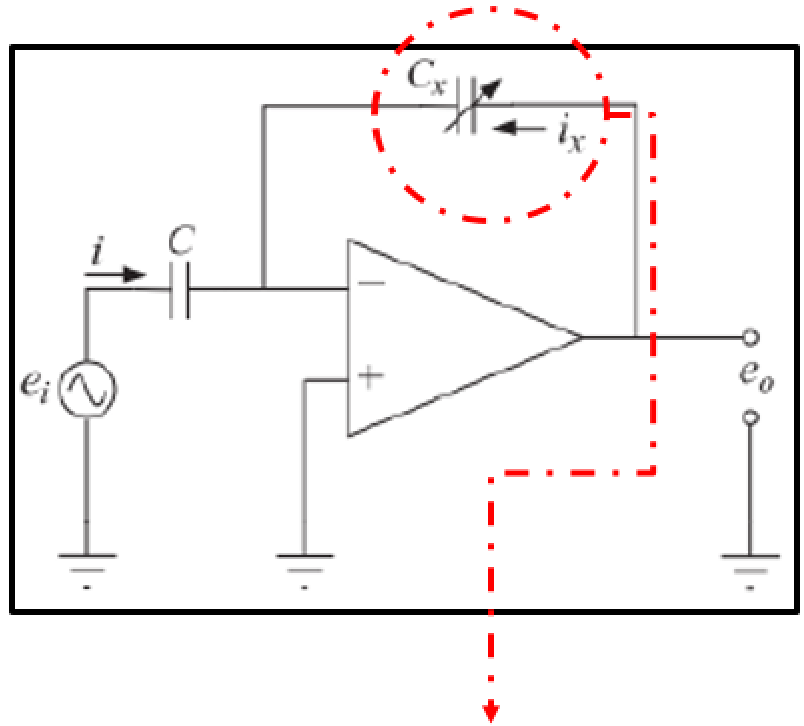
$$\boxed{\int i\,dt = C\,e_i}$$

$$e_o = -\frac{C e_i}{C_x}$$

$$\boxed{C_x = \frac{\epsilon A}{x}}$$

$$e_o = -\frac{C e_i}{\epsilon A}x$$

$$e_o \propto x$$



Displacement measuring capacitor

The output voltage changes linearly with displacement

Linearization Techniques

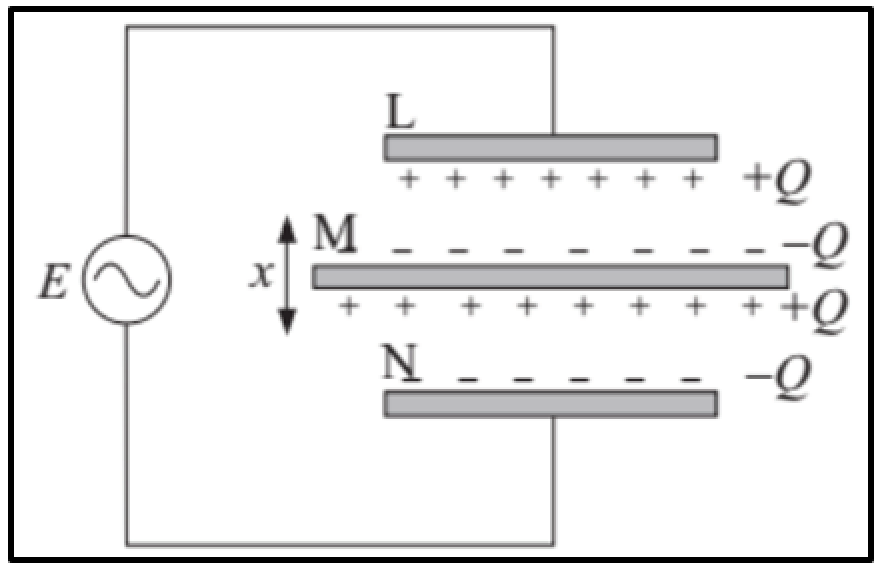
4. By using a differential arrangement of capacitors

$$\boxed{Q = EC_{LN}} \qquad E_{LM} = \frac{Q}{C_{LM}} = \frac{EC_{LN}}{C_{LM}} \qquad (1)$$

$$E_{MN} = \frac{Q}{C_{MN}} = \frac{EC_{LN}}{C_{MN}} \qquad (2)$$

$$C_{LN} = \frac{\epsilon A}{2d} \qquad (3)$$

'*d*' is the distance between two adjacent plates



When 'M' is midway, $C_{LM} = C_{MN}$

If 'M' is displaced upwards by a distance x

$$C_{LM} = \frac{\epsilon A}{d-x}, C_{MN} = \frac{\epsilon A}{d+x} \qquad (4)$$

Substituting (3) & (4) in (1) & (2)

$$E_{LM} = \frac{E(d-x)}{2d}, E_{MN} = \frac{E(d+x)}{2d}$$

$$\Delta E = E_{LM} - E_{MN} = \frac{E}{d}x$$

$$\boxed{\Delta E \propto x}$$

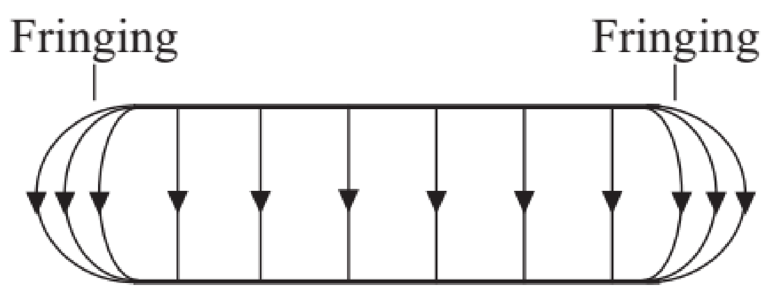
The voltage difference changes linearly with displacement

1. Change in the gap x between the plates

- **fringing flux**

1. Change in the gap *x* between the plates

- **Effect of fringing flux**
  - Variation in spacing (If *x< l or w : accurate results C vs* x^{-1}*)*
  - Increases with plate spacing with respect to plate dimensions
  - Measured capacitance can be much larger than calculated
    - When plate spacing increases relative to the plates length and width



1. Change in the gap *x* between the plates

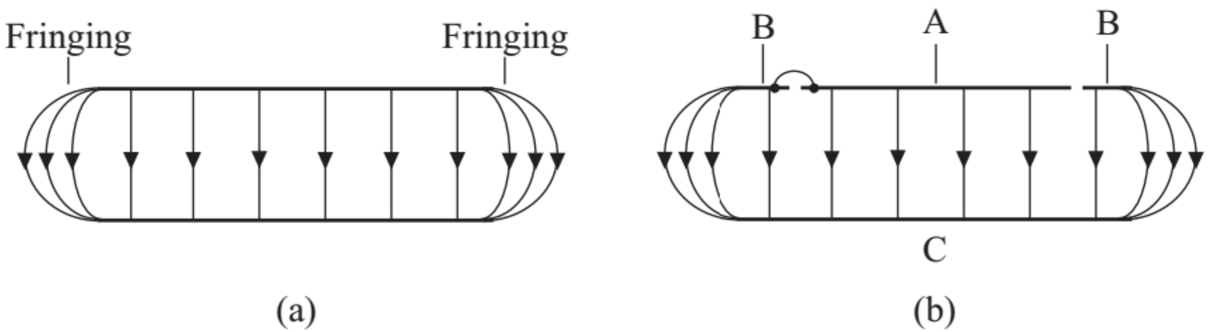


Fig. 6.21 (a) Fringing of flux at the ends of plates of a parallel-plate capacitor. (b) Guard ring (B) to eliminate the effect of fringing in a capacitor. B is at the same electrical potential with A.

- ❑ **Guard ring to eliminate the fringing effect**
  - ❑ Circular plates A of the capacitor is surrounded (but, electrically connected) by a concentric annular plate B in the same plane
  - ❑ Fringing effect is at the plate B

Example 6.7

Figure 6.22 shows a circuit with a variable air gap parallel plate capacitor as the sensing element. Show that the circuit acts as a velocity sensor for very small displacements, and find the proportionality constant between the voltage e_o and the input velocity v. Nominal (zero displacement) capacitance C is 50 pF and the nominal (zero displacement) distance between the capacitor plates x_0 is 5 mm.

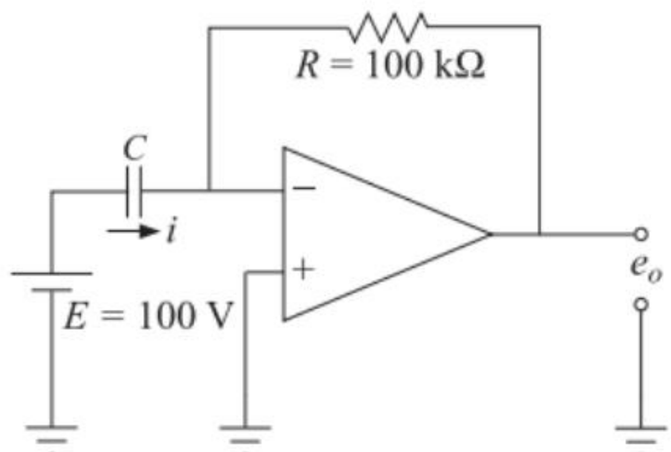
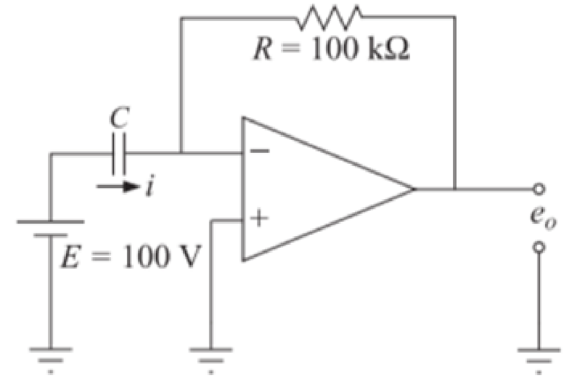


Fig. 6.22 Variable air gap parallel plate capacitor (Example 6.7).

Example 6.7



Solution

We know, $C = \dfrac{\varepsilon A}{x}$, where terms have their usual meaning. Therefore,

$$\frac{dx}{dt} = \frac{d}{dt}\left(\frac{\varepsilon A}{C}\right) = -\frac{\varepsilon A}{C^2}\frac{dC}{dt} = -\frac{Cx}{C^2}\frac{dC}{dt}$$

$$= -\frac{x}{C}\frac{dC}{dt} \qquad \text{(i)}$$

We also know, $C = \dfrac{Q}{E}$. Therefore,

$$\frac{dC}{dt} = \frac{1}{E}\frac{dQ}{dt} = \frac{i}{E}$$

where i denotes current. Substituting the value of $\dfrac{dC}{dt}$ in Eq. (i), we get on rearranging

$$i = -\frac{EC}{x}\frac{dx}{dt}$$

Therefore,

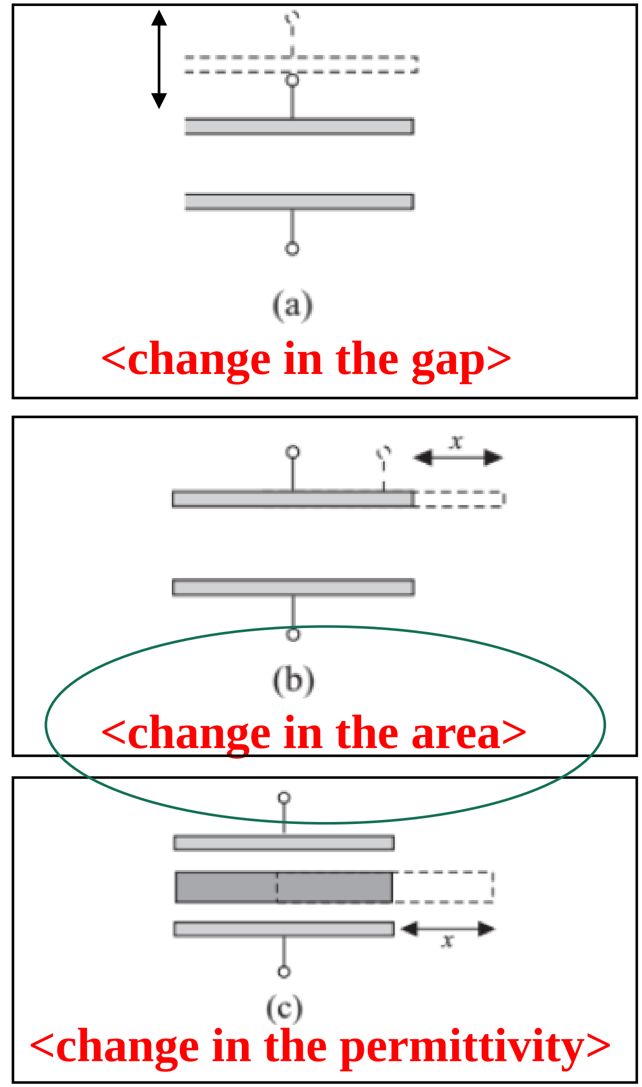
$$e_o = -iR = \frac{ECR}{x}\frac{dx}{dt} = \frac{(100)(50 \times 10^{-12})(100 \times 10^3)}{0.5}\frac{dx}{dt} = 1.0 \times 10^{-3} v$$

Capacitive Transducers

Change in capacitance is used to measure displacement.

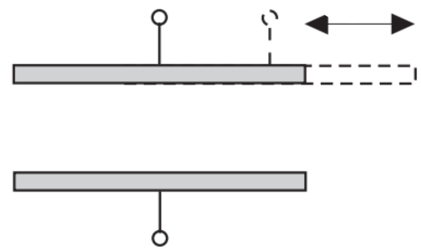
$$\boxed{C = \frac{\varepsilon A}{x} \text{ farad}}$$

- $\epsilon = \epsilon_o \epsilon_r$ is the permittivity of intervening medium (farad/meters)
  - *The absolute permittivity, often simply called permittivity and denoted by the Greek letter ε (epsilon), is a measure of the electric polarizability. he ability of a substance to store electrical energy in an electric field.*
- x is the distance between plates (meters)
- A is the overlapping area of plates (meters^2)



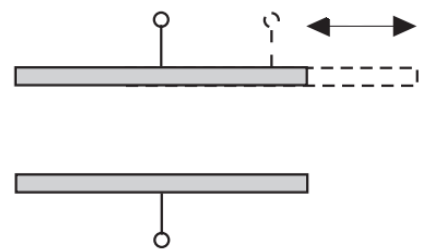
2. Change in the effective overlapping area A btw plates

- **Parallel-plate capacitor**



2. Change in the effective overlapping area A btw plates

- **Parallel-plate capacitor**



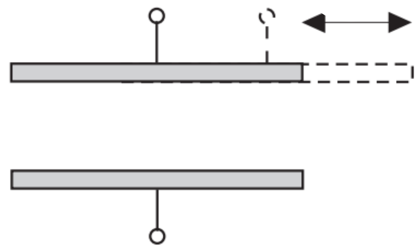
- **For overlap length l, width w and spacing x**
  - **if one of the plates is displaced along l, the area of overlap changes**

$$C = \frac{\varepsilon l w}{x}$$

- C **is a linear function of** l

2. Change in the effective overlapping area A btw plates

- **Parallel-plate capacitor**



- **For overlap length l, width w and spacing x**
  - **if one of the plates is displaced along l, the area of overlap changes**

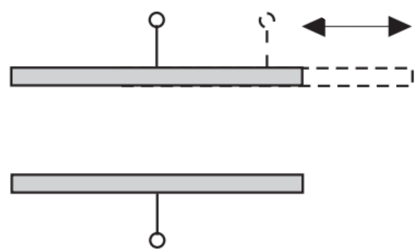
$$C = \frac{\varepsilon l w}{x}$$

$\Rightarrow$ **Sensitivity,** $dC/dl = \varepsilon w / x = \text{constant}$

- **C is a linear function of l and, sensitivity S is a constant**

2. Change in the effective overlapping area A btw plates

- **Parallel-plate capacitor**



- **For overlap length *l*, width *w* and spacing *x***
  - **if one of the plates is displaced along *l*, the area of overlap changes**

$$C = \frac{\varepsilon l w}{x}$$

Sensitivity, $dC/dl = \varepsilon w/x = \text{constant}$

- **Fringing effect does introduce non-linearity**

2. Change in the effective overlapping area A btw plates

Parallel Plate Capacitor

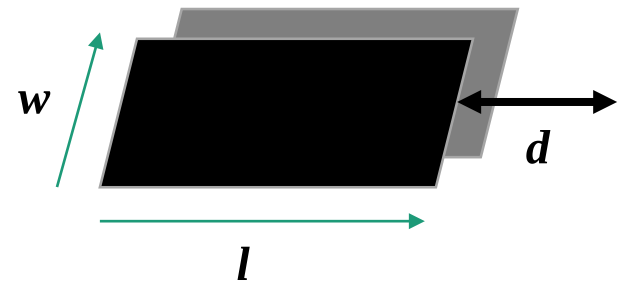
$$\boxed{C = \frac{\varepsilon A}{x}}$$

l: Length of the plate

w: width of the plate

Area of overlap = A = lw

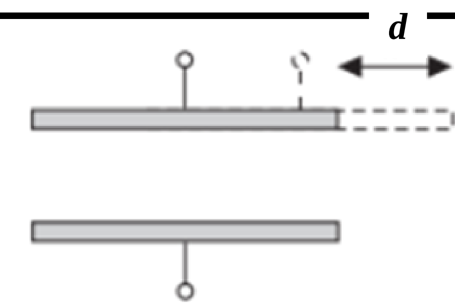
x: gap between plates



$$C_o = \frac{\epsilon l w}{x}$$

$$C = \frac{\epsilon \omega}{x} * (l - d) -= k * (l - d)$$

$$\boxed{C \propto (l - d)} \rightarrow \boxed{\Delta C \propto -\Delta d}$$

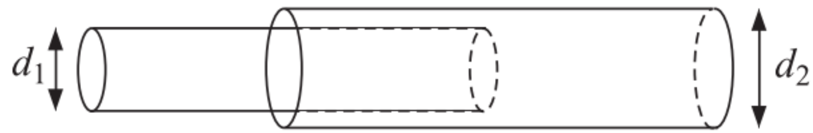


(b)

<change in the area>

Therefore, capacitance changes linearly and no extra circuitry is required for linearization.

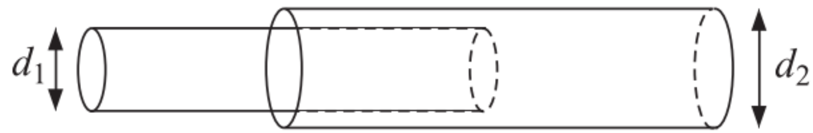
2. Change in the effective overlapping area A btw plates



- **Co-axial parallel cylinders**

$$C = \frac{2\pi\varepsilon l}{\ln(d_2/d_1)}$$

2. Change in the effective overlapping area A btw plates



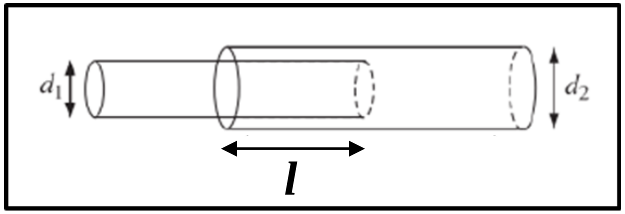
- **Co-axial parallel cylinders**

$$C = \frac{2\pi\varepsilon l}{\ln(d_2/d_1)}$$

$$\Rightarrow \quad \boxed{C \propto l}$$

2. Change in the effective overlapping area A btw plates

Coaxial Parallel Cylinder



* $$C = \frac{2\pi\epsilon l}{\ln d_2/d_1}$$

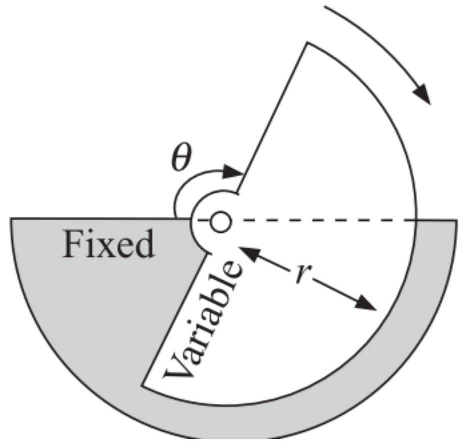
$$\boxed{C \propto l} \longrightarrow \boxed{\Delta C \propto \Delta l}$$

→ Therefore, capacitance is directly proportional to the overlapping length of parallel cylinder.

→ The variation of capacitance with length is linear, therefore no linearization is required.

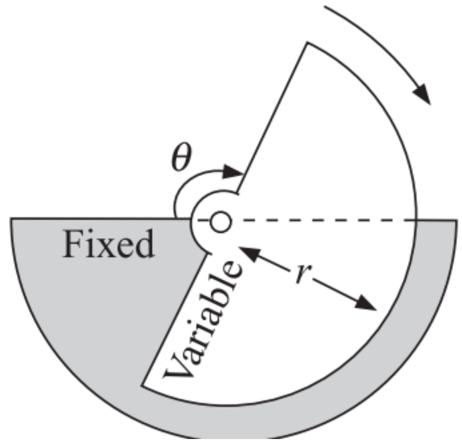
*The derivation was done in EMFT course.

2. Change in the effective overlapping area A btw plates



- ❑ **Semicircular parallel plates**
  - ❑ To measure angular displacements

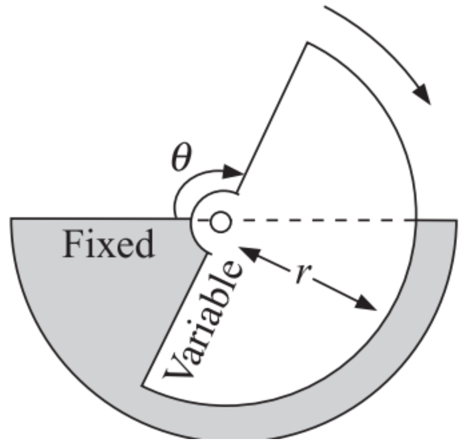
2. Change in the effective overlapping area A btw plates



- **Semicircular parallel plates**
  - capacitance is maximum when plates completely overlap, i.e. when θ= 180°

$$C_{max} = \frac{\varepsilon A}{x} = \frac{\varepsilon \pi r^2}{2x}$$

2. Change in the effective overlapping area A btw plates

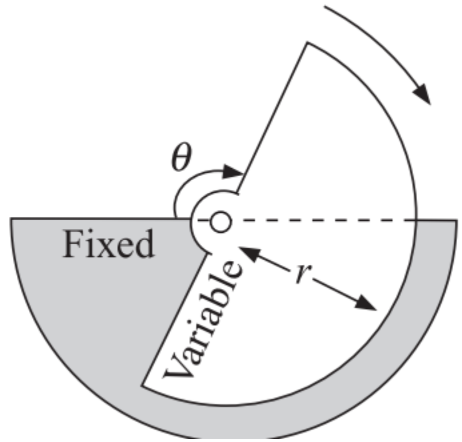


- **Semicircular parallel plates**
  - **At any angle θ**

$$C_{max} = \frac{\varepsilon A}{x} = \frac{\varepsilon \pi r^2}{2x}$$

$$C = \frac{\varepsilon \pi r^2}{2x} \frac{\theta}{180}$$

2. Change in the effective overlapping area A btw plates



- **Semicircular parallel plates**
  - **At any angle θ**

$$C = \frac{\varepsilon \pi r^2}{2x}\frac{\theta}{180}$$

$$\Rightarrow \qquad C \propto \theta$$

2. Change in the effective overlapping area A btw plates

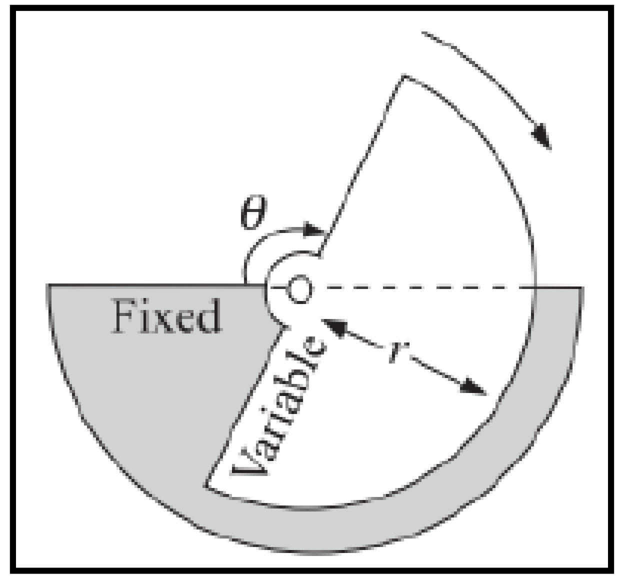
Semicircular Parallel Plates

Angular displacement can be measured using this method.

Capacitance is maximum when the plates completely overlap i.e., when θ=180°

$$C_{Max} = \frac{\epsilon}{x} A = \frac{\epsilon}{x} * \frac{\pi r^2}{2}$$

At any angle 'θ' between 0° and 180°



$$C = \frac{\pi \epsilon r^2}{x} * \frac{\theta}{360}$$

$$\boxed{C \propto \theta}$$

$$\boxed{\Delta C \propto \Delta \theta}$$

Capacitance changes linearly with angular displacement.

2. Change in the effective overlapping area A btw plates

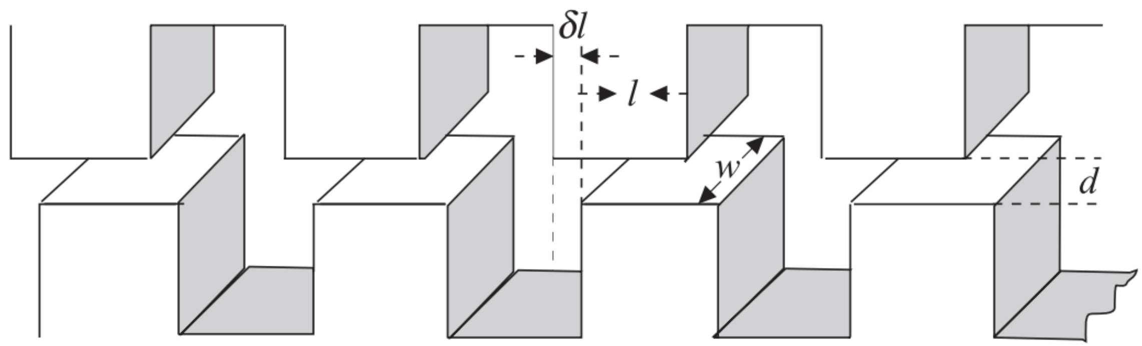


Fig. 6.25 Serrated electrode capacitor having variable effective tooth length.

- ❑ **Serrated parallel electrodes**
  - ❑ **Used to measure small angular variations**

2. Change in the effective overlapping area A btw plates

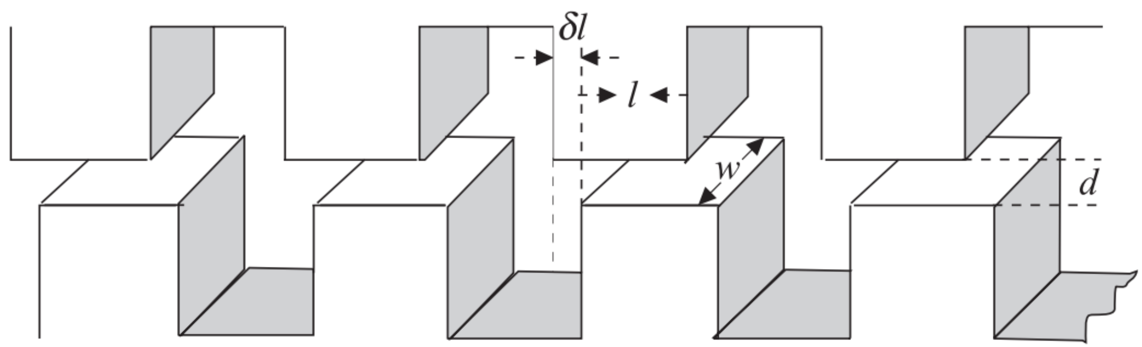


Fig. 6.25 Serrated electrode capacitor having variable effective tooth length.

- **Serrated parallel electrodes**
  - **for n pairs of teeth,**

If l is the active length of a tooth pair
w is the width of a tooth
d is the distance between the pair of nearby teeth
n is the number of pairs of teeth

then the capacitance of the serrated electrode air capacitor is given by

$$C = \frac{\varepsilon_0 n l w}{d}$$

2. Change in the effective overlapping area A btw plates

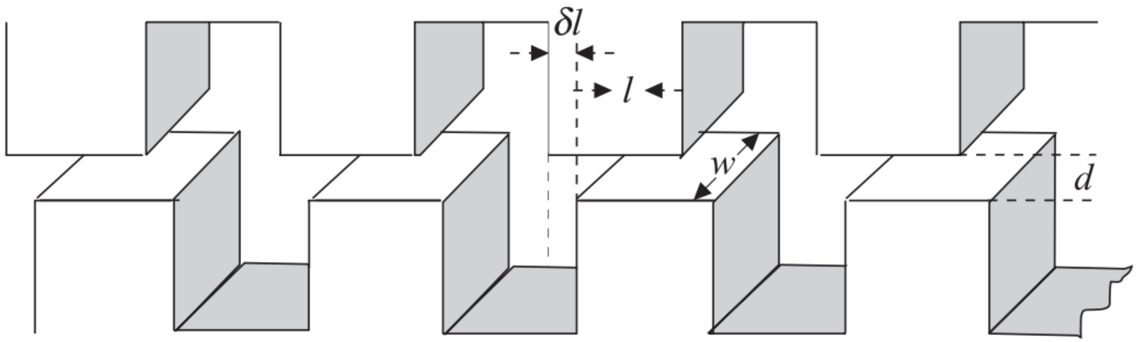


Fig. 6.25 Serrated electrode capacitor having variable effective tooth length.

- **Serrated parallel electrodes**
  - **For a small displacement δl, the change in capacitance**

$$C = \frac{\varepsilon_0 n l w}{d}$$

$$\Rightarrow \quad \delta C = \frac{\varepsilon_0 n(l+\delta l)w}{d} - \frac{\varepsilon_0 n l w}{d} = \frac{\varepsilon_0 n l w}{d}\left(\frac{\delta l}{l}\right) = C\left(\frac{\delta l}{l}\right)$$

2. Change in the effective overlapping area A btw plates

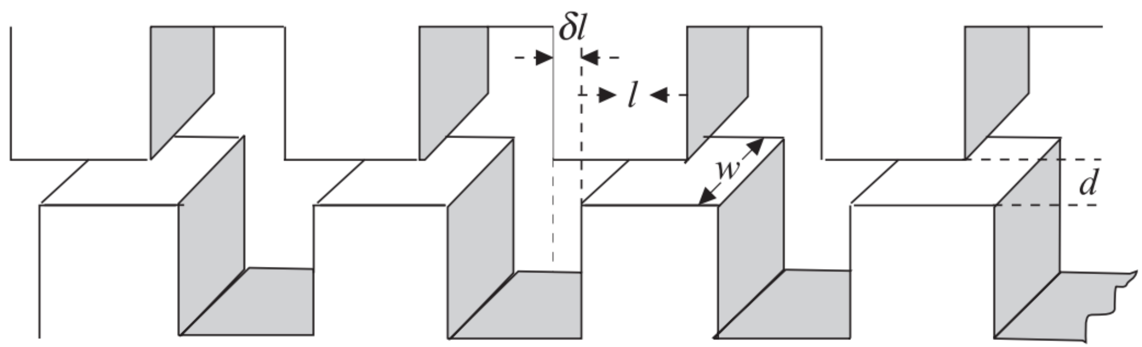


Fig. 6.25 Serrated electrode capacitor having variable effective tooth length.

- **Serrated parallel electrodes**
  - **For a small displacement δl, the change in capacitance**

$$C = \frac{\varepsilon_0 n l w}{d}$$

$$\delta C = \frac{\varepsilon_0 n (l + \delta l) w}{d} - \frac{\varepsilon_0 n l w}{d} = \frac{\varepsilon_0 n l w}{d}\left(\frac{\delta l}{l}\right) = C\left(\frac{\delta l}{l}\right)$$

$$\Rightarrow \quad \frac{\delta C}{C} = \frac{\delta l}{l}$$

2. Change in the effective overlapping area A btw plates

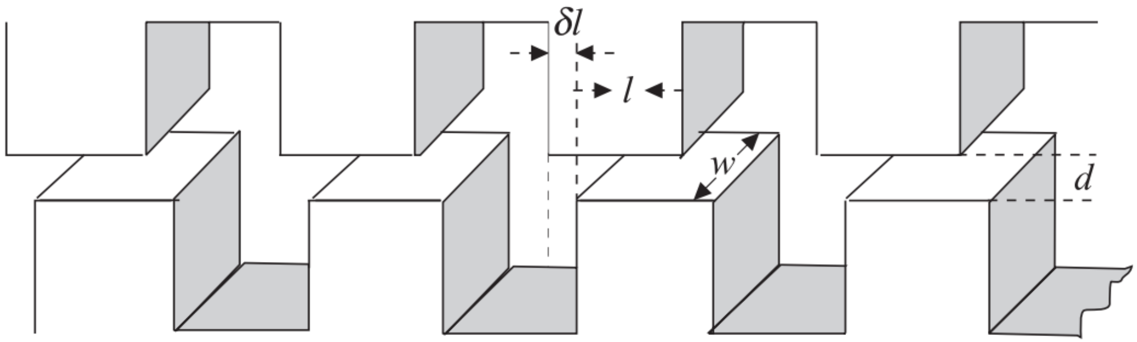


Fig. 6.25 Serrated electrode capacitor having variable effective tooth length.

- **Serrated parallel electrodes**
  - **Fringing effect correction**

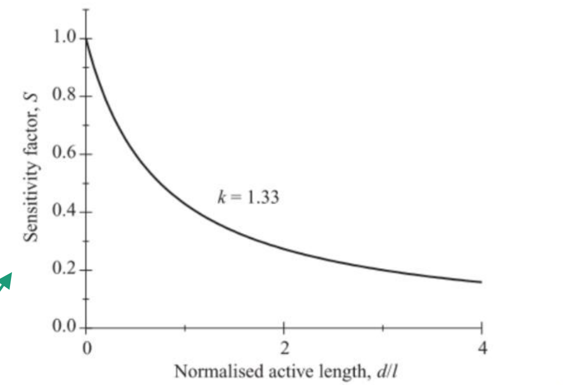


Fig. 6.26 Variation of sensitivity with normalised active tooth length of a serrated electrode capacitor.

$$\frac{\delta C}{C} = \frac{\delta l}{l} \cdot \frac{1}{1 + k(d/l)} \equiv S \cdot \frac{\delta l}{l}$$

k is constant for a set-up

S is often called the *sensitivity factor* $= \dfrac{1}{1 + k(d/l)}$

2. Change in the effective overlapping area A btw plates

Example 6.9

If the air gap between the teeth of two electrodes of a serrated type capacitive transducer is 0.1 cm and the active tooth length is 1 cm, what is the sensitivity factor of the sensor? Assume the constant term as 4.

Solution

We know from Eq. (6.20) that the sensitivity factor is given by

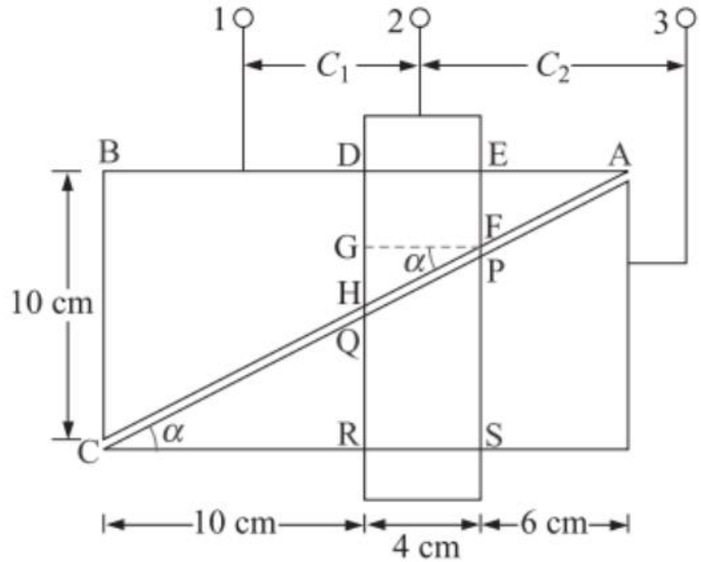
$$S = \frac{1}{1 + (kd/l)}$$

Given: $l = 1$ cm, $d = 0.1$ cm and $k = 4$. Therefore, the required sensitivity factor is

$$S = \frac{1}{1 + [(4)(0.1)]/(1)} = 0.714$$

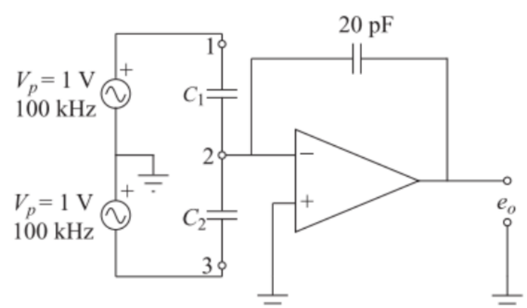
Example 6.10

A capacitive type displacement transducer consists of two triangular plates, placed side by side, with a negligible gap in between them and a rectangular plate moving laterally with an air gap of 1 mm between the fixed plates and the moving plate. The schematic diagram, indicating appropriate dimensions, is shown below.



(a) With the position of the moving plate shown in the figure above, what are the values of the capacitances C_1 and C_2 thus formed?

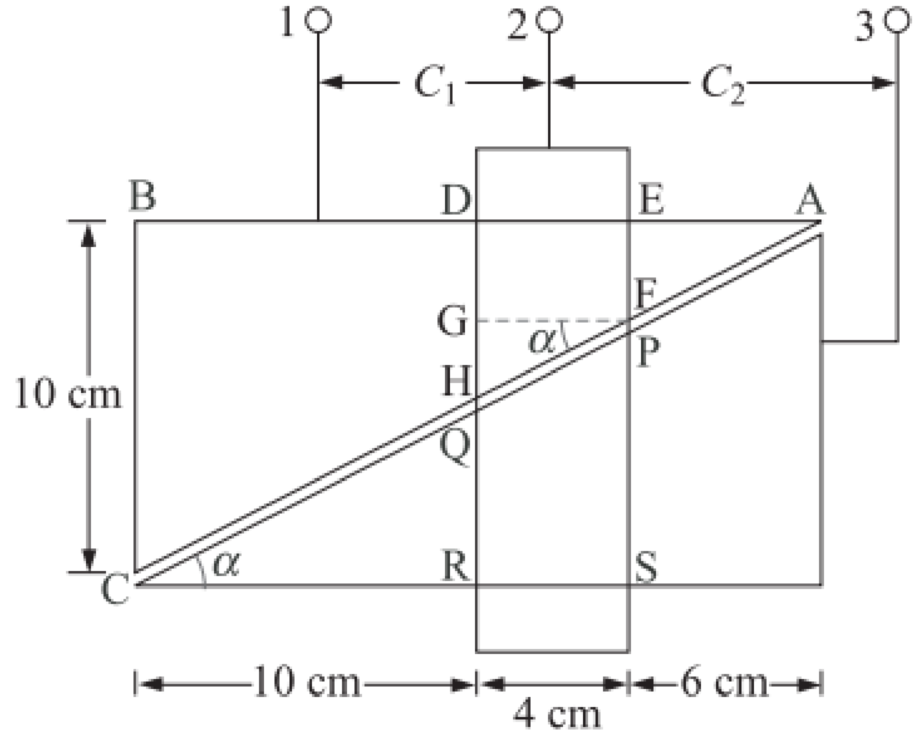
(b) The above sensor is incorporated in a capacitance measuring circuit as shown in the following figure.



Assuming an ideal op-amp, what is the output voltage under the conditions mentioned above?

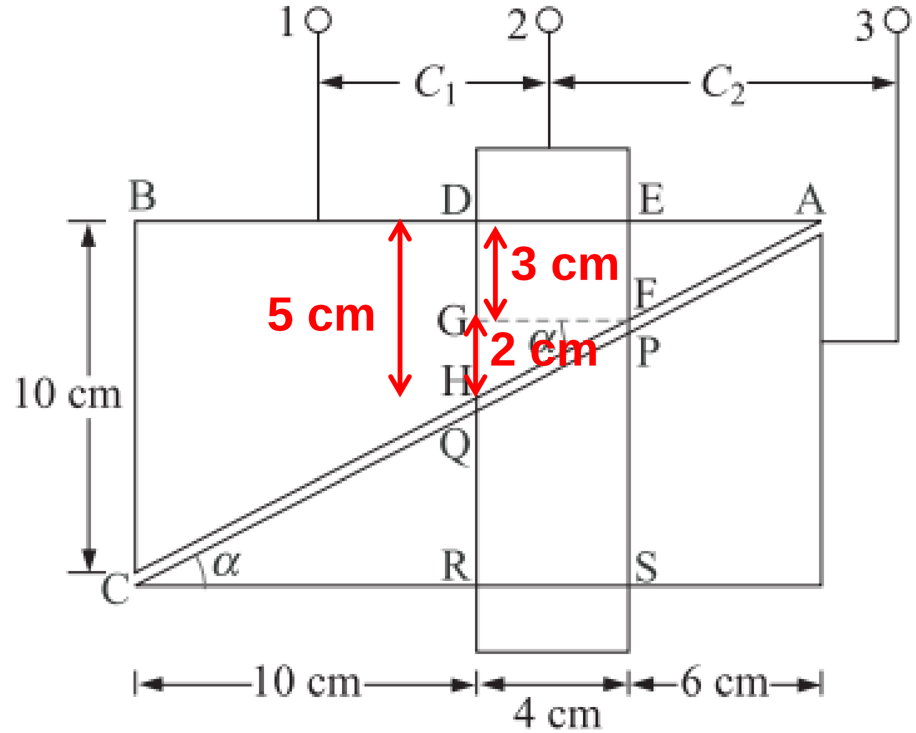
- Example 6.10: a capacitive displacement transducer

C_1 =? C_2 = ?



- Example 6.10: a capacitive displacement transducer

C_1 =? C_2 = ?



Solution

Given: BC = 10 cm, AB = 20 cm, and the air gap between the fixed and moving plates d = 1 mm = 10^{-3} m.

(a) Now

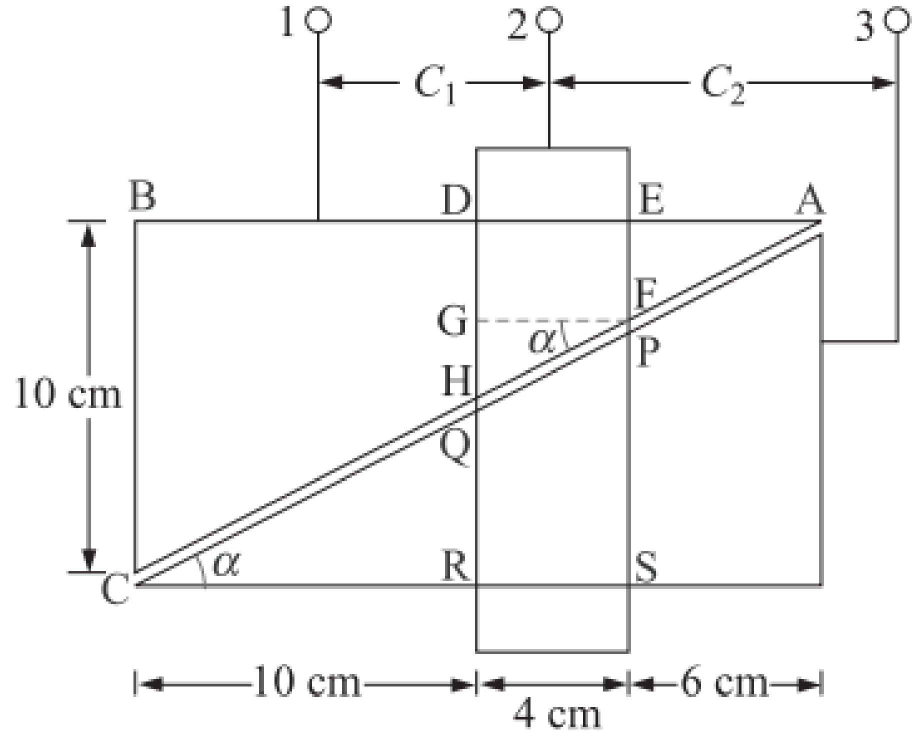
$$\tan\alpha = \frac{BC}{AB} = \frac{10}{20} = \frac{1}{2} = \frac{GH}{FG}$$

$$\therefore\ GH = \frac{FG}{2} = \frac{4}{2} = 2\,\text{cm} \qquad DH = \frac{BC}{2} = \frac{10}{2} = 5\,\text{cm}$$

$$EF = DG = DH - GH = 5 - 2 = 3\,\text{cm}$$

- Example 6.10: a capacitive displacement transducer

C_1 =? C_2 = ?



Using trigonometry

Area of DEFH

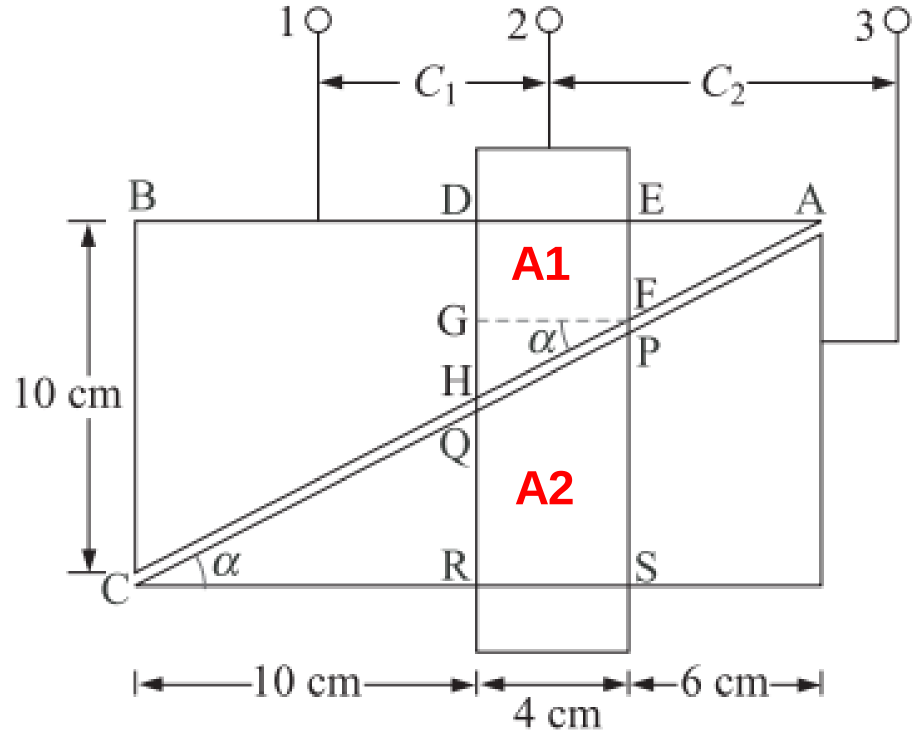
$$A_1 = \square\mathrm{DEFC} + \triangle\mathrm{FGH} = \left(4 \times 3 + \frac{4 \times 2}{2}\right) = 16\,\mathrm{cm}^2 = 16 \times 10^{-4}\,\mathrm{m}^2$$

Area of PQRS

$$A_2 = \square\mathrm{DESR} - \square\mathrm{DEFH} = 4 \times 10 - 16 = 24\,\mathrm{cm}^2 = 24 \times 10^{-4}\,\mathrm{m}^2$$

- Example 6.10: a capacitive displacement transducer

C_1 =? C_2 = ?



Using trigonometry

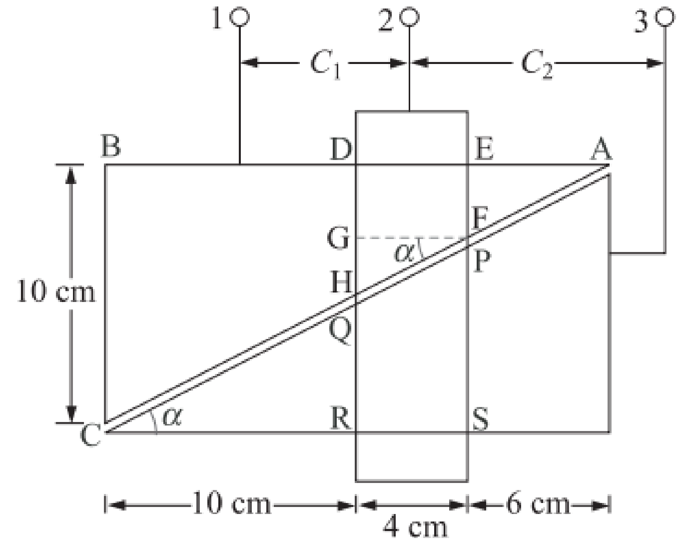
$$A_1 = 16 \times 10^{-4}\, m^2$$
$$A_2 = 24 \times 10^{-4}\, m^2$$

$$C_1 = \frac{\varepsilon_0 A_1}{d} = \frac{(8.85 \times 10^{-12})(16 \times 10^{-4})}{10^{-3}} = 14.17\,\text{pF}$$

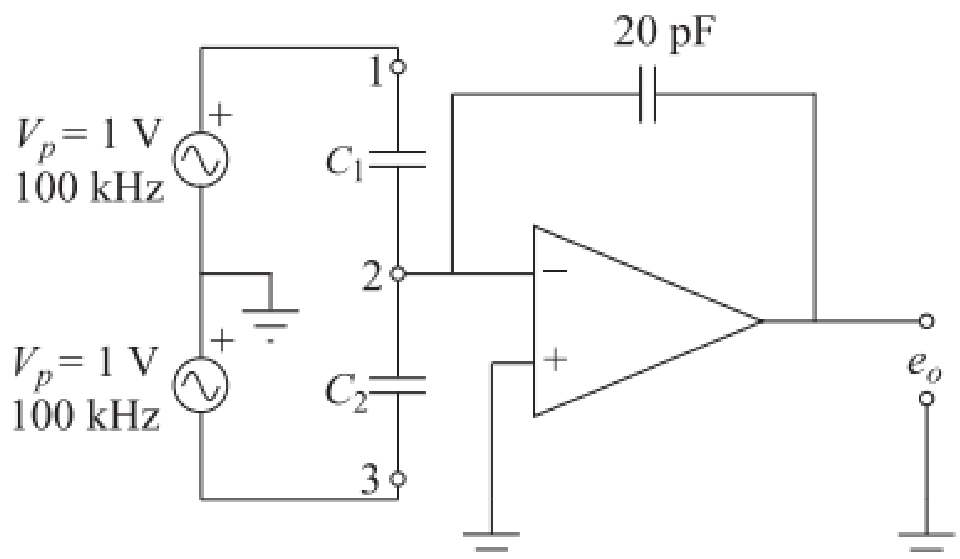
$$C_2 = \frac{\varepsilon_0 A_2}{d} = \frac{(8.85 \times 10^{-12})(24 \times 10^{-4})}{10^{-3}} = 21.25\,\text{pF}$$

- Example 6.10: a capacitive displacement transducer

  Output voltage, e_o =?

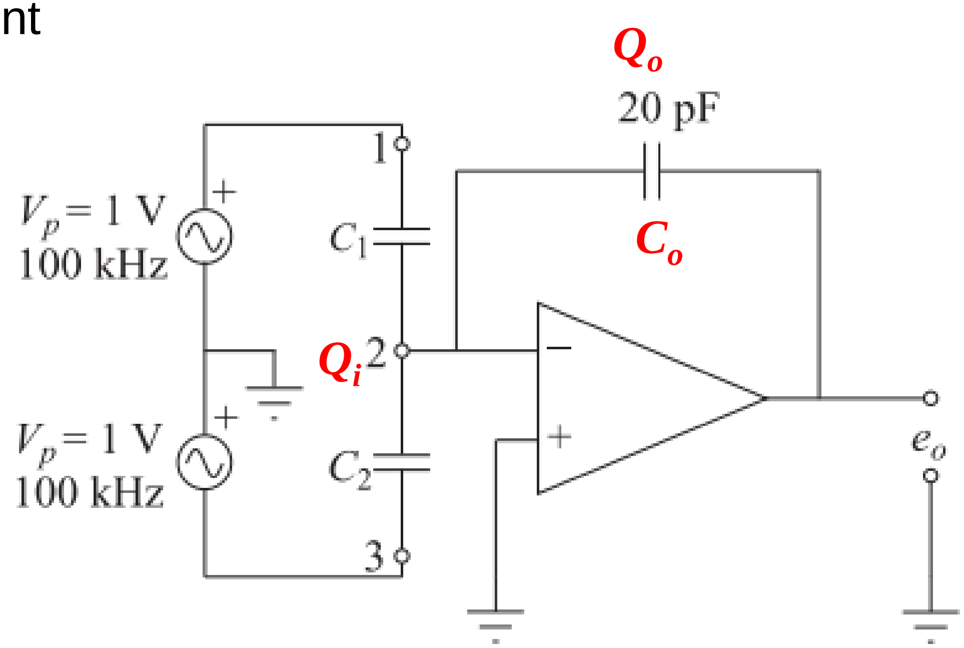


$$C_1 = 14.17\ pF$$
$$C_2 = 21.25\ pF$$



- Example 6.10: a capacitive displacement transducer

  Output voltage, e_o =?



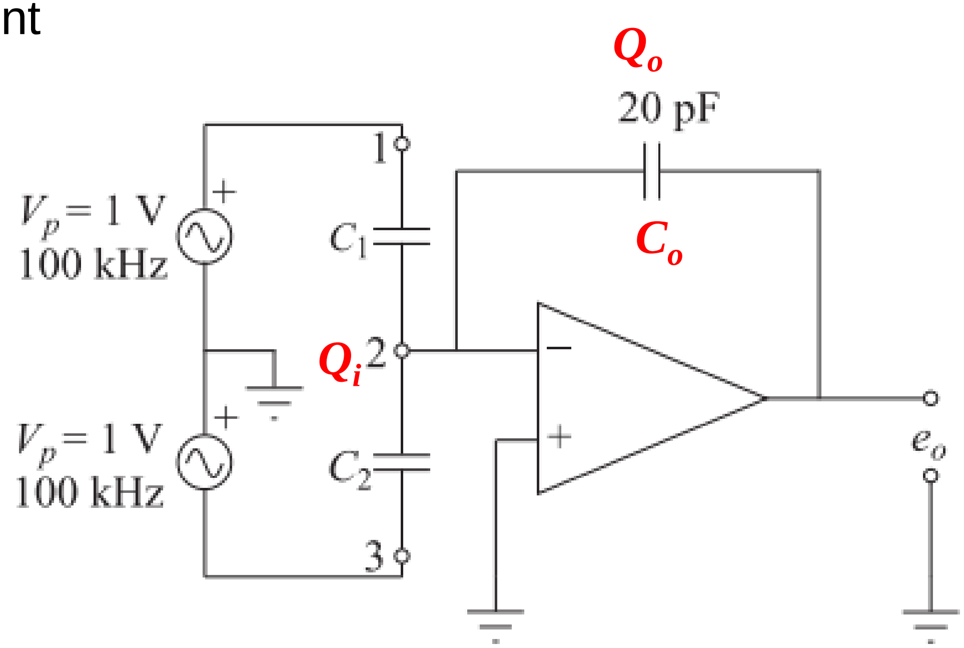
$$C_1 = 14.17\ pF$$

$$C_2 = 21.25\ pF$$

- Example 6.10: a capacitive displacement transducer

  Output voltage, e_o =?

$$C_1 = 14.17\ pF$$
$$C_2 = 21.25\ pF$$

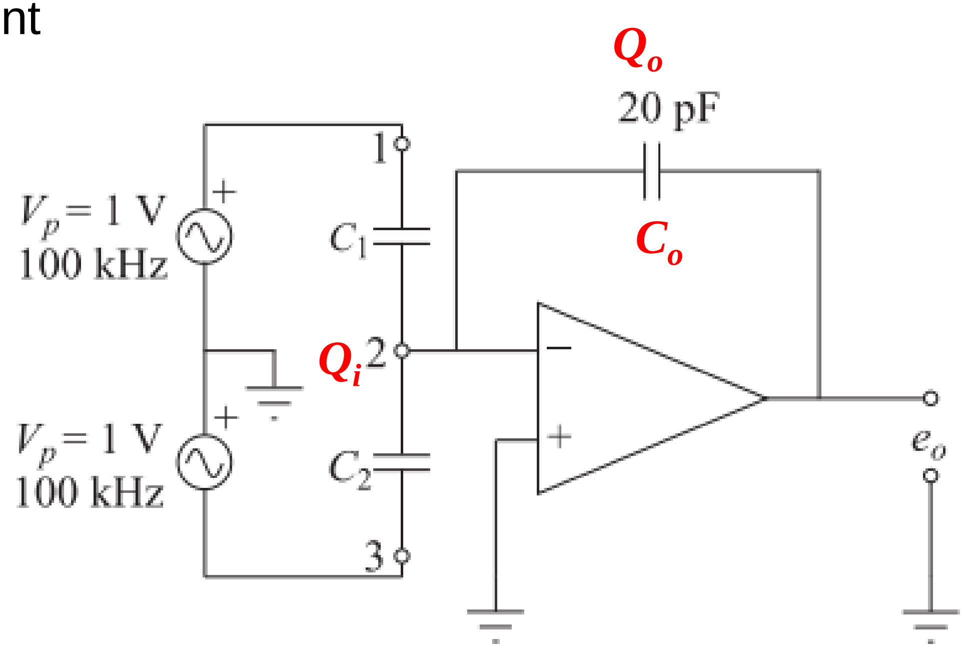


$$Q_i = V_p C_2 - V_p C_1$$

- Example 6.10: a capacitive displacement transducer

  Output voltage, e_o =?

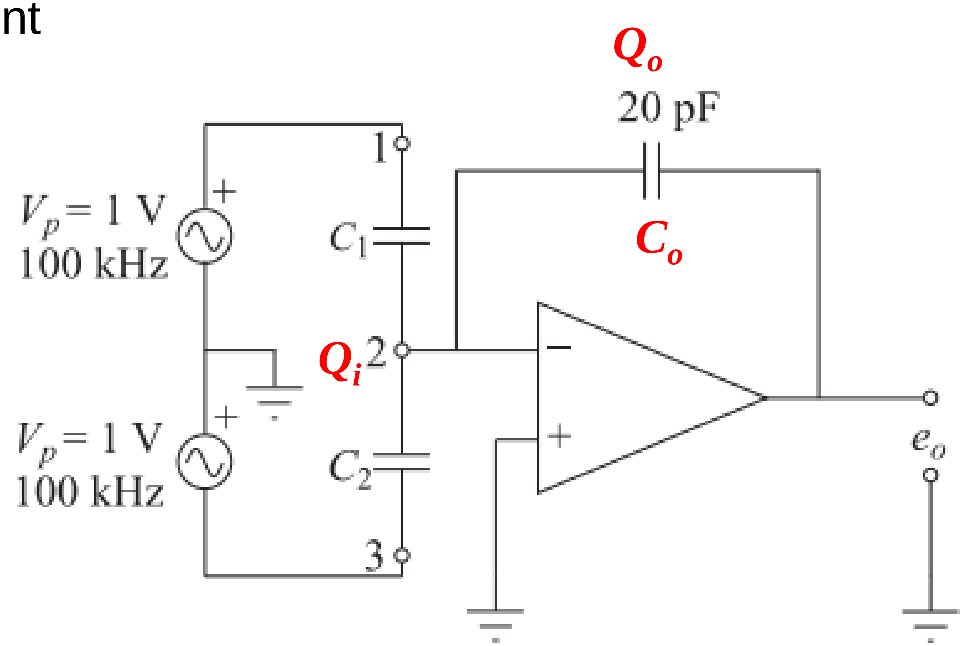
$$C_1 = 14.17\ pF$$
$$C_2 = 21.25\ pF$$



$$Q_i = V_p C_2 - V_p C_1 = V_p (C_2 - C_1)$$

- Example 6.10: a capacitive displacement transducer

Output voltage, e_o =?



$$C_1 = 14.17\ pF$$

$$C_2 = 21.25\ pF$$

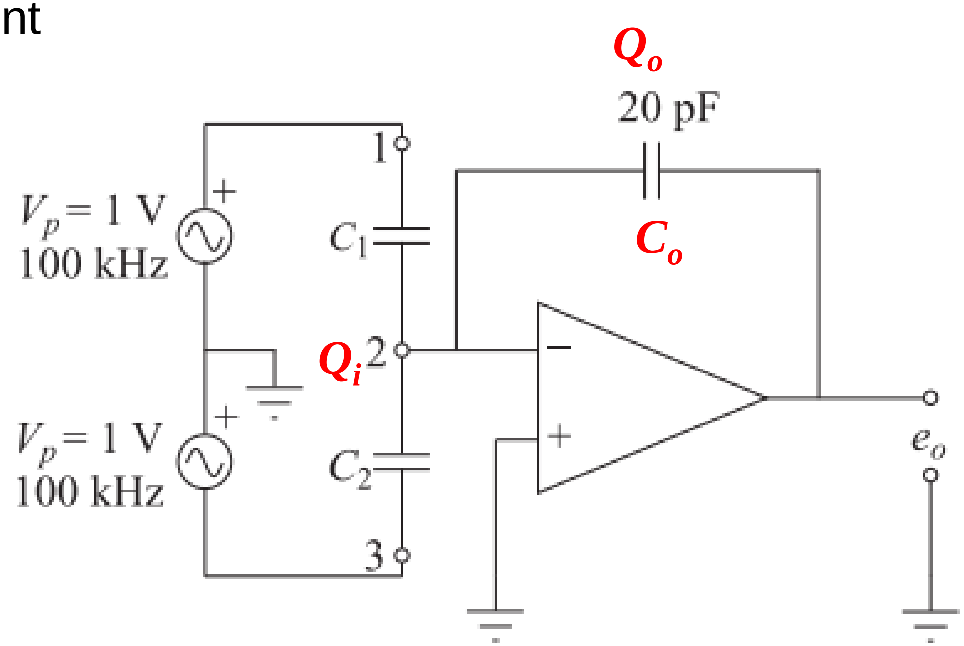
$$Q_i = V_p C_2 - V_p C_1 = V_p (C_2 - C_1)$$

$$\Rightarrow \quad Q_i = 1(21.25 - 14.17)$$

$$= 7.08\ pC$$

- Example 6.10: a capacitive displacement transducer

Output voltage, e_o =?



$$C_1 = 14.17\ pF$$

$$C_2 = 21.25\ pF$$

$$Q_i = V_p C_2 - V_p C_1 = V_p (C_2 - C_1)$$

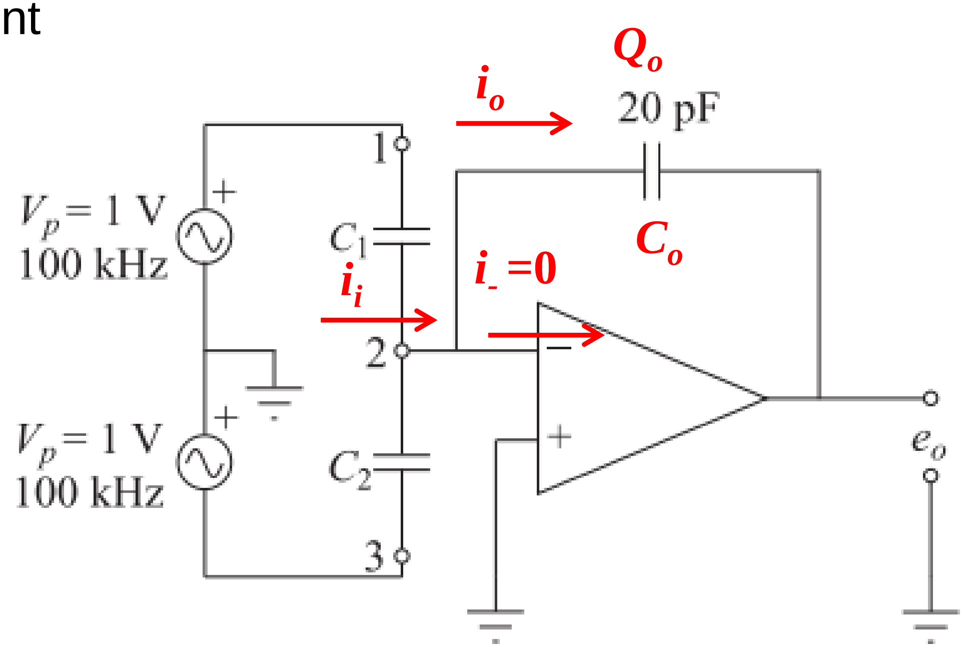
$$\Rightarrow \quad Q_i = 1(21.25 - 14.17)$$

$$= 7.08\ pC$$

$$e_o = ?$$

- Example 6.10: a capacitive displacement transducer

  Output voltage, e_o =?



$C_1 = 14.17\ pF$

$C_2 = 21.25\ pF$

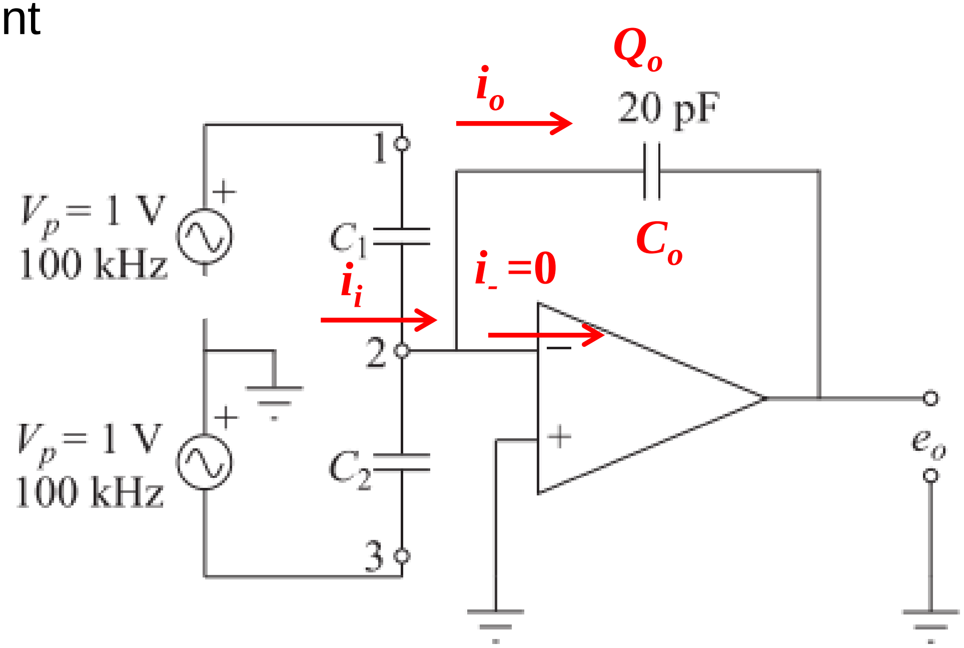
$Q_i = 7.08\ pC$

$e_o = ?$

Since $e_o = \frac{Q_o}{C_o} = \frac{\int i_o\, dt}{C_o}$

- Example 6.10: a capacitive displacement transducer

Output voltage, e_o =?



$$C_1 = 14.17\ pF$$

$$C_2 = 21.25\ pF$$

$Q_i = 7.08\ pC$

$e_o = ?$

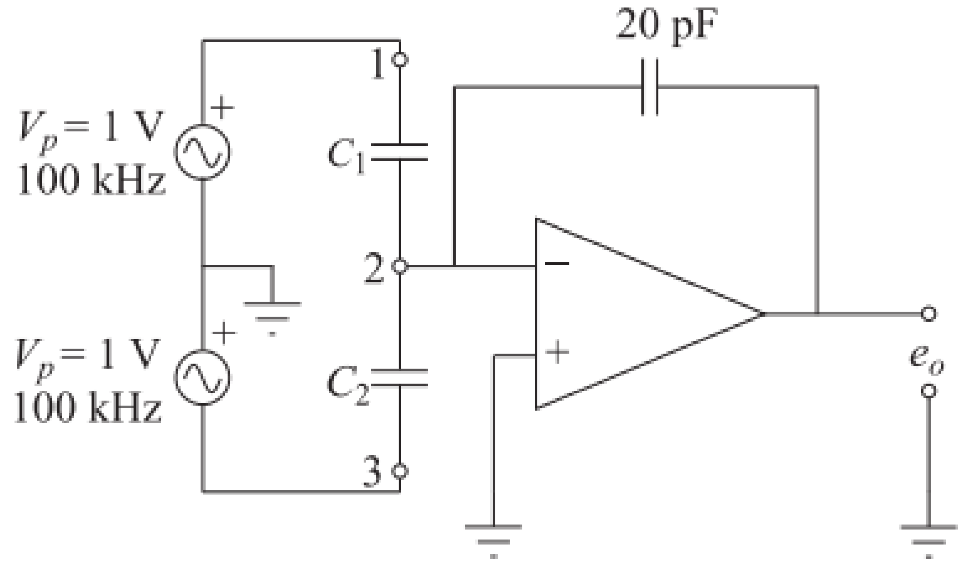
$$e_o = \frac{Q_o}{C_o} = \frac{\int i_o\, dt}{C_o}$$

$$i_o = i_i$$

$$\Rightarrow \quad e_o = \frac{\int i_i\, dt}{C_o} = \frac{Q_i}{C_o}$$

- Example 6.10: a capacitive displacement transducer

  Output voltage, e_o =?



$$C_1 = 14.17\ pF$$

$$C_2 = 21.25\ pF$$

$Q_i = 7.08\,pC$

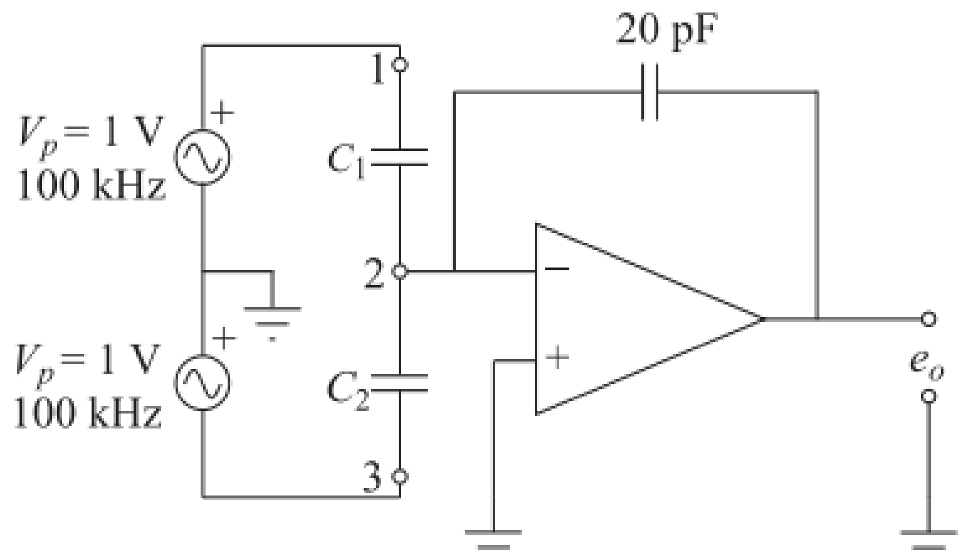
$e_o = ?$

$$e_o = \frac{Q_i}{C_o} = \frac{7.08\,pF}{20\,pC}$$

$e_o = 0.354\,V$

- Example 6.10: a capacitive displacement transducer

Output voltage, e_o =?



$C_1 = 14.17\ pF$

$C_2 = 21.25\ pF$

$$Q = VC_2 - VC_1 = V(C_2 - C_1) = 7.08\,\text{pC}$$

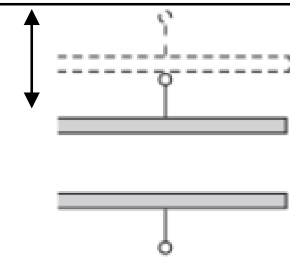
$$e_o = \frac{Q}{C} = \frac{7.08}{20} = 0.354\,\text{V}$$

Capacitive Transducers

Change in capacitance is used to measure displacement.

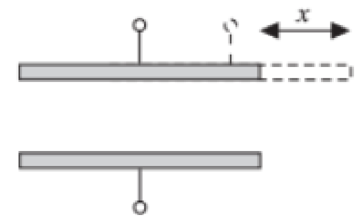
$$\boxed{C = \frac{\varepsilon A}{x} \text{ farad}}$$

- $\epsilon = \epsilon_o \epsilon_r$ is the permittivity of intervening medium (farad/meters)
  - *The absolute permittivity, often simply called permittivity and denoted by the Greek letter ε (epsilon), is a measure of the electric polarizability. he ability of a substance to store electrical energy in an electric field.*
- x is the distance between plates (meters)
- A is the overlapping area of plates (meters^2)



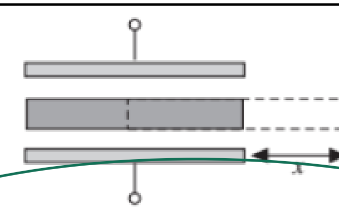
(a)

<change in the gap>



(b)

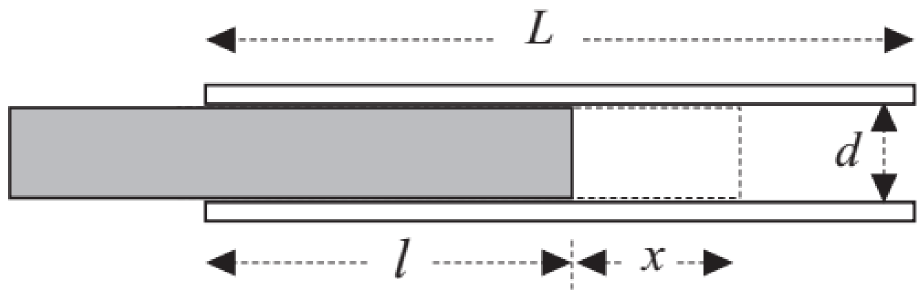
<change in the area>



(c)

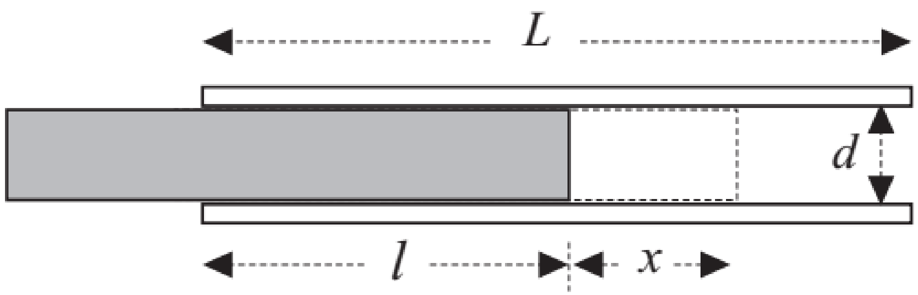
<change in the permittivity>

3. Change in the relative permittivity ε_r



- ❑ **Lateral shift of the dielectric**

3. Change in the relative permittivity ε_r



- **Lateral shift of the dielectric**
  - **for width *w*,**

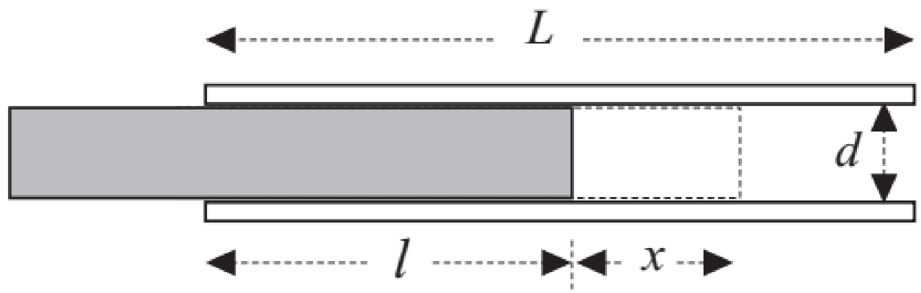
$$C = \varepsilon_0 \frac{w(L-l)}{d} + \varepsilon_0 \varepsilon_r \frac{wl}{d}$$

The relative permittivity of a few common dielectrics are given in Table 6.6.

Table 6.6 Relative permittivity of common dielectrics

Material	Vacuum	Air	Polythene	Silica	Quartz	Glass	Mica	Water	$BaTiO_3$
ε_r	1.00	1.0005	2.3	3.8	4.5	5.3–7.5	7	80	10^3–10^5

3. Change in the relative permittivity ε_r

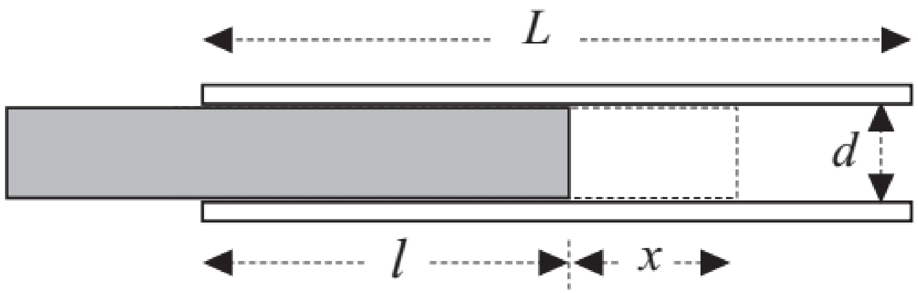


- Lateral shift of the dielectric
- If dielectric is displaced by x,

$$C = \varepsilon_0 \frac{w(L-l)}{d} + \varepsilon_0 \varepsilon_r \frac{wl}{d}$$

$$\Rightarrow \qquad C + \Delta C = \varepsilon_0 \frac{w(L-l-x)}{d} + \varepsilon_0 \varepsilon_r \frac{w(l+x)}{d}$$

3. Change in the relative permittivity ε_r



- Lateral shift of the dielectric
- If dielectric is displaced by x,

$$C + \Delta C = \varepsilon_0 \frac{w(L - l - x)}{d} + \varepsilon_0 \varepsilon_r \frac{w(l + x)}{d}$$

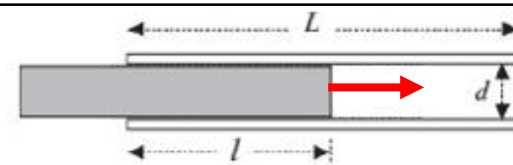
$$\Rightarrow \qquad \Delta C = \frac{\varepsilon_0 w(\varepsilon_r - 1)}{d} x$$

$$\Delta C \propto x$$

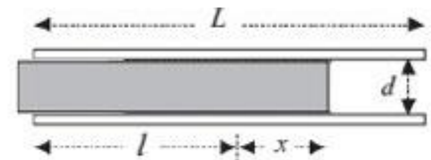
3. Change in the relative permittivity ε_r

Lateral Shift of Dielectric

$$C = \epsilon_0 \frac{w(L-l)}{d} + \epsilon_0 \epsilon_r \frac{wl}{d}$$



$$C + \Delta C = \epsilon_0 \frac{w(L-l-x)}{d} + \epsilon_0 \epsilon_r \frac{w(l+x)}{d}$$



$$\Delta C = \epsilon_0 \frac{w(\epsilon_r - 1)}{d} x$$

$$\boxed{\Delta C \propto x}$$

Therefore, change in capacitance is linearly related to displacement.

3. Change in the relative permittivity ε_r

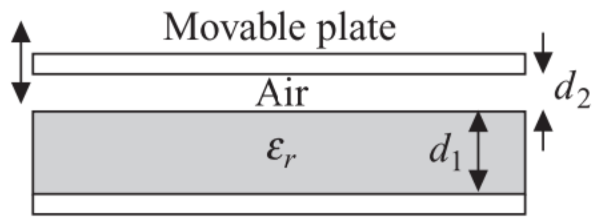


Fig. 6.28 Vertical shift of plate causing a variable permittivity.

- ❑ **Vertical shift of the movable plate**
  - ❑ permittivity change due to the vertical shift of one of the plates of the capacitor

$$C = \frac{\varepsilon_0 A}{d_2 + (d_1/\varepsilon_r)} \tag{6.21}$$

where A indicates the area of each of the plates and the dielectric. Next, we displace the movable top plate so that the air gap becomes $(d_2 - \delta d_2)$. This increases the capacitance by δC and we have

$$C + \delta C = \frac{\varepsilon_0 A}{d_2 - \delta d_2 + (d_1/\varepsilon_r)} \tag{6.22}$$

Solving 6.21 and 6.24, the Sensitivity depends on:

1. The ratio (d_1/d_2)
2. The relative permittivity ε_r of the dielectric layer

Capacitive Transducer

Table 6.7 Merits and demerits of capacitive transducers

Merits	*Demerits*
1. High sensitivity.	1. Noise generation from stray capacitance arising from the transmission line.
2. Good frequency response.	2. Temperature sensitivity.
3. High input impedance. So, not much loading.	3. Complex instrumentation.
4. Minimum mechanical loading.	

Displacement Measurement

- **Classification**
  - **Electrical**
  - **Pneumatic**
  - **Optical**
  - **Ultrasonic**
  - **Magnetostrictive**
  - **Digital**

Pneumatic Transducers

- They are also called "nozzle-flapper transducer"
- Many applications in small displacement measurement

Due to the presence of flapper, there will be a back pressure that will alter the output pressure or signal pressure (P_o)

Altering the gap between nozzle and flapper (x) alters the resistance to airflow and hence the output pressure

Increase in x will lower the resistance and fall in output pressure (P_o)

P_o can be calibrated in terms of gap (x) , that is, (displacement)

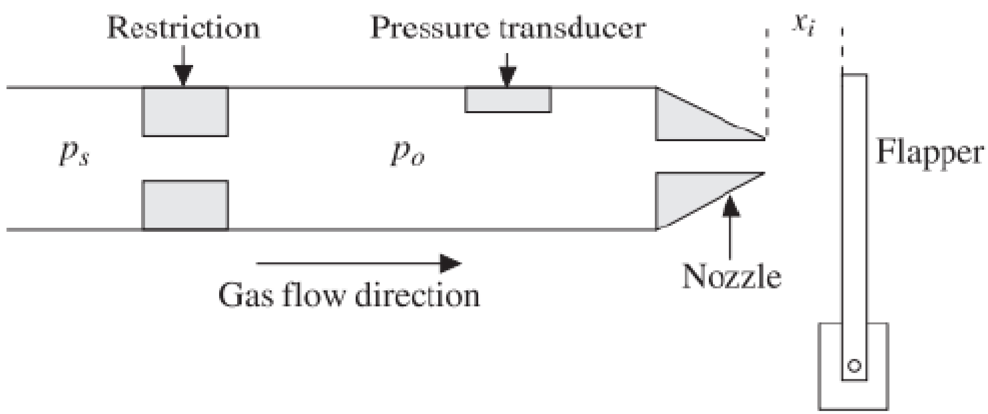
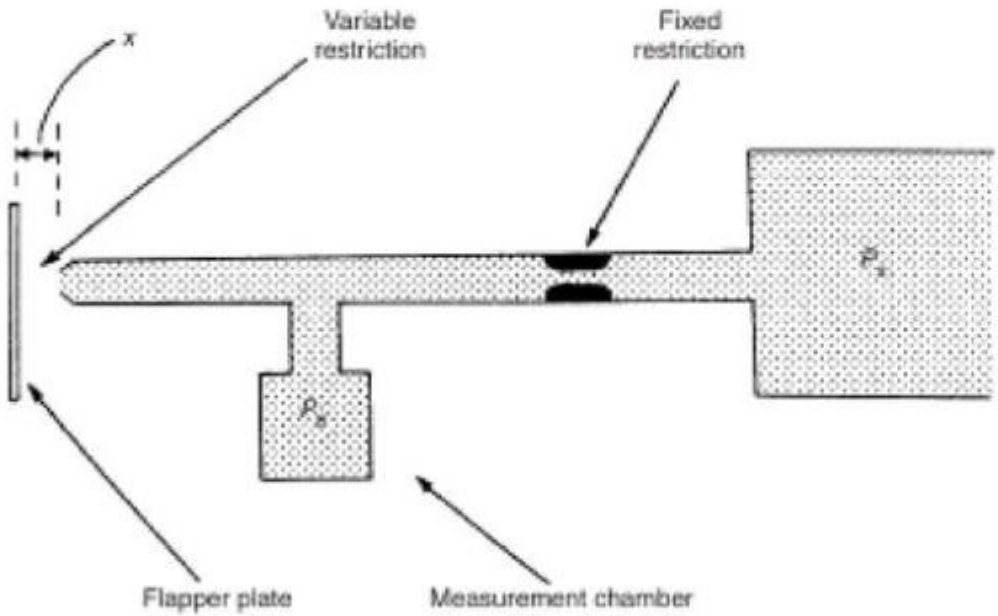


Fig. 6.1 Schematic diagram of nozzle-flapper transducer.

Pneumatic Transducers

Also called Nozzle flapper. The nozzle flapper is a displacement transducer that translates displacements into a pressure change. A secondary pressure-measuring device is therefore required within the instrument. The general form of a nozzle flapper is shown schematically in Figure



Displacement Measurement

- **Classification**
  - **Electrical**
  - **Pneumatic**
  - **Optical**
  - **Ultrasonic**
  - **Magnetostrictive**
  - **Digital**

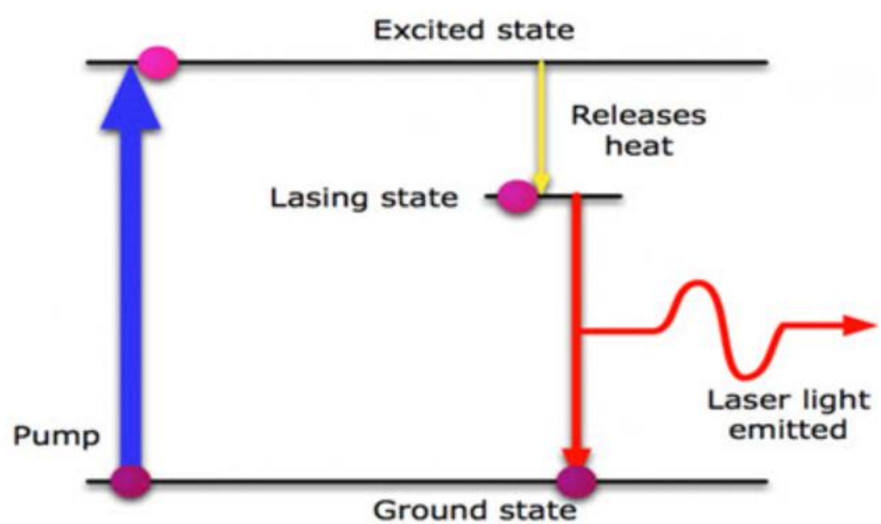
Optical Transducers

- Help us for small displacements measurement with high precision.
- Laser transducers are commercially available.
  - Triangulation
  - Time-of-Flight (ToF)

Concept Check?

LASER (Light Amplification by Stimulated Emission Radiation)

A laser is created, when the electrons in the atoms in special glasses, crystals, or gasses absorb energy from an electrical current they become excited. The excited electrons move from a lower-energy orbit to a higher-energy orbit around the atom's nucleus. When they return to their normal or ground state this leads to the electrons emit photons (particles of light). These photons are all at the same wavelength and coherent. The ordinary visible light comprises multiple wavelengths and is not coherent.



LASAR Light Emission Process

Optical Transducers

- Help us small displacements measurement with high precision.
- Laser transducers are commercially available.
  - **Triangulation**

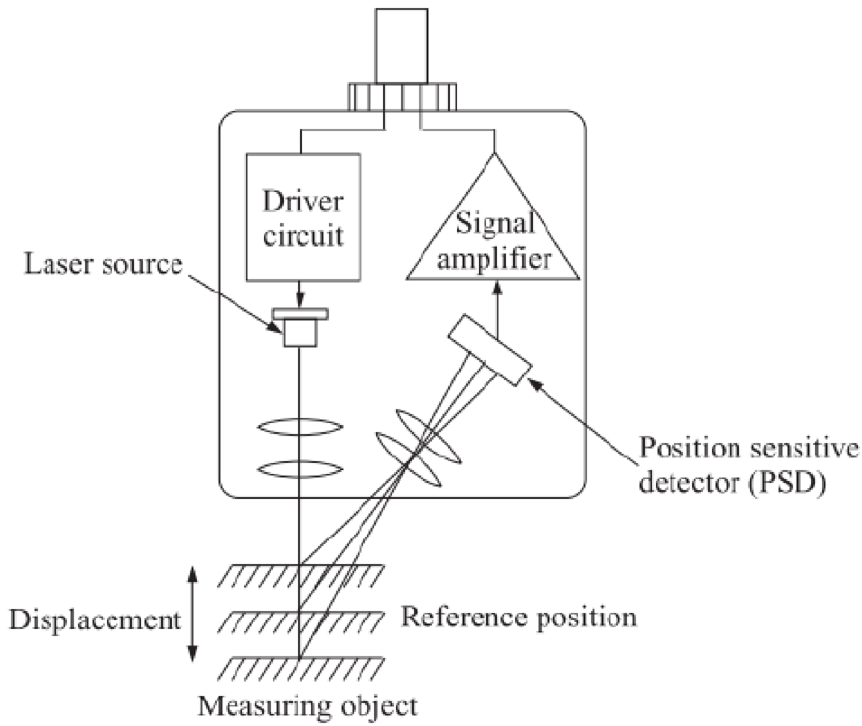
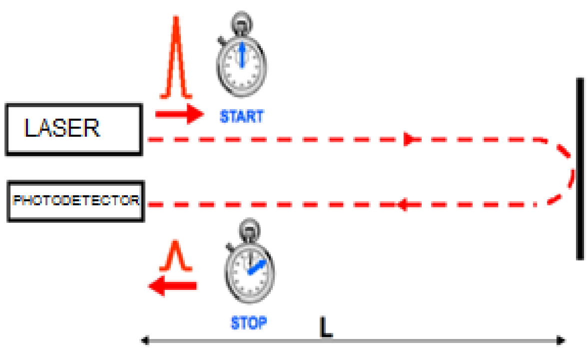


Fig. 6.30 Laser displacement transducer.

Optical Transducers

- Help us small displacements measurement with high precision.
- Laser transducers are commercially available.
  - Triangulation
  - ***Time-of-flight method***

The time-of-flight (TOF) sensors derive range from the time light takes to travel from the sensor to the target and return. For very long range distance measurements (up to many kms) time-of-flight laser range finders using pulsed laser beams are used.



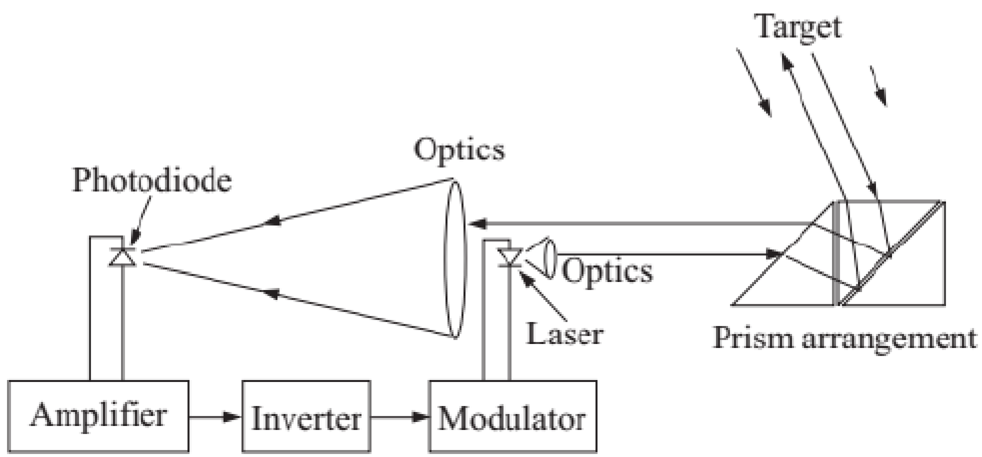
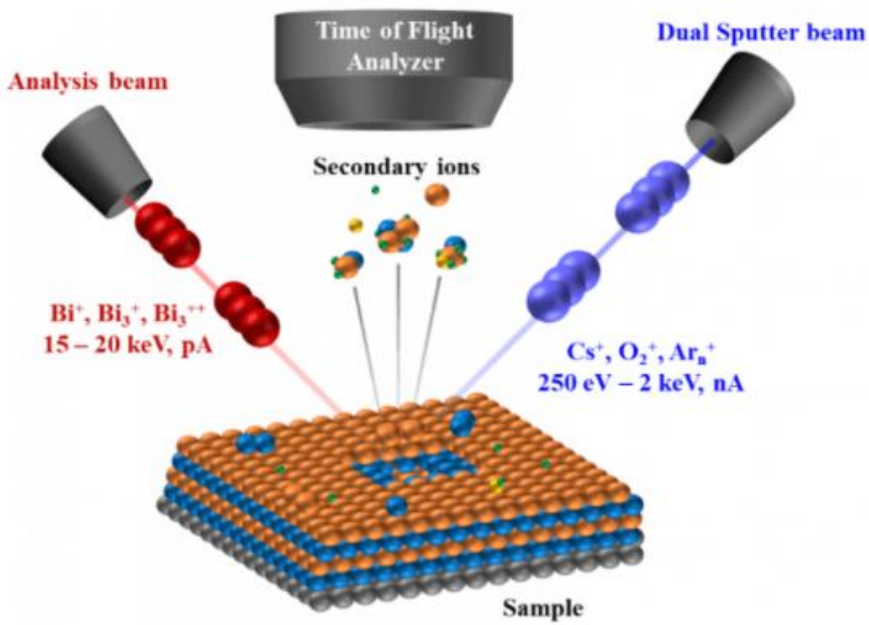


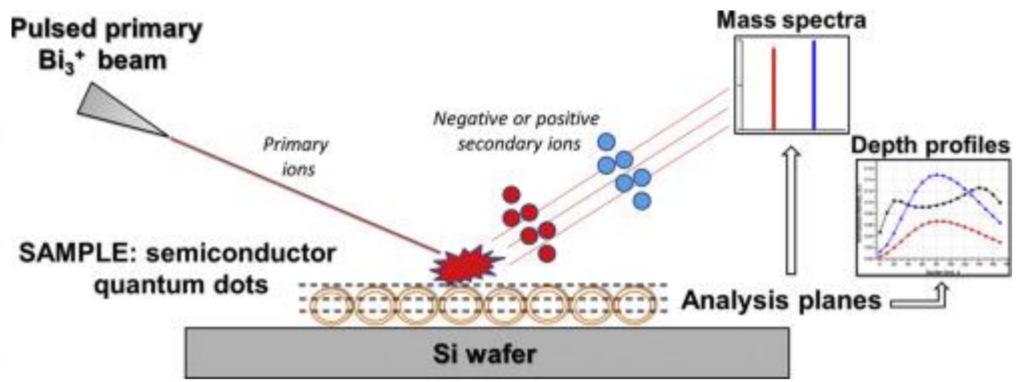
Fig. 6.33 Modulated beam TOF laser displacement transducer.

Optical Transducers

- Time-of-Flight (ToF)

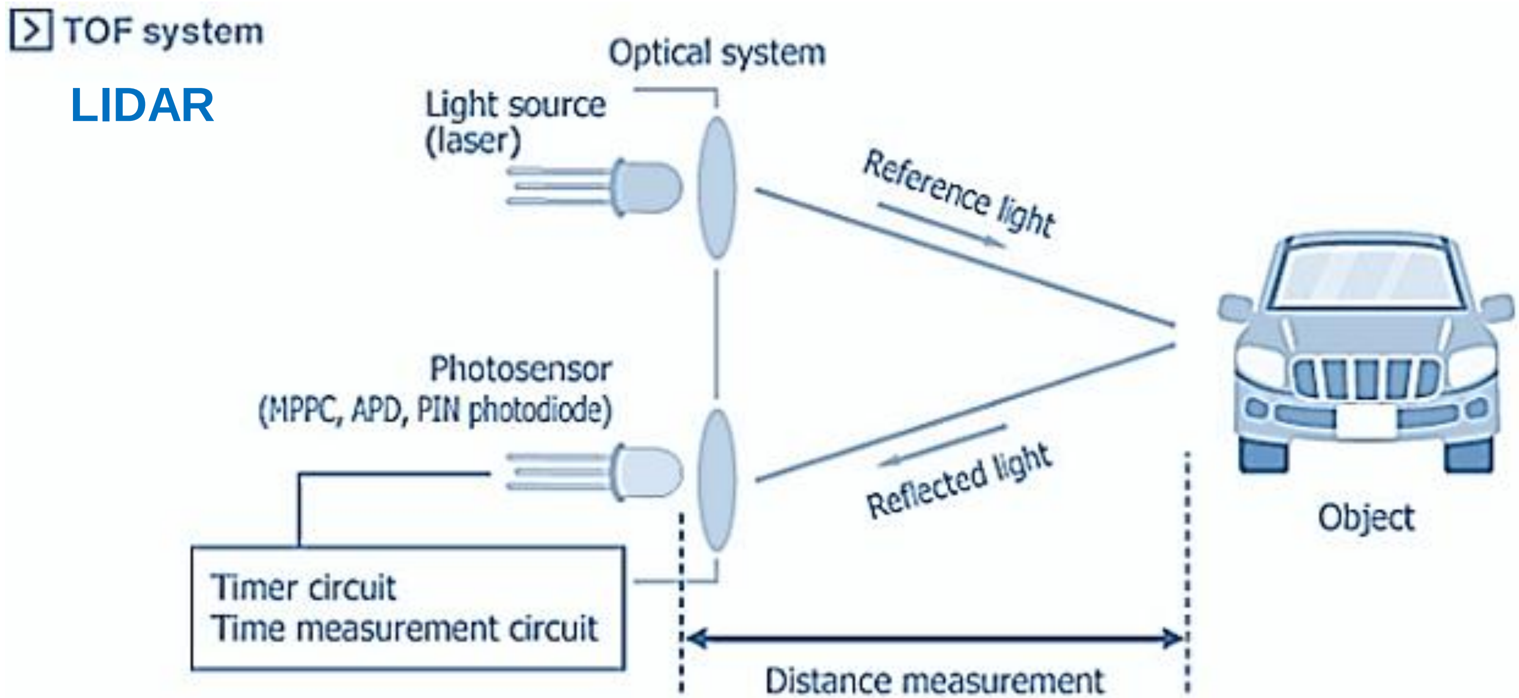
Time-of-Flight Secondary Ion Mass Spectrometry





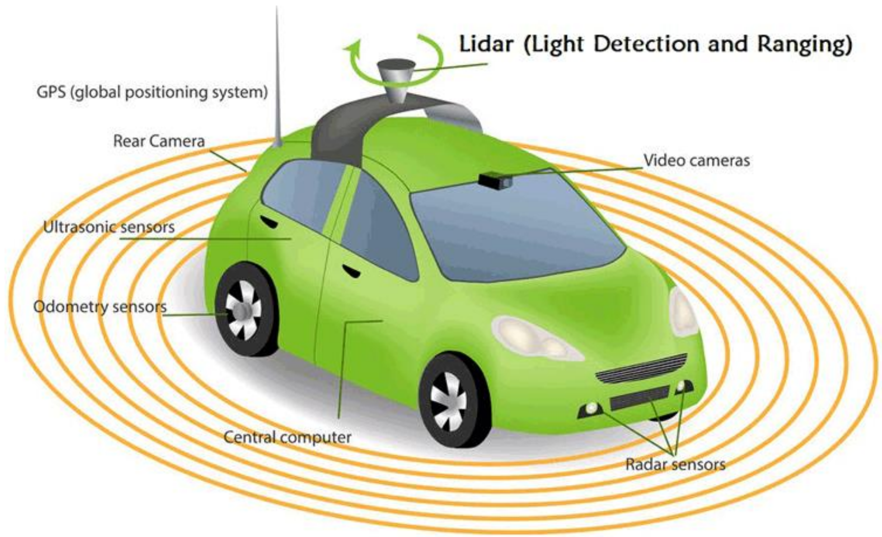
Optical Transducers

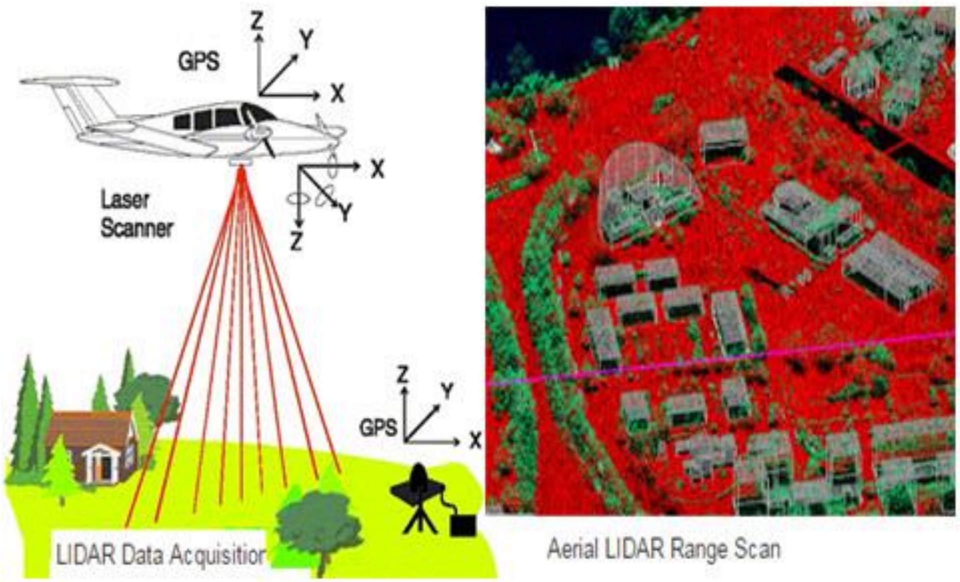
LIDAR

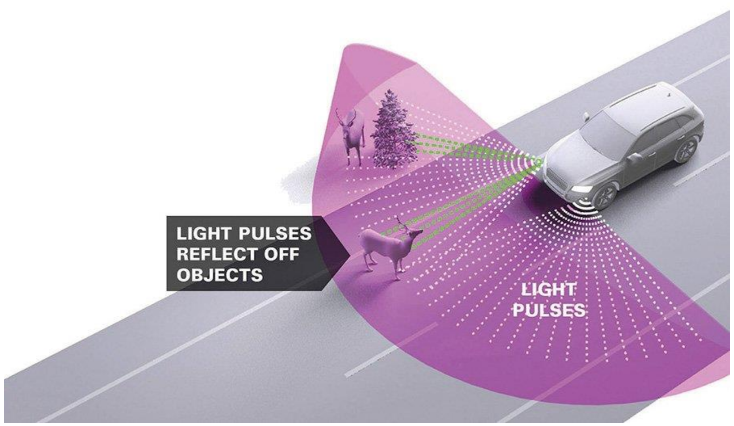


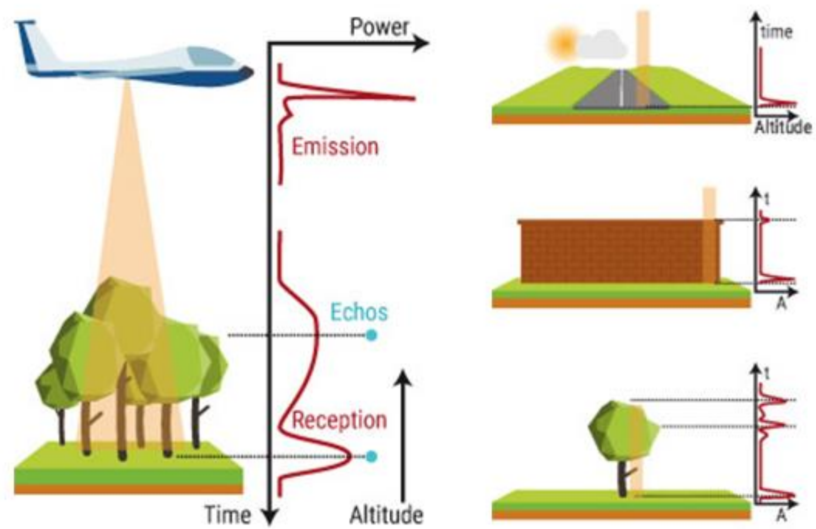
LIDAR — Light Detection and Ranging — is a remote sensing method used to examine the surface of the Earth

LIDAR — Light Detection and Ranging Systems?





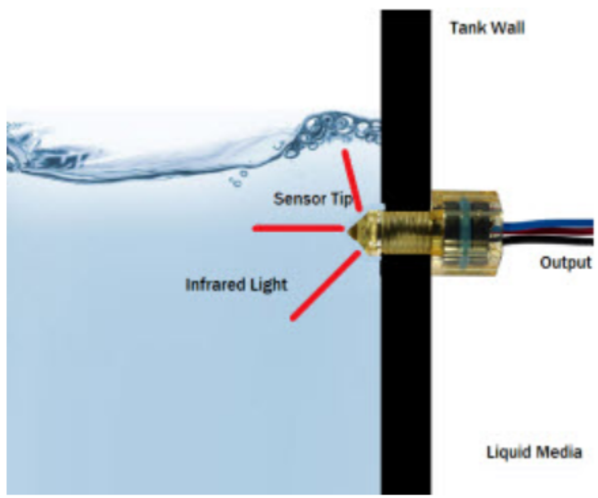




Optical Transducers

Optical Sensor Based Liquid Level Indicator

Optical Sensor Based Liquid Level Indicator consist of two main parts an infrared LED coupled with a light transistor, and a transparent prism tip in the front. The LED projects an infrared light outward, when the sensor tip is surrounded by air the light reacts by bouncing back with-in the tip before returning to the transistor. When the sensor is dipped in liquid, the light disperses throughout and less is returned to the transistor. The amount of reflected light to the transistor affects output levels, making point level sensing possible



Optical Level Sensor

Fibre-Optic Transducers

- In a single optical fibre transducer, light is injected into a fibre through a fibre optic coupler, located at some distance from the distal end of the fibre.
- Injected light travels toward the front face of the fibre, where it exits in the shape of a cone.

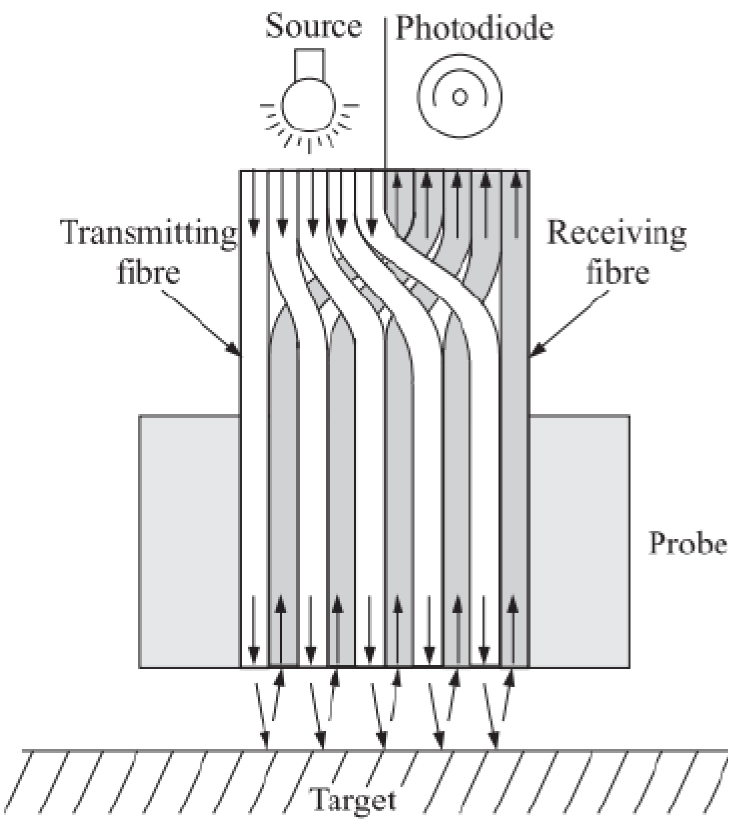


Fig. 6.36 Fibre-optic displacement transducer.

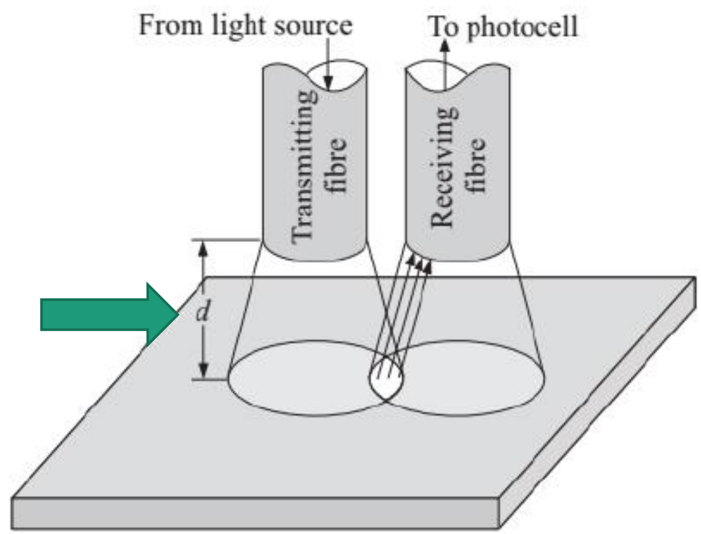
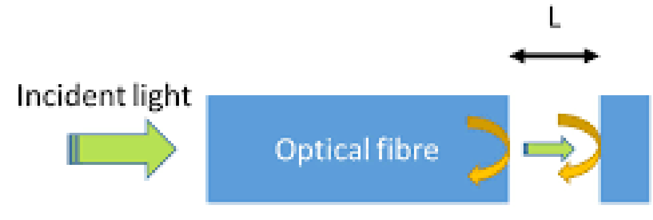
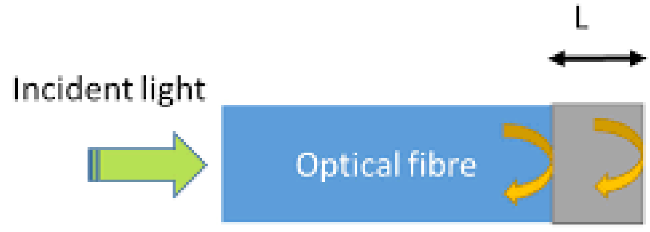


Fig. 6.39 Transmission and reception of light by adjacent fibres.

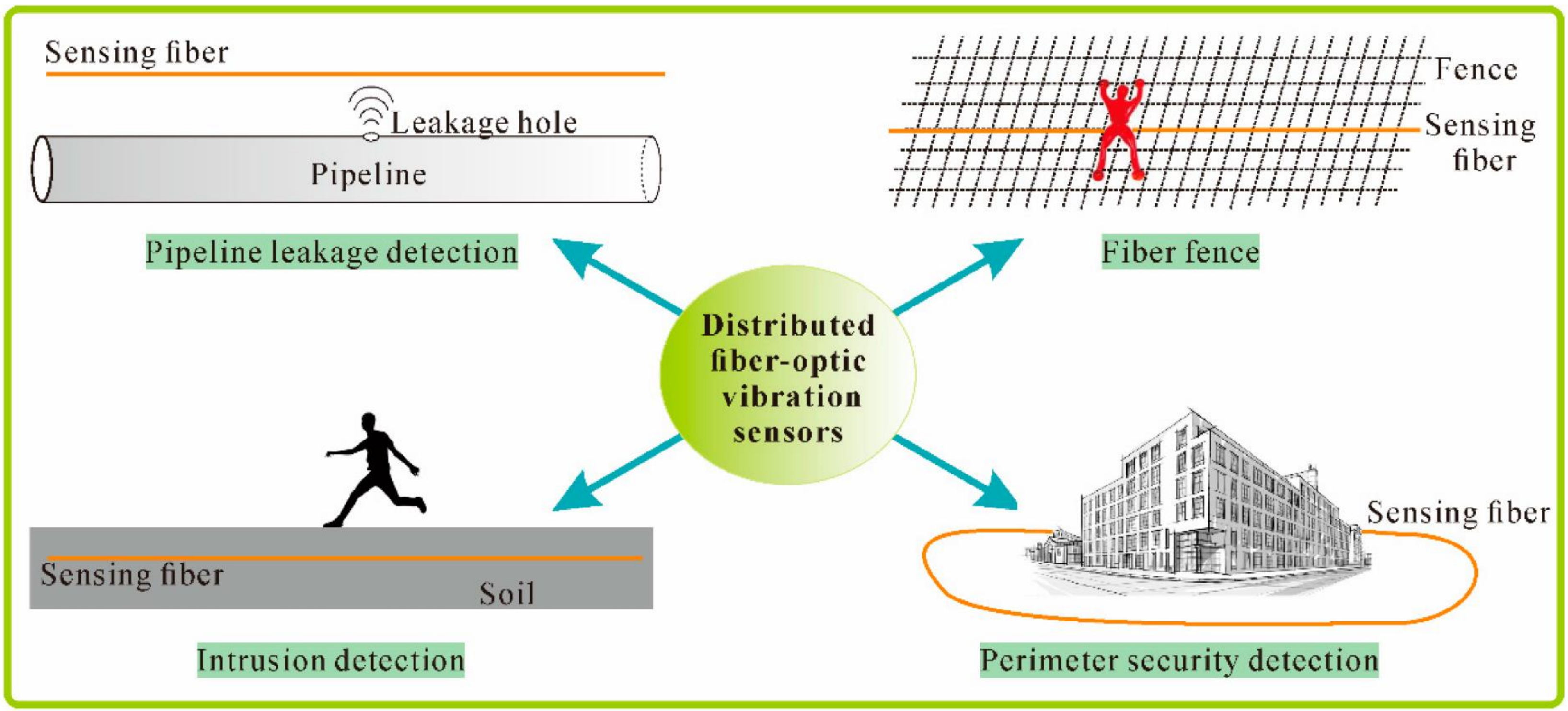
Fibre-Optic Transducers



(a)



(b)



Fibre-Optic Transducers

Table 6.8 Advantages and disadvantages of fibre-optic displacement transducers

Advantages	*Disadvantages*
1. Can operate directly with a large variety of surfaces, from specular to diffuse.	1. Works well on highly reflective surfaces less effective on duller surfaces.
2. Works well with materials from conductors to insulators.	2. Re-calibration is generally required often, since the reflectance of targetsurfaces may vary.
3. Non-contacting measurement.	3. Can measure the roughness of the target surface only up to the order of the spacing of the transmitting and receiving fibres.
4. Contains neither moving parts nor electrical circuitry. Therefore,completely immune to all forms of electrical interference.	4. A misalignment, or dust accumulation on the cable tip degrades sensor performance.
5. No possibility of a spark. Therefore, safe even in the most hazardous environments. Also, no danger of electrical shock to personnel repairing broken fibres.	

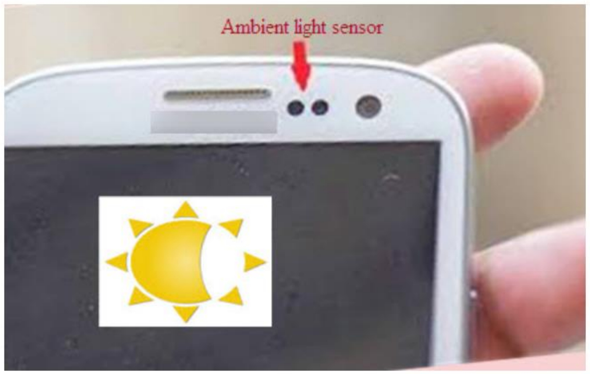
General Types of Optical Transducers

There are different kinds of optical sensors, the most common types which we have been using in our real world applications as given below.

- Photoconductive devices used to measure the resistance by converting a change of incident light into a change of resistance.
- The photovoltaic cell (solar cell) converts an amount of incident light into an output voltage.
- The Photodiodes convert an amount of incident light into an output current.

Ambient Light Sensors

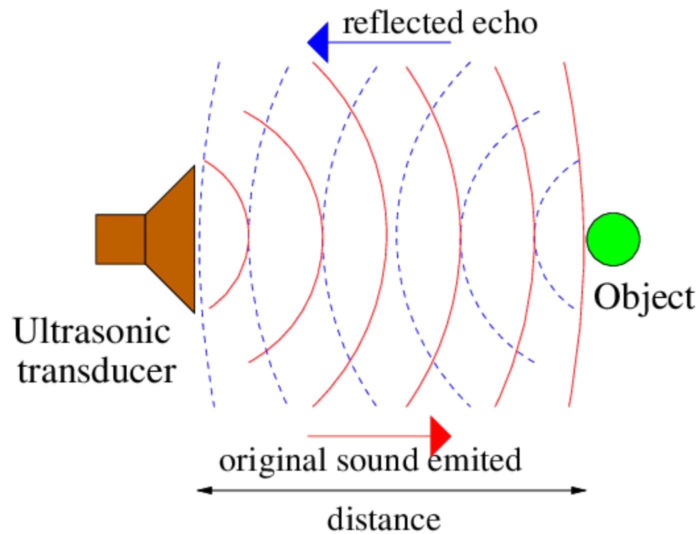
mostly we have seen this sensor on our mobile handsets. It will extend the battery life and enables easy-to-view displays that are optimized for the environment.



Ambient Light Sensors

Displacement Measurement

- Classification
  - Electrical
  - Pneumatic
  - Optical
  - Ultrasonic
  - Magnetostrictive
  - Digital



Ultrasonic Transducers

- If the velocity of sound propagation is known, the distance to an object can be calculated from the time delay between the emitted and reflected sounds
- Works of TOF principle and Echo Ranging

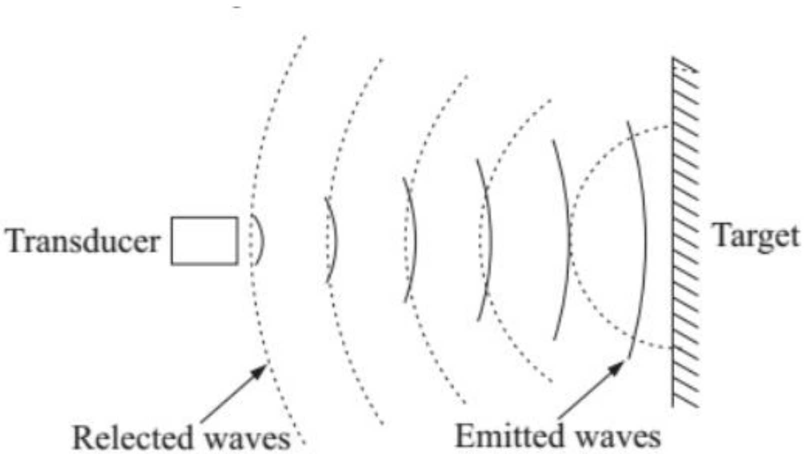


Fig. 6.43 Ultrasonic displacement measurement.

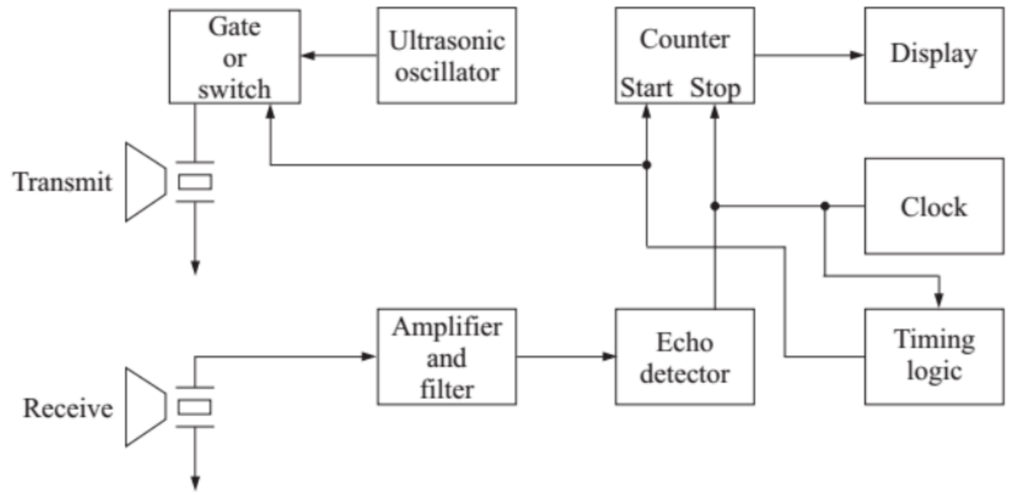


Fig. 6.44 Block diagram of a typical ultrasonic displacement measurement system.

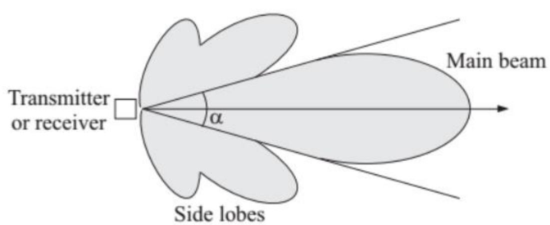
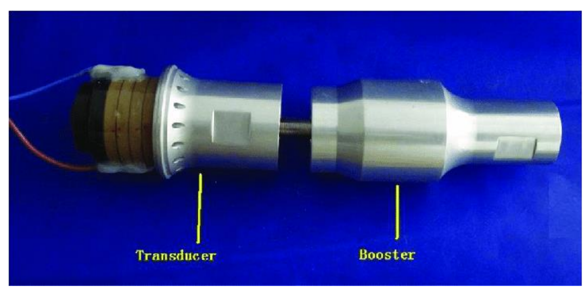


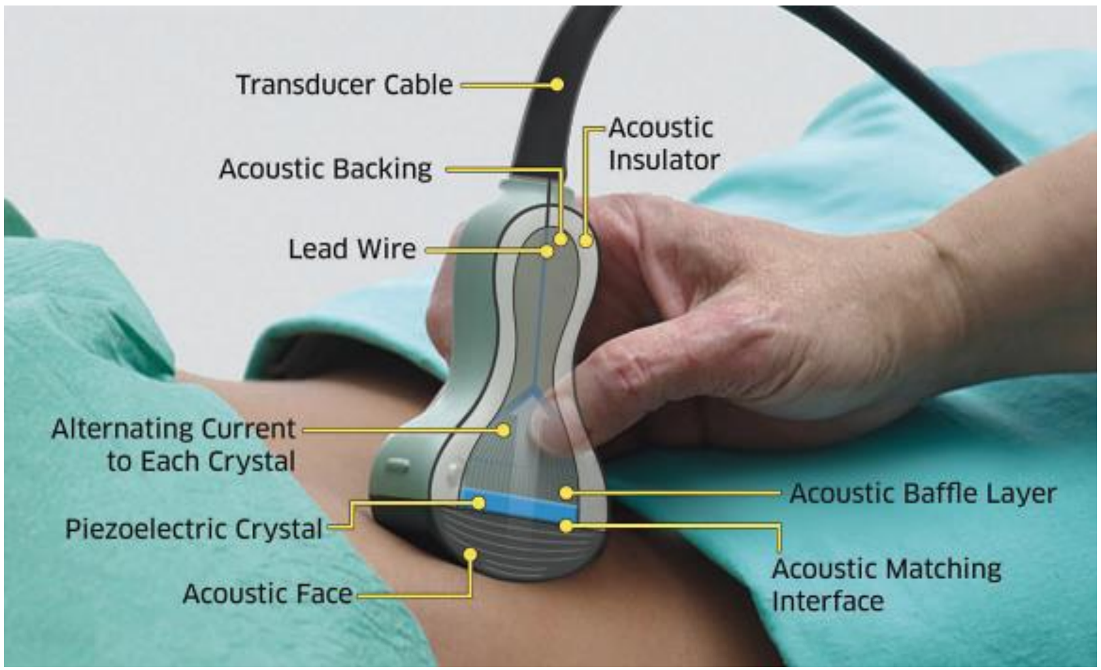
Fig. 6.45 Intensity distribution pattern of ultrasonic beam.

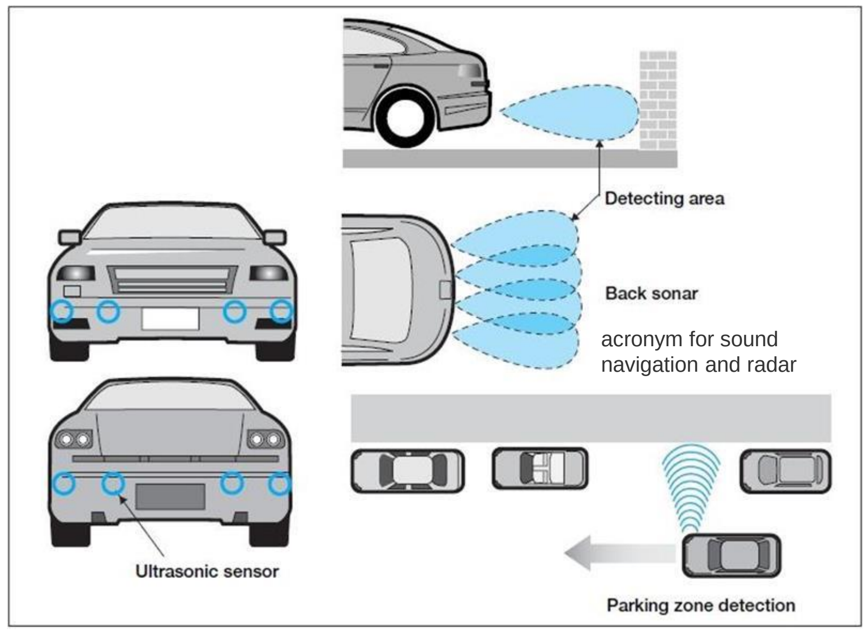


Ultrasonic Transducers

Characteristics of ultrasound?

- Ultrasound is an acoustic wave with a very high frequency, beyond human hearing. Since the audible frequency range is said to be between 20Hz and 20kHz, ultrasound generally means acoustic waves above 20kHz.
- Ultrasound is a vibration of matter, it can also be used to examine the characteristics of that matter. Ultrasonic diagnosis uses this feature to detect and visualise the variance in reflectance and transmittance corresponding to the water content and density of the matter in the medium, for example an organ in your body.





Ultrasonic Transducers

Table 6.9 Advantages and disadvantages of echo ranging

Advantages	*Disadvantages*
1. Non-contact measurement.	1. Moderate accuracy: 0.1 to 2% of the range.
2. Works with almost any surface type.	2. Requires near-perpendicular incidence on the target.
3. Resistant to vibration, radiation, background light, and noise.	3. Affected by dust, dirt, high humidity or air turbulence.
4. Low cost.	4. Limited speed of response.

Displacement Measurement

- **Classification**
  - **Electrical**
  - **Pneumatic**
  - **Optical**
  - **Ultrasonic**
  - **Magnetostrictive**
  - **Digital**

Recall? Coupling Diagram

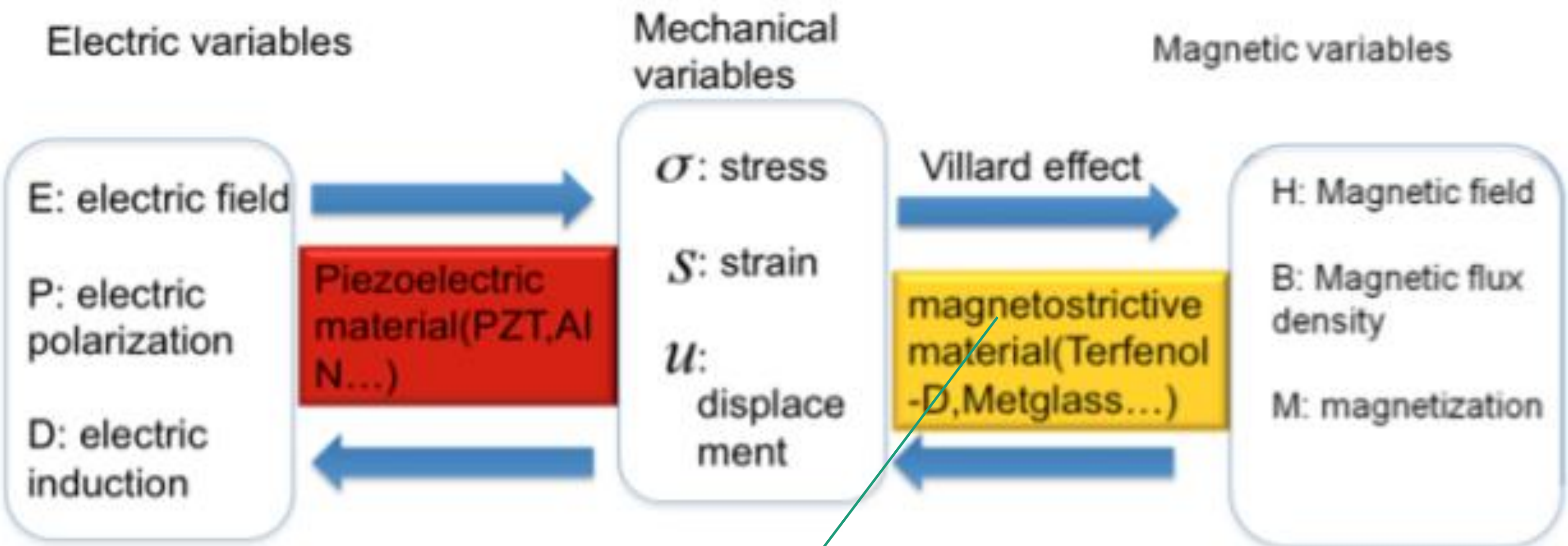


Figure 1.1 Composite material conversion mechanisms

Magnetostrictive materials transduce or convert magnetic energy to mechanical energy and vice versa.

https://tel.archives-ouvertes.fr/tel-01630261/document

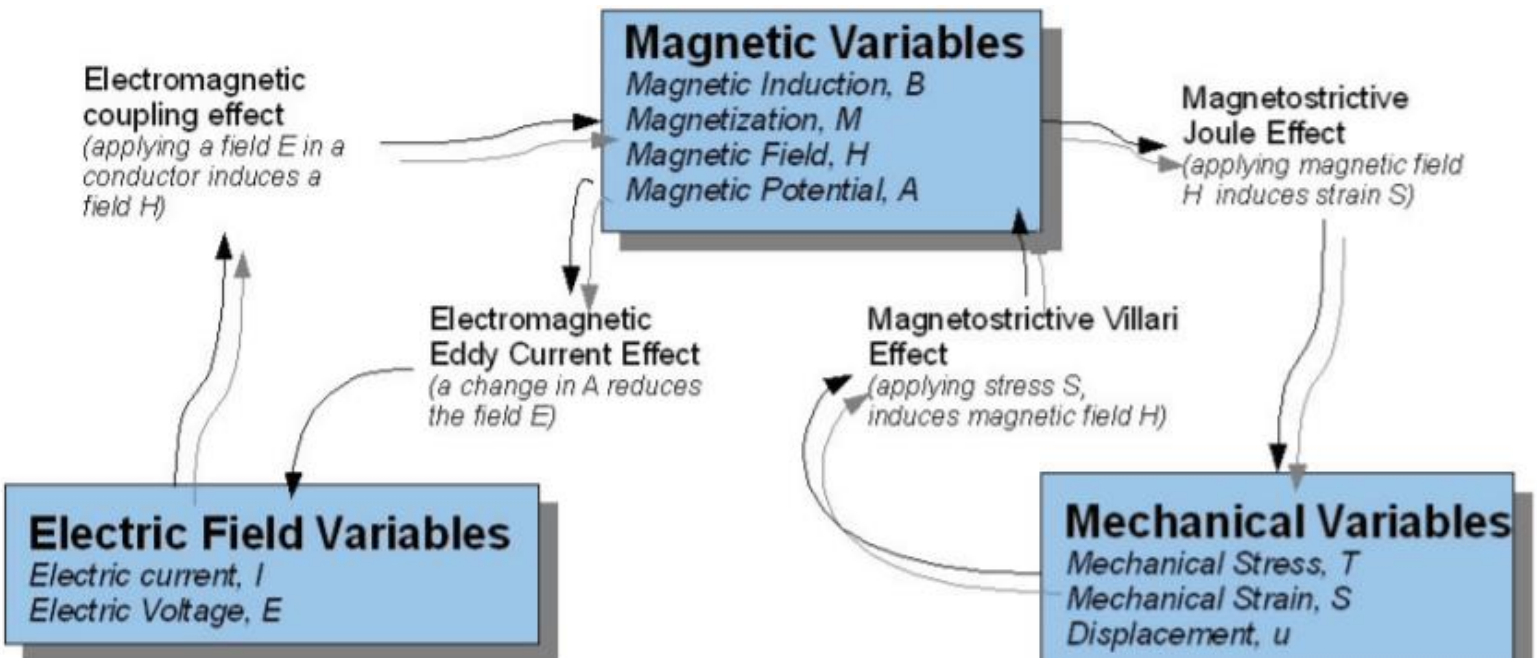
Ch.5 Transducers..

Magnetostriction *describes the change in dimensions of a* ***material*** *due to a change in its magnetization*

The magnetostrictive materials will change shape when it is subjected to a magnetic field. This occurs because magnetic domains in the material align with the magnetic field. Similarly, when the material is strained (stretched or compressed), its magnetic energy changes. This phenomenon is reversible and for this matter it can be use to build actuators, sensors or to make energy conversion.

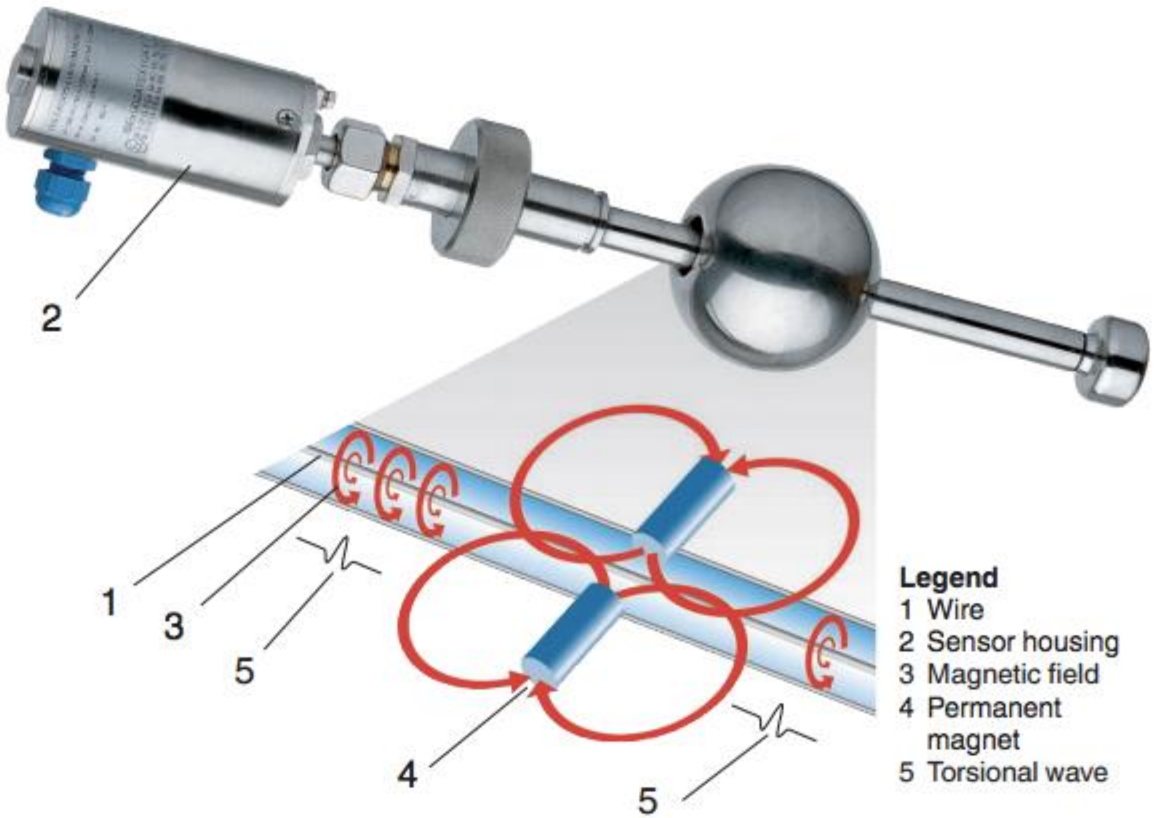
It is possible to simplify the processes into two reversible energy conversion steps:

- from electric to magnetic;
- from magnetic to mechanical.



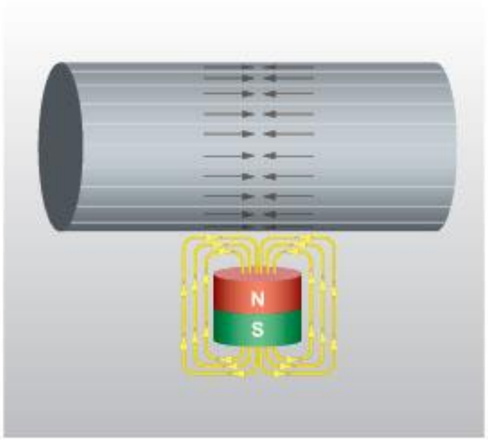
http://www.elkraft.ntnu.no/eno/Papers2008/Martino.pdf

Magnetostrictive Transducer



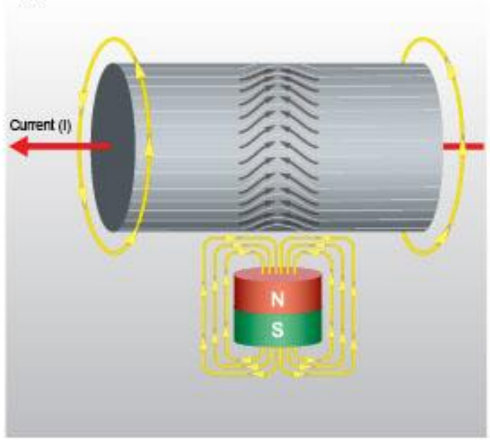
Magnetostrictive Transducer

Initial Condition



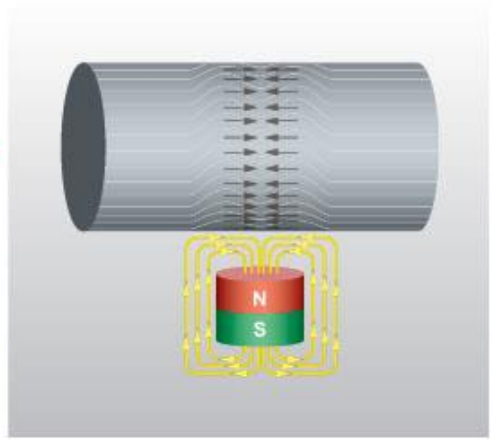
The waveguide tube is magnetized only at the position of the permanent, moving magnet. In practice, the permanent magnet is attached to the moving part of the machine or the piston of a hydraulic or pneumatic cylinder.

Current Pulse Applied



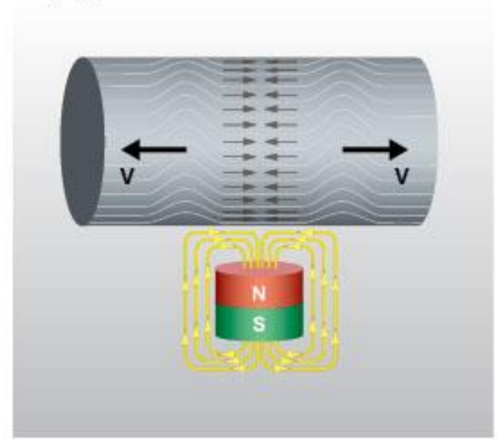
A short duration, (1-3 µsec) current pulse is applied to the waveguide conductor. The magnetic field of the permanent magnet and the magnetic field created by the current pulse interact, causing torsional deflection of the waveguide element.

Current Pulse Turned Off

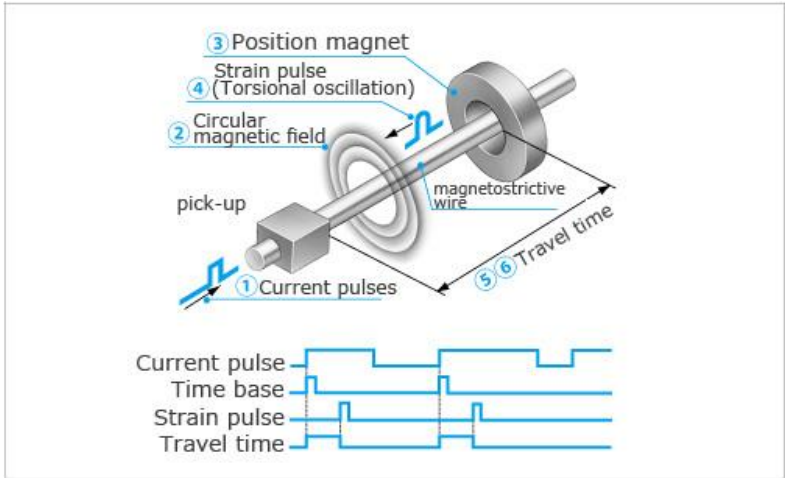


The torsion on the waveguide element abruptly relaxes, and the mechanical wave propagation begins.

Wave Propagation



The mechanical wave propagates in both directions along the waveguide at a nominal velocity of 2850 meters/second. The detection of the mechanical wave in the signal converter completes one measurement cycle. Measurement cycles are typically repeated at rates of 0.5 to 5 milliseconds, depending on the length of the sensor.



Magnetostrictive Transducer

Suppose, a current pulse, called *interrogation pulse*, is sent through a waveguide which has a magnet in its path at a place (Fig. 6.47). Then, a torsional force is induced in the waveguide at the location of the magnet[8]. The force owes its origin to the interaction between the magnetic field produced by the current pulse and the permanent magnet. The torsional pulse generates a strain wave that travels at the acoustic speed (~2850 m/s) in the waveguide changing its magnetic permeability instantaneously[9] at the points through which the wave passes.

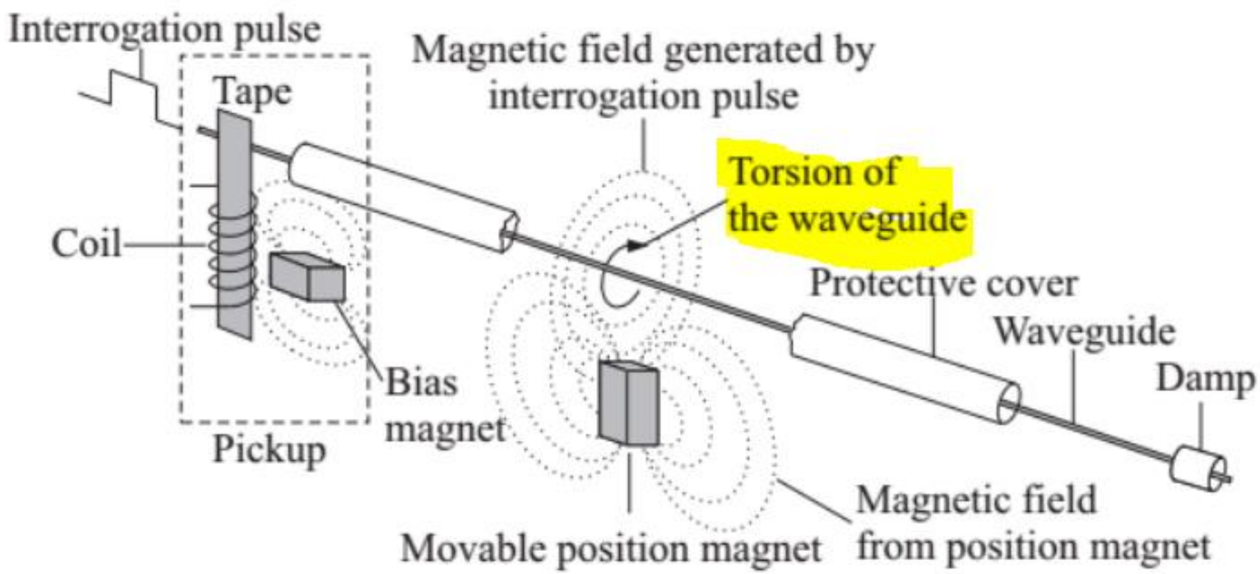


Fig. 6.47 Magnetostrictive displacement transducer action.

[8]Wiedemann effect, see Section 5.2 at page 119.
[9]Villari effect.

How do magnetostrictive sensors work?

MAY 22, 2018 BY DANIELLE COLLINS — LEAVE A COMMENT

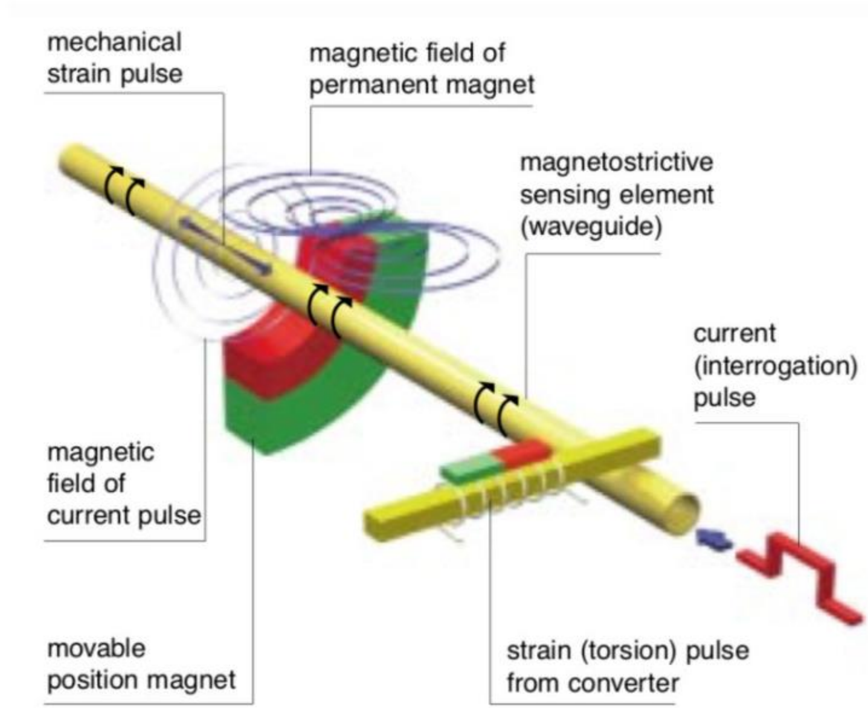
When a ferromagnetic material — such as iron, nickel, or cobalt — is subjected to an external magnetic field, the magnetic domains within the material align, creating internal stresses that cause the material's shape or dimensions to change. This phenomenon is referred to as magnetostriction. Conversely, when a magenetostrictive material is subjected to a stress, its magnetic properties will change. This is known as the Villari effect.

Another manifestation of magnetostriction is the Wiedemann effect: When a wire is subjected to a magnetic field oriented parallel to its length, and a current is passed through the wire, the wire experiences torsional strain at the location where the magnetic field occurs.

The Wiedemann and Villari effects form the basis of linear magnetostrictive sensors.

In magnetostrictive sensors, the wire, or bar, is referred to as a waveguide. It is typically made from an iron alloy and is mounted to a stationary part of the machine. The magnetic field is provided by a magnet, referred to as a position magnet, which is attached to the moving part being measured. Short pulses of current (1-3 μs) are applied to a conductor attached to the waveguide.

As the Wiedemann effect states, torsional strain (twist) is induced in the waveguide, due to the interaction of the magnetic field caused by the current and the magnetic field caused by the position magnet. Because the current is applied as a pulse (referred to as an interrogation pulse), the twist travels down the wire as an ultrasonic wave, moving at approximately 2850 m/s. This twist, or mechanical pulse, is detected by a signal converter (also referred to as a strain pulse converter), which relies on the Villari effect to create a voltage pulse indicating receipt of the mechanical strain wave.



The basic components of a magnetostrictive sensor include the waveguide, the position magnet, and a strain pulse converter.
Image credit: MTS Systems Corporation

The time between the initial current pulse and the detection of the mechanical pulse indicates the location of the position magnet, and therefore, the position of the moving part being measured. The interrogation rate, or update rate, can range from one time per second to over 4000 times per second, with the maximum update rate determined by the length of the waveguide

Displacement Measurement

- **Classification**
  - **Electrical**
  - **Pneumatic**
  - **Optical**
  - **Ultrasonic**
  - **Magnetostrictive**
  - **Digital**

Digital Displacement Transducers

- **DDT**
  - As compared to previous transducers which generate analogue signals in proportional to displacement. The Digital transducer presents information in discrete samples.
  - These transducers are **ENCODERS** as they generate coded messages in measurement.

Encoders can be divided into three categories:

1. Tachometer type
2. Incremental type
3. Absolute type.

Digital Displacement Transducers

Tachometer Type

The coding in such a transducer is schematically shown in Fig. 6.48. Because of this kind of coding, it has a single output signal which consists of a pulse for each increment of the displacement. These pulses can be counted by a digital counter which, in turn, can be calibrated in terms of displacement in suitable units.

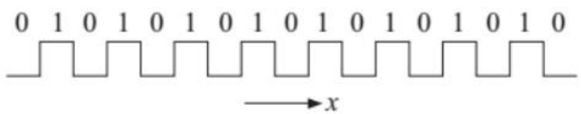


Fig. 6.48 Coding of a tachometer encoder.

Incremental Type

In this type at least two, sometimes three, tracks of coding are employed to solve the reverse-motion problem (Fig. 6.49).

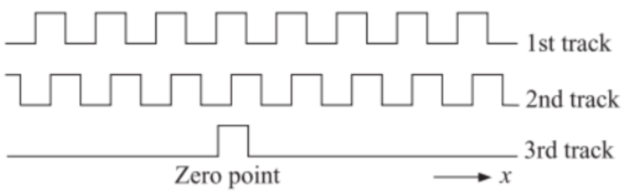


Fig. 6.49 Coding of an incremental encoder.

Absolute Type

Such encoders employ four or more bit binary coded strips or discs, as shown in Fig. 6.50.

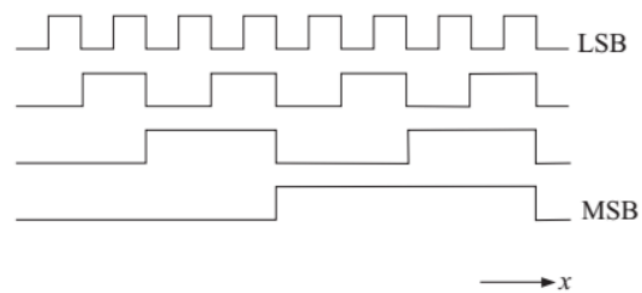


Fig. 6.50 Coding of an absolute encoder.

Comparison of Displacement Transducers?

A comparison of the accuracy and range of commercially available transducers is given in Fig. 6.55. The graph is more suggestive than exhaustive.

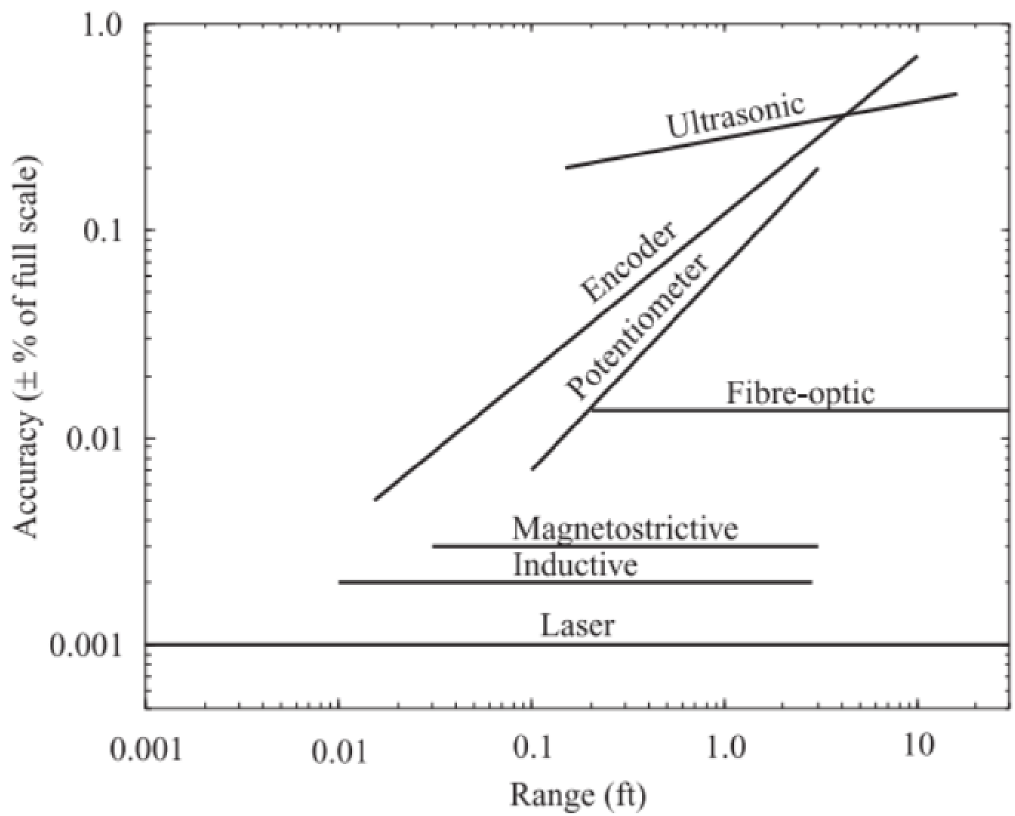


Fig. 6.55 Comparison of accuracy and range of commercially available displacement transducers.

There are, of course, other kinds of transducers for measurement of displacement. For example, piezoelectric transducers can measure very small displacements, and so on.

Proximity Sensor

Proximity Sensor

What are they?

Proximity Sensor

What are they?

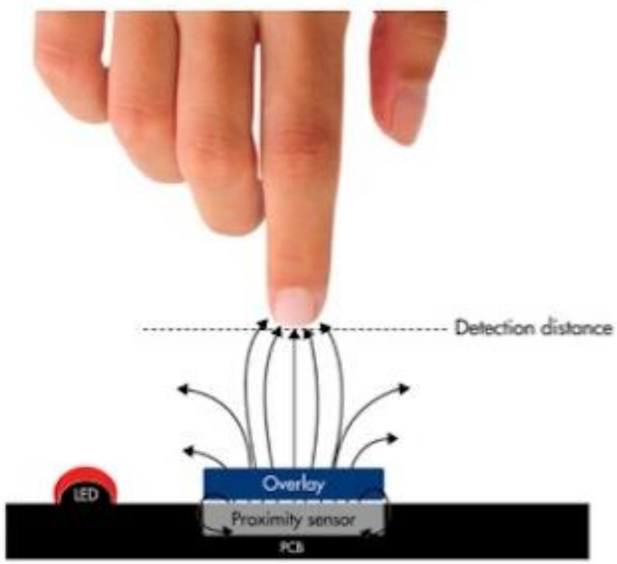
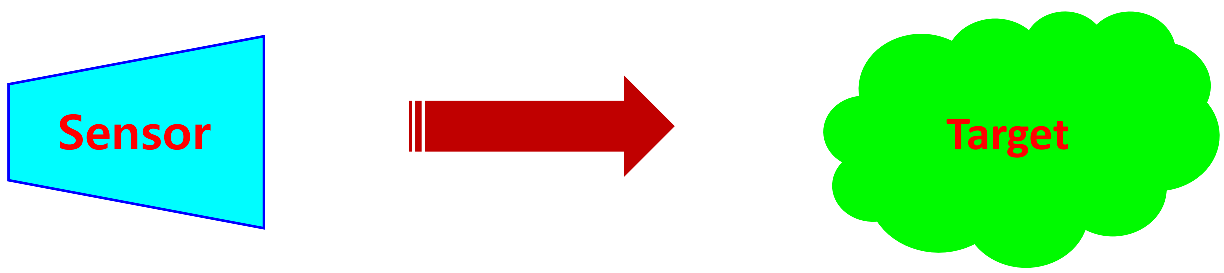


Figure 2: Electric field lines and detection distance of proximity sensor

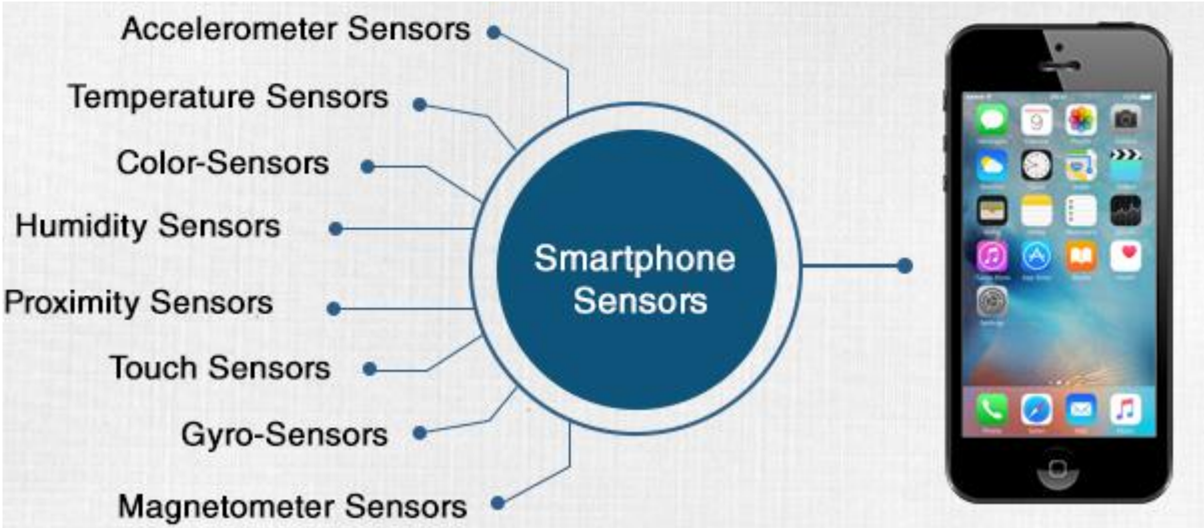
Proximity Sensor

- Detect and measure distance of nearby objects without physical contact

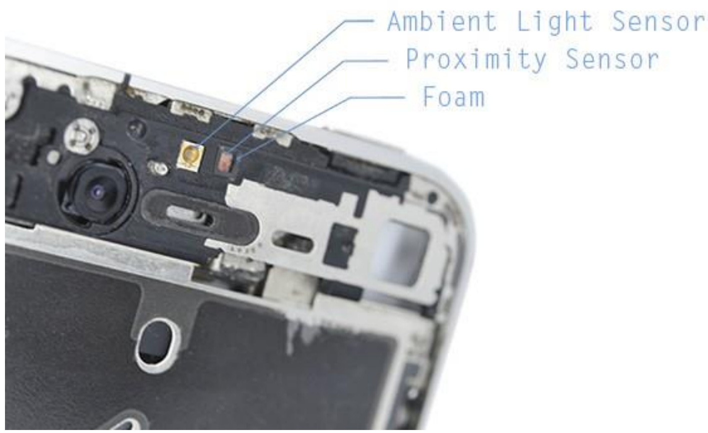
- A proximity sensor often emits an electromagnetic field or a beam of electromagnetic radiation, and looks for changes in the field or return signal.



Proximity Sensor
Where are they?



Proximity Sensor: The proximity sensor, is comprised of an infrared LED and an IR light detector. It is placed near the earpiece of a phone, when you place the handset up to your ear, the sensor lets the system know that you're most probably in a call and that the screen has to be turned off.



Applications of Proximity Sensors

Proximity sensor in a mobile phone plays a role in detecting and avoiding accidental touch screen taps when the phone is held close to the ear.

Proximity sensor used as parking sensor in car bumpers/fenders to alert driver of obstacles while parking.

Proximity Sensors

Proximity sensors are the devices which help **detects and measure the distance of nearby devices *without physical contact.***

The maximum distance that a proximity sensor can detect is called its ***nominal range.***

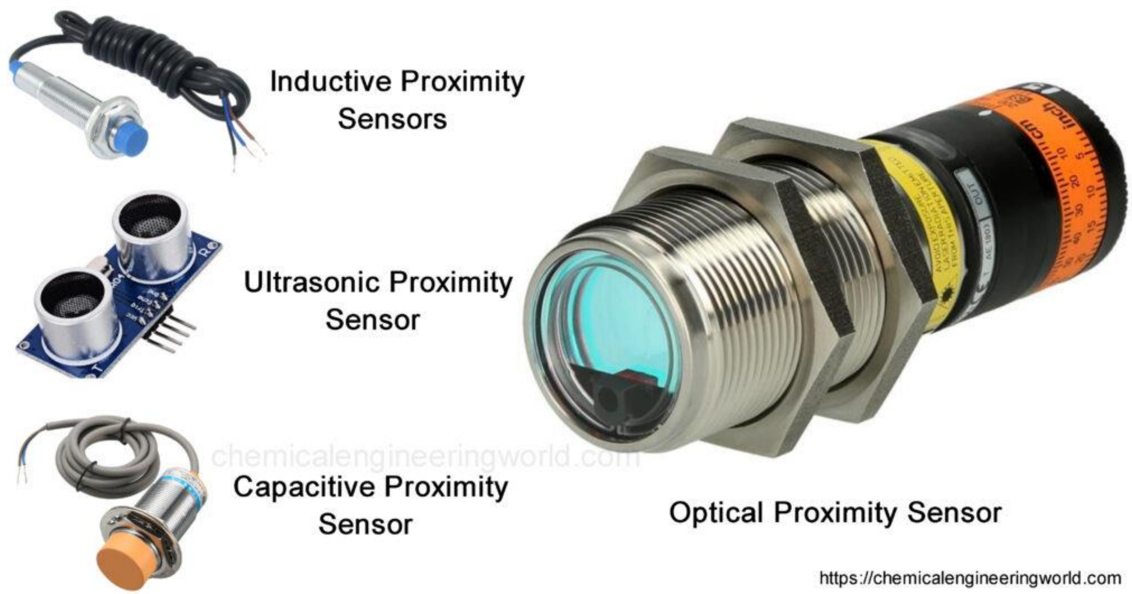
Proximity sensors can have a **high reliability and long functional life** because of the absence of mechanical parts and lack of physical contacts between the sensor and target.

Proximity sensors are generally based on the following principle.

- *Inductive Proximity Sensors*
- *Capacitive Proximity Sensors*
- *Hall Effect Proximity Sensors*
- *Optical Proximity Sensors*
- *Ultrasonic Proximity Sensors*

Proximity Sensor

- Detect and measure distance of nearby objects without physical contact.
  - **Nominal range:** the maximum distance that a proximity sensor can detect.
  - **Types**
    1. **Inductive**
    2. **Capacitive**
    3. **Hall effect**
    4. **Optical**
    5. **Ultrasonic**



Proximity Sensor

- Detect and measure distance of nearby objects without physical contact
  - **Nominal range:** the maximum distance that a proximity sensor can detect
  - Types
    1. Inductive
    2. Capacitive
    3. Hall effect
    4. Optical
    5. Ultrasonic
- **Applications**
  - To measure surface roughness, machine vibration, distance etc.
  - Industrial automation such as conveyor lines (counting, jam detection, etc.), machine tools (safety interlock, sequencing).

Inductive Proximity Sensor

- Generates an electromagnetic field and measures the change in the field owing to the presence of the object
  - **Detect only metallic object**

Inductive Proximity Sensor

- Generates an electromagnetic field and measures the change in the field owing to the presence of the object
  - **Detect only metallic object**
  - **They are usually based on the following principles:**
    1. **Variation of reluctance**
    2. **Eddy-current generation**

Concepts Check?

Ohm's Law for Magnetic Circuit

Recall

$$\boxed{\text{Effect} = \frac{\text{cause}}{\text{opposition}}}$$

For Electric Circuit

$$I = \frac{V}{R}$$

Effect = **Flux**

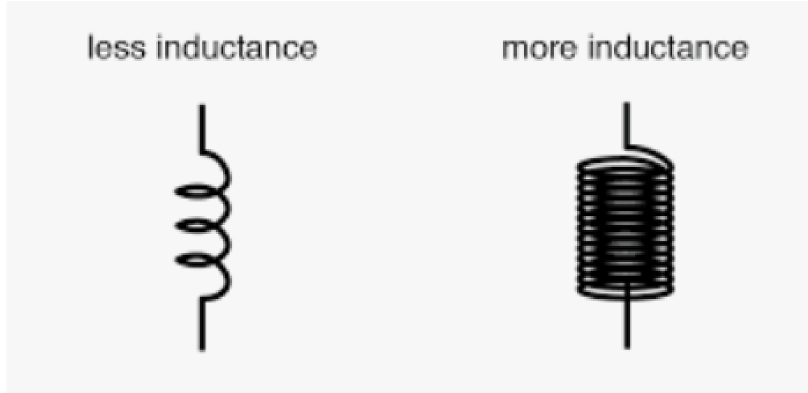
Cause = **Magnetomotive force**

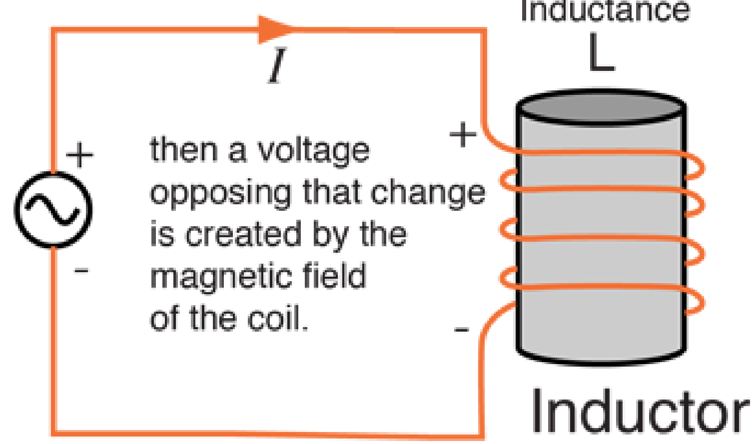
Opposition = **Reluctance**

For Magnetic Circuit

$$\Phi = \frac{\mathcal{F}}{\mathcal{R}}$$

About Inductance?





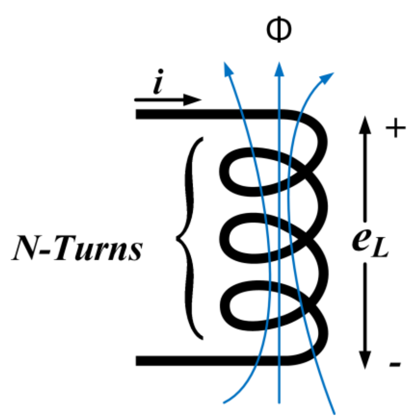
In electromagnetism and electronics, **inductance** is the tendency of an electrical conductor to oppose a change in the electric current flowing through it. The flow of electric current creates a magnetic field around the conductor.

$$L = \frac{\Phi(i)}{i}$$

L = inductance

$\Phi(i)$ = magnetic flux of current i

i = current



$$e_L = N\frac{\Delta\phi}{\Delta t}$$

$$L = N\frac{\Delta\phi}{\Delta i}$$

Where L is the inductance in Henry, e_L is the induced counter-emf in volts and is the rate of change of current in A/s.

Recall: Week 9: Synchro (RVDT)

❑ Based on Variations of Reluctance

- ❑ Magnetic reluctance, or magnetic resistance, is a concept used in the analysis of magnetic circuits. It is defined as the ratio of magnetomotive force to magnetic flux.
- ❑ It represents the opposition to magnetic flux, and depends on the geometry and composition of an object

$$\mathcal{R} = \frac{\mathcal{F}}{\phi}$$

$\mathcal{R}$ = reluctance in ampere-turns per weber

$\mathcal{F}$ = magnetomotive force

ϕ = magnetic flux in webers

❑ To measure angles

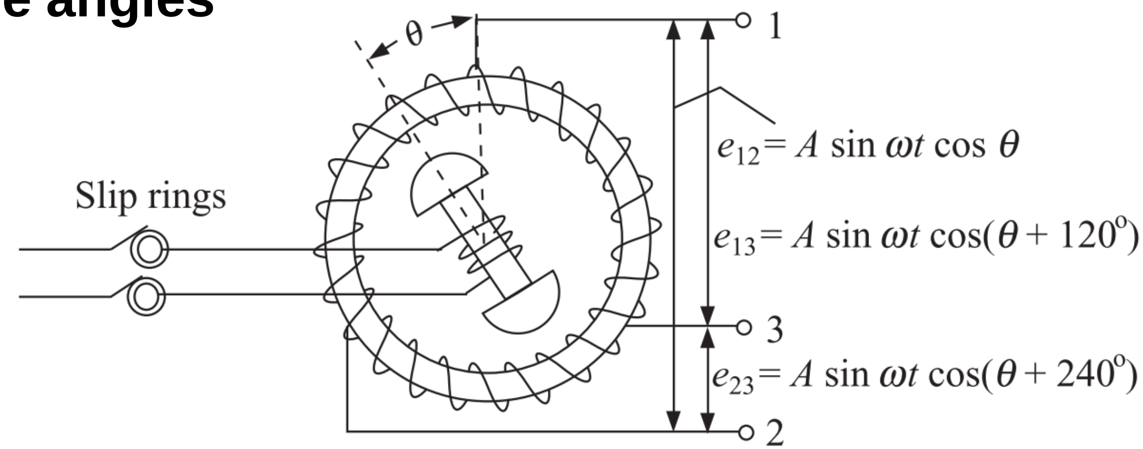


Fig. 6.16 Schematic presentation of a synchro.

❑ Essentially a transformer

- ❑ Rotor: single phase winding
- ❑ Stator: three phase winding (the phases being displaced by 120 degree)

Inductive Proximity Sensor

❑ Variation of reluctance

- ❑ The property of a magnetic circuit of opposing the passage of magnetic flux lines, equal to the ratio of the magnetomotive force to the magnetic flux.

$$\mathcal{R} = \frac{\mathcal{F}}{\phi}$$

$\mathcal{R}$ = reluctance in ampere-turns per weber

$\mathcal{F}$ = magnetomotive force

ϕ = magnetic flux in webers

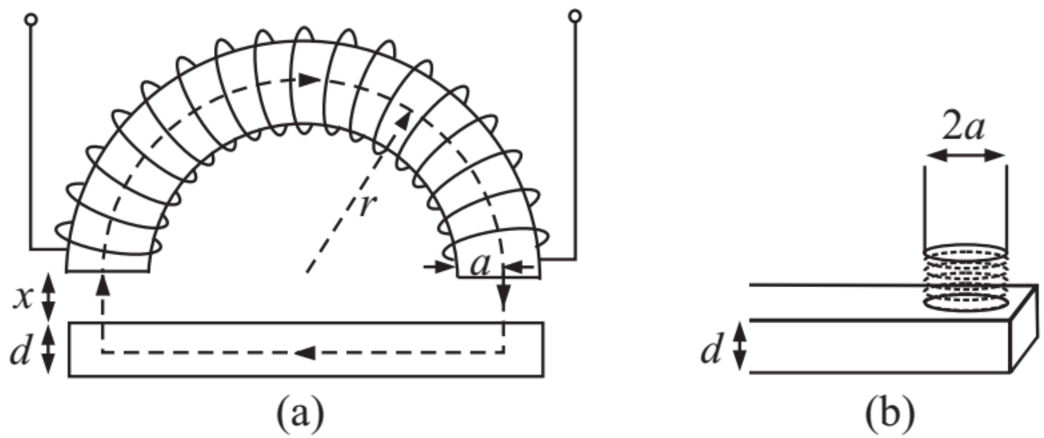


Fig. 6.56 (a) Magnetic circuit, and (b) path of the magnetic flux through the plate.

❑ Magnetic circuit consisting of

1. a semicircular ring with an electrical winding, working as an electromagnet
2. an air gap
3. a plate of magnetic material

Inductive Proximity Sensor

- **Variation of reluctance**
  - **self-inductance L of a coil**

$$L = \frac{N^2}{R} \quad \text{where,} \quad R = \frac{l}{\mu A}$$

N is the number of turns in the coil
R is the reluctance of the magnetic circuit
l is the length of the magnetic path
A is the area of cross-section of the magnetic path
μ is the effective permeability of the medium in and around the coil

Inductive Proximity Sensor

- **Variation of reluctance**
  - **self-inductance L of a coil**

$$L = \frac{N^2}{R} \quad \text{where,} \quad R = \frac{l}{\mu A}$$

N is the number of turns in the coil
R is the reluctance of the magnetic circuit
l is the length of the magnetic path
A is the area of cross-section of the magnetic path
μ is the effective permeability of the medium in and around the coil.

$$\boxed{R = \frac{1}{\mu G} \quad \text{where,} \quad G = \frac{A}{l} = \text{geometric form factor}}$$

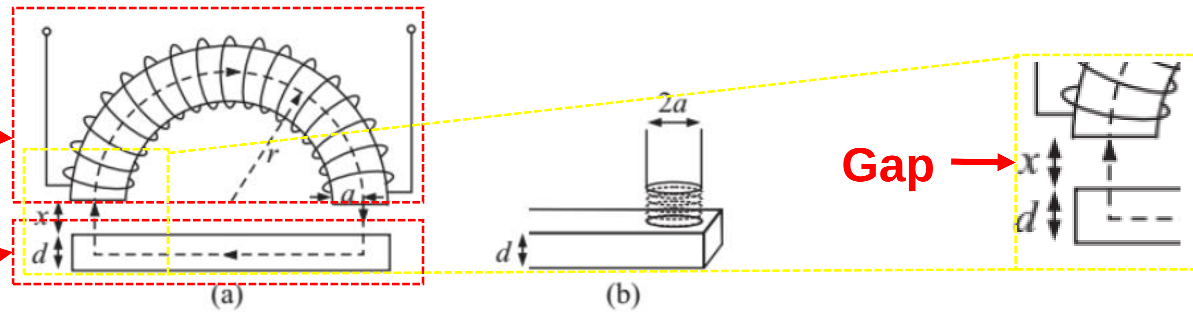
- **Variation in either μ or G varies reluctance which, in turn, varies the inductance**
  - **μ or G can vary due to displacement of various parts of the magnetic circuit**

Inductive Proximity Sensor

Variation of Reluctance

Electromagnet/
Proximity Sensors

Magnetic Plate/
Target



(a) Magnetic circuit, and (b) path of the magnetic flux through the plate.

$$R_{total} = R_{magnet} + R_{gap} + R_{plate}$$

$$R_{magnet} = \frac{l_{magnet}}{\mu_m A} = \frac{\pi r}{\mu_m (\pi a^2)} = \frac{r}{\mu_m a^2}$$

μ_m be the permeability of the magnet material
μ_p be the permeability of the material of the plate
μ_0 be the permeability of the air-gap between the magnet and the plate.

$$R_{gap} = \frac{2 l_{gap}}{\mu_0 A_{gap}} = \frac{2x}{\mu_0 (\pi a^2)}$$

l_n $\quad 2r \quad r$

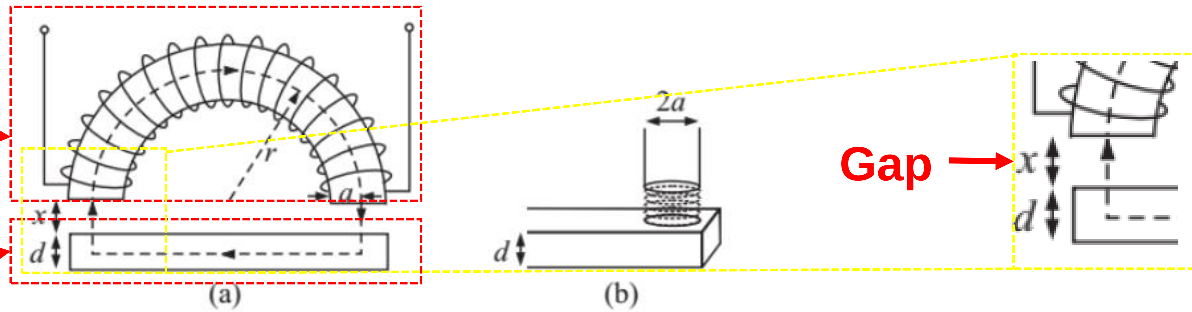
$$\boxed{R_{total} = \frac{r}{\mu_m a^2} + \frac{2x}{\mu_0 (\pi a^2)} + \frac{r}{\mu_p (ad)}}$$

Inductive Proximity Sensor

Variation of Reluctance

Electromagnet/
Proximity Sensors

Magnetic Plate/
Target



(a) Magnetic circuit, and (b) path of the magnetic flux through the plate.

$$R_{total} = \frac{r}{\mu_m a^2} + \frac{2x}{\mu_0(\pi a^2)} + \frac{r}{\mu_p(ad)} = \frac{r}{a}\left(\frac{1}{\mu_m a} + \frac{1}{\mu_p d}\right) + \frac{2x}{\mu_0(\pi a^2)}$$

$$R_{total} = R_0 + kx$$

$R_0 = \frac{r}{a}\left(\frac{1}{\mu_m a} + \frac{1}{\mu_p d}\right)$ [reluctance for zero air gap]

$k = \frac{2}{\mu_0(\pi a^2)}$

$L_0 = \frac{N^2}{R_0}, \alpha = \frac{k}{R_0}$

The inductance has non linear relationship with the air gap 'x'.

Inductive Proximity Sensor

- ❑ **Variation of reluctance**

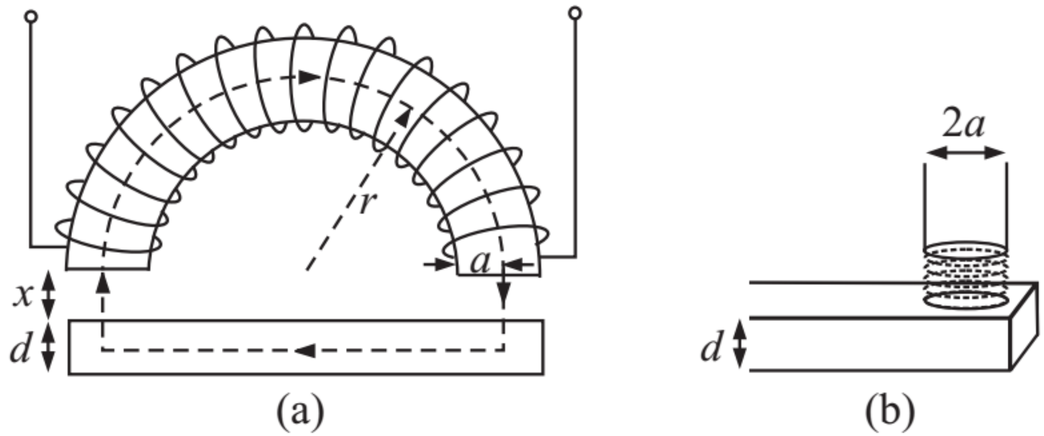


Fig. 6.56 (a) Magnetic circuit, and (b) path of the magnetic flux through the plate.

$$R_{\mathrm{total}} = R_{\mathrm{magnet}} + R_{\mathrm{gap}} + R_{\mathrm{plate}}$$

Inductive Proximity Sensor

- **Variation of reluctance**

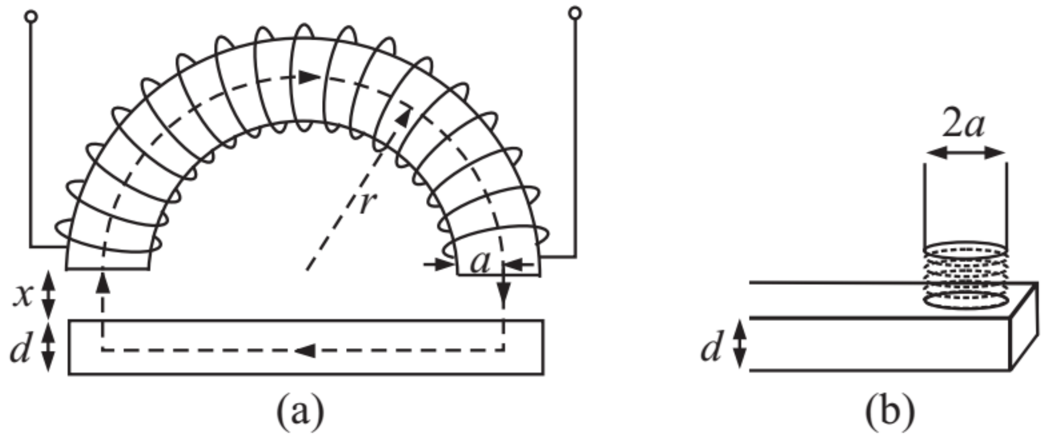


Fig. 6.56 (a) Magnetic circuit, and (b) path of the magnetic flux through the plate.

$$R_{\text{total}} = R_{\text{magnet}} + R_{\text{gap}} + R_{\text{plate}}$$

$$R_{\text{magnet}} = \frac{l_{\text{magnet}}}{\mu_m A} = \frac{\pi r}{\mu_m (\pi a^2)} = \frac{r}{\mu_m a^2}$$

$$R_{\text{gap}} = \frac{2x}{\mu_0 (\pi a^2)}$$

$$R_{\text{plate}} = \frac{2r}{\mu_p (2ad)} = \frac{r}{\mu_p ad}$$

μ_m be the permeability of the magnet material
μ_p be the permeability of the material of the plate
μ_0 be the permeability of the air-gap between the magnet and the plate.

Inductive Proximity Sensor

- **Variation of reluctance**

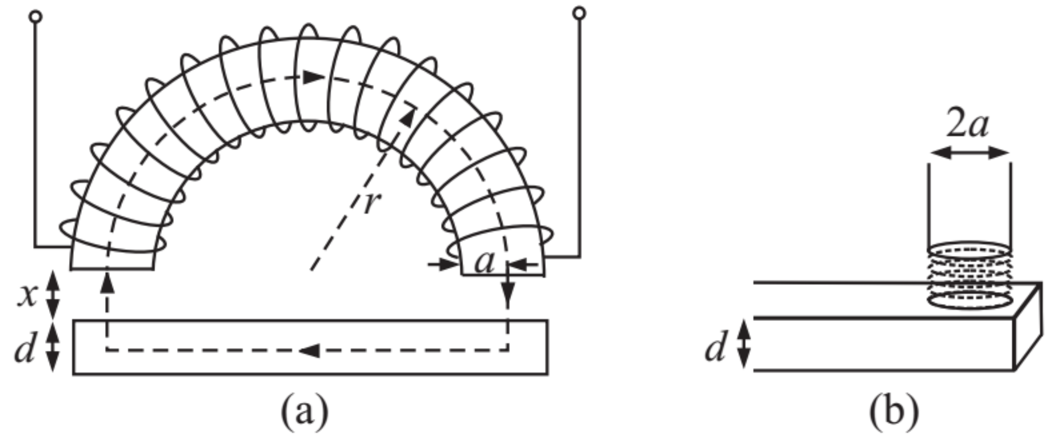


Fig. 6.56 (a) Magnetic circuit, and (b) path of the magnetic flux through the plate.

$$R_{\text{total}} = R_{\text{magnet}} + R_{\text{gap}} + R_{\text{plate}}$$

$$R_{\text{magnet}} = \frac{l_{\text{magnet}}}{\mu_m A} = \frac{\pi r}{\mu_m(\pi a^2)} = \frac{r}{\mu_m a^2}$$

$$R_{\text{gap}} = \frac{2x}{\mu_0(\pi a^2)}$$

$$R_{\text{plate}} = \frac{2r}{\mu_p(2ad)} = \frac{r}{\mu_p ad}$$

$$R_{\text{total}} = R_0 + kx$$

$$R_0 = \frac{r}{a}\left[\frac{1}{\mu_m a} + \frac{1}{\mu_p d}\right] = \text{reluctance for zero air-gap}$$

$$k = \frac{2}{\mu_0 \pi a^2}$$

Inductive Proximity Sensor

- Variation of reluctance

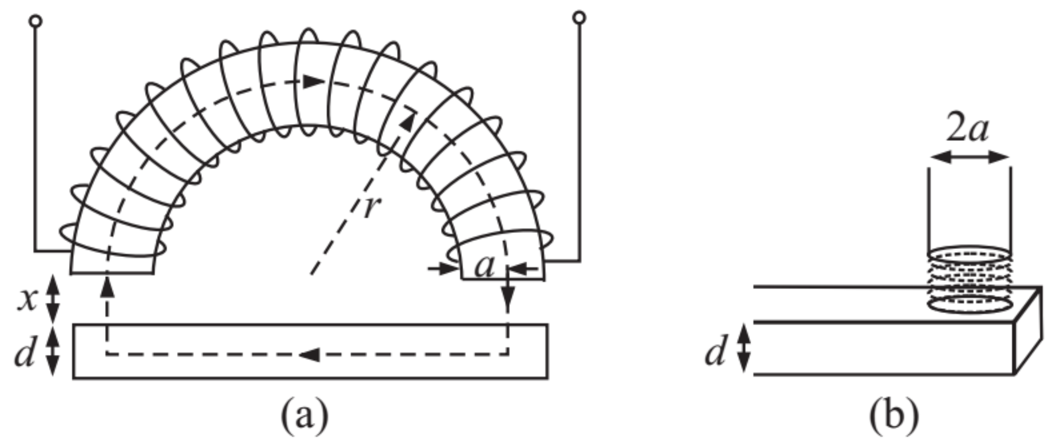


Fig. 6.56 (a) Magnetic circuit, and (b) path of the magnetic flux through the plate.

$$R_{\text{total}} = R_{\text{magnet}} + R_{\text{gap}} + R_{\text{plate}}$$

$$R_{\text{total}} = R_0 + kx$$

$$R_0 = \frac{r}{a}\left[\frac{1}{\mu_m a} + \frac{1}{\mu_p d}\right] = \text{reluctance for zero air-gap}$$

$$k = \frac{2}{\mu_0 \pi a^2}$$

$$L = \frac{N^2}{R} = \frac{N^2}{R_0 + kx} = \frac{L_0}{1 + \alpha x}$$

$$L_0 = \frac{N^2}{R_0} = \text{inductance from zero air-gap}$$

$$\alpha = \frac{k}{R_0}$$

Inductive Proximity Sensor

- **Variation of reluctance**

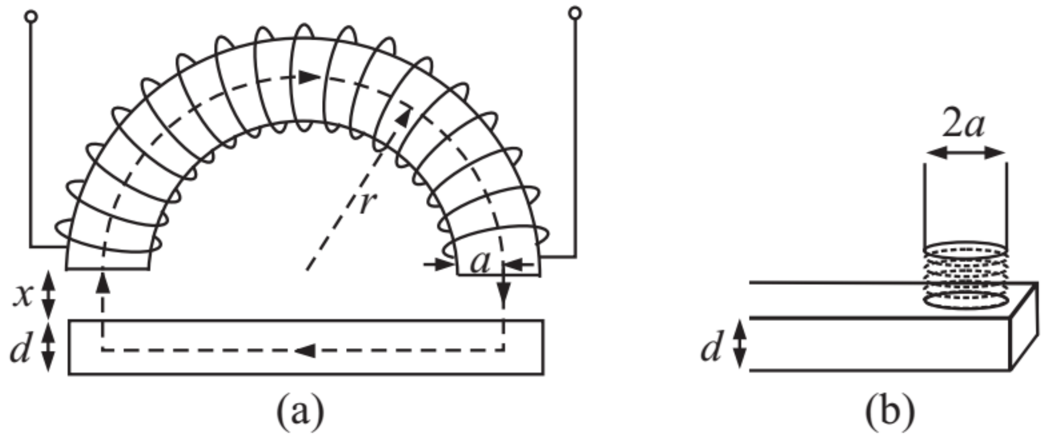


Fig. 6.56 (a) Magnetic circuit, and (b) path of the magnetic flux through the plate.

$$R_{\text{total}} = R_{\text{magnet}} + R_{\text{gap}} + R_{\text{plate}}$$

$$L = \frac{N^2}{R} = \frac{N^2}{R_0 + kx} = \frac{L_0}{1 + \alpha x}$$

$$L_0 = \frac{N^2}{R_0} = \text{inductance from zero air-gap}$$

$$\alpha = \frac{k}{R_0}$$

- Self-inductance is a function, though nonlinear, of the plate displacement *x*
- They have a small range, typically 3 mm ± 10%

Recall Ch. 5

Magnetic Effects

Table 5.3 Magnetic effects used in transducers

Effect	*Year of discovery*	*What it is*	*Application*
Faraday effect	1831	Generation of electricity in a coil with the change in the ambient magnetic field	Reluctance based transducers
Joule effect (Magnetostriction)	1842	Change in shape of a ferromagnetic body with magnetisation	In combination with piezoelectric elements for magnetometers and potentiometers
ΔE effect	1846	Change in Young's modulus with magnetisation	Acoustic delay line components for magnetic field measurement
Matteucci effect	1847	Torsion of a ferromagnetic rod in a longitudinal field changes magnetisation	Magnetoelastic sensors
Thomson effect	1856	Change in resistance with magnetic field	Magnetoresistive sensors
Wiedemann effect	1858	A torsion is produced in a current carrying ferromagnetic rod when subjected to a longitudinal field	Torque and force measurement Displacement measurement Level measurement
Villari effect	1865	Effect on magnetisation by tensile or compressive stress	Magnetoelastic sensors
Hall effect	1879	A current carrying crystal produces a transverse voltage when subjected to a magnetic field vertical to its surface	Magnetogalvanic sensors
Skin effect	1903	Displacement of current from the interior of material to surface layer due to eddy currents	Distance and proximity sensors
Josephson effect	1962	Quantum tunnelling between two superconducting materials with an extremely thin separating layer	SQUID magnetometers

Inductive Proximity Sensor

- **Eddy-current proximity sensor**

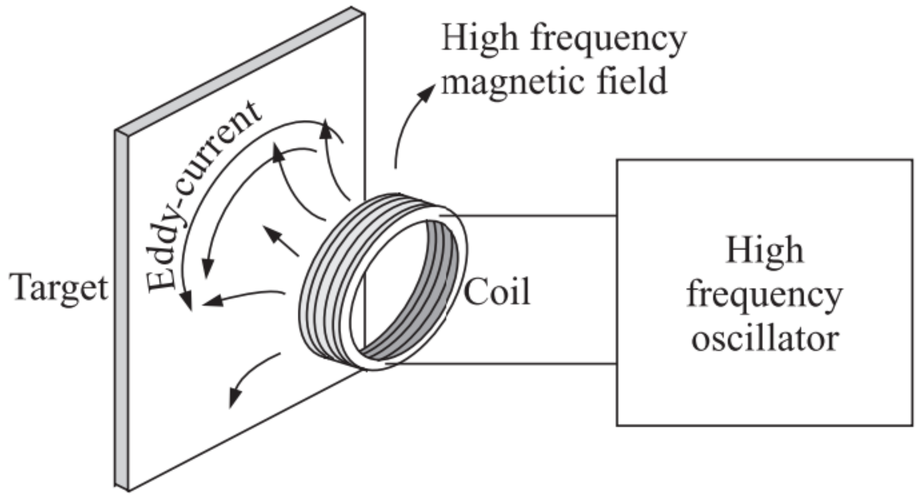


Fig. 6.57 Eddy-current generation.

Inductive Proximity Sensor

- Eddy-current proximity sensor

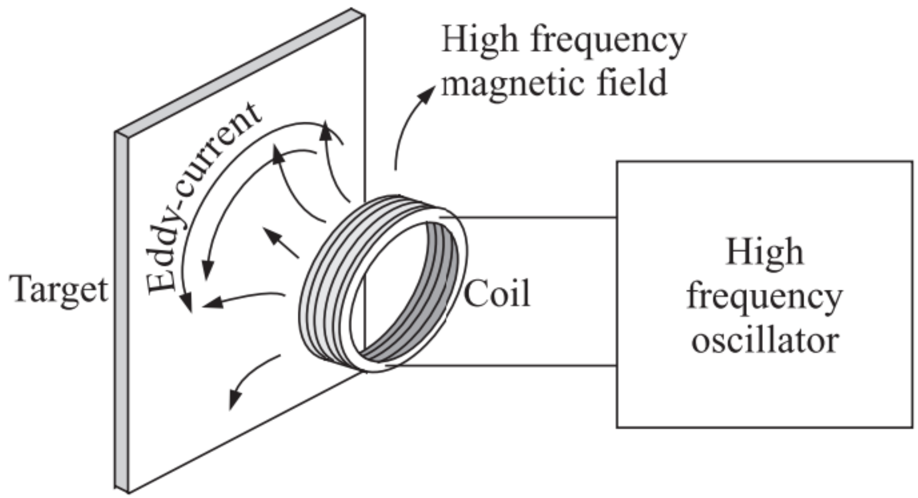


Fig. 6.57 Eddy-current generation.

What are eddy-currents?

Inductive Proximity Sensor

- **Eddy-current proximity sensor**
  - Eddy-currents are generated in a conducting plate in proximity of a coil carrying ac
  - Magnetic field (@Target) due to the eddy-currents opposes the field produced by the coil
    - Consequence: reduction of the coil inductance

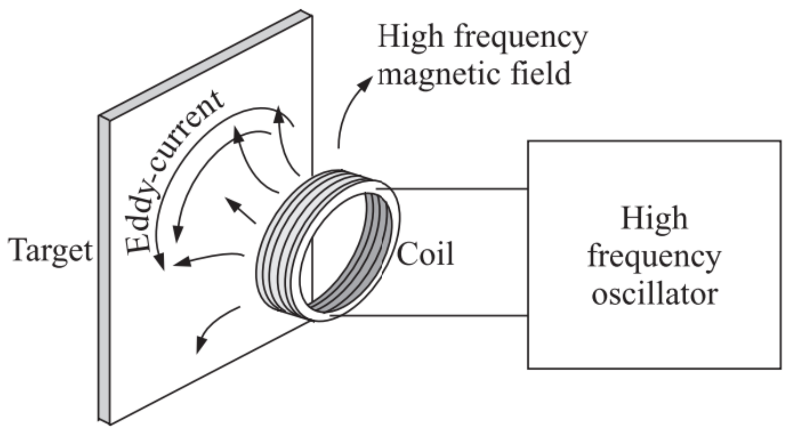


Fig. 6.57 Eddy-current generation.

- This effect depends on the distance between the target and the coil: proximity sensing
- Near the target, higher the eddy-current and lower the inductance (reduced flux @ coil)

Inductive Proximity Sensor

- ❑ **Eddy-current proximity sensor**
    - ❑ **Setup**

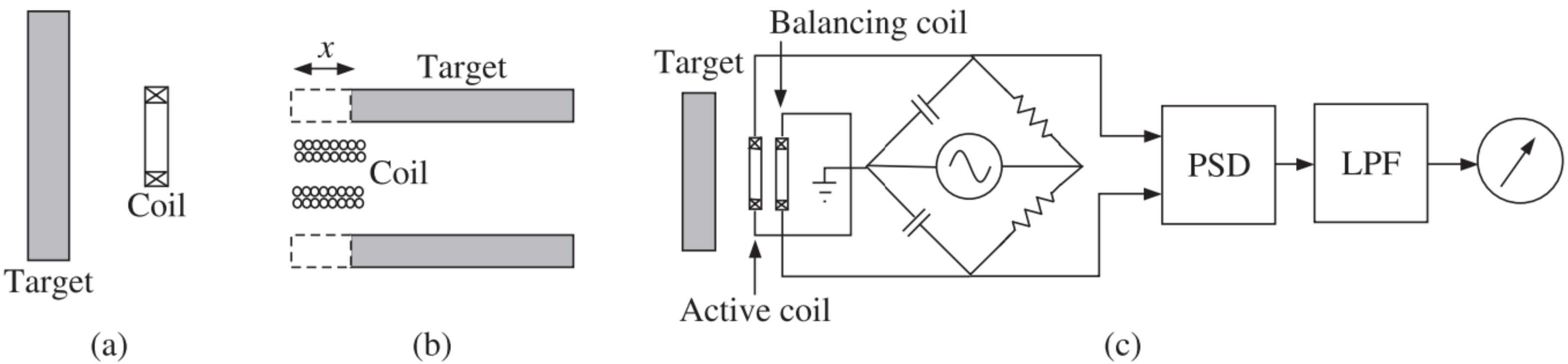


Fig. 6.58 Schematic diagram of placement of eddy-current generation type transducers: (a) target and coil at right angles, (b) coaxial target and coil, and (c) measuring arrangement.

- ❑ Probe consists of two coils: one (active) for the measurement and the other (balancing) for temperature compensation
- ❑ Two coils are connected in parallel to two capacitors forming two arms of a bridge

Inductive Proximity Sensor

- ❑ **Eddy-current proximity sensor**
  - ❑ **Setup**

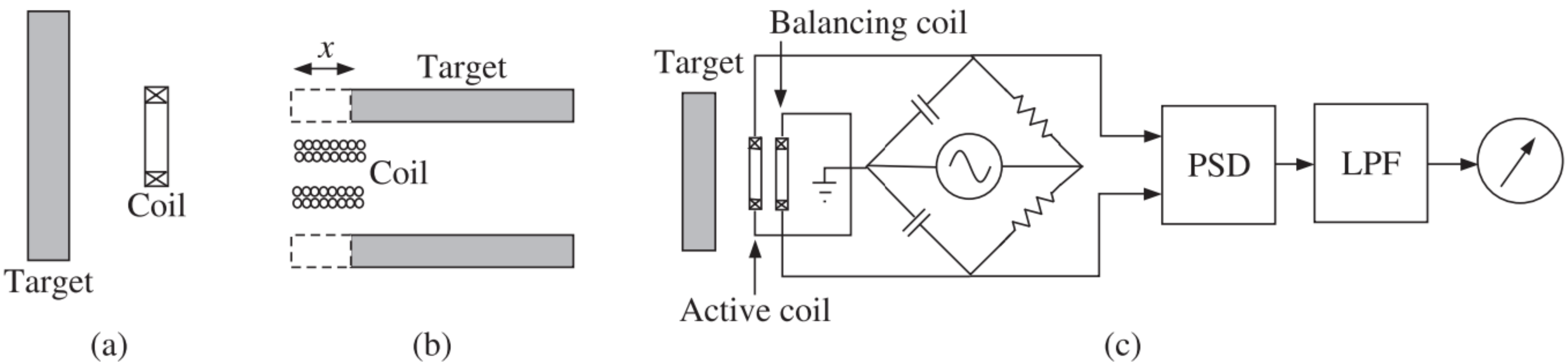


Fig. 6.58 Schematic diagram of placement of eddy-current generation type transducers: (a) target and coil at right angles, (b) coaxial target and coil, and (c) measuring arrangement.

- ❑ Target's displacement causes a bridge unbalance producing a voltage proportional to the target displacement
- ❑ This unbalanced voltage is demodulated and low-pass filtered to produce a dc output which can be calibrated to indicate the extent of target displacement

Inductive Proximity Sensor

- ❑ **Eddy-current proximity sensor**

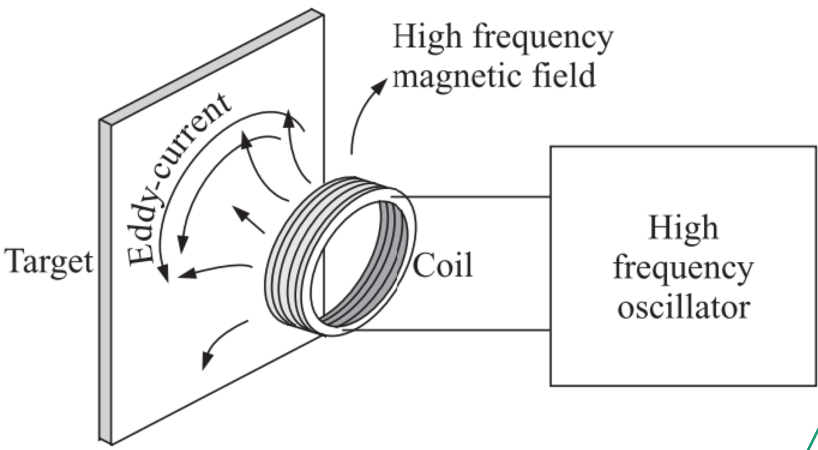


Fig. 6.57 Eddy-current generation.

$$\delta = 50.3\sqrt{\frac{\rho}{f\mu}}\ \text{mm}$$

ρ is the resistivity in μΩ-cm
f is the excitation frequency in Hz
μ is the permeability of the target material

- ❑ Skin depth: the eddy currents are confined to shallow depths, called skin depth, near the conductive target surface
    - ❑ **The target material must be at least three times thicker than the skin depth**
    - ❑ A lower thickness will make the target hot changing the thickness owing to thermal expansion

Inductive Proximity Sensor

- ❑ Eddy-current proximity sensor
  - ❑ Alternative Method: measurement of the phase difference and amplitude of the incident ac and that generated by the eddy current in the target

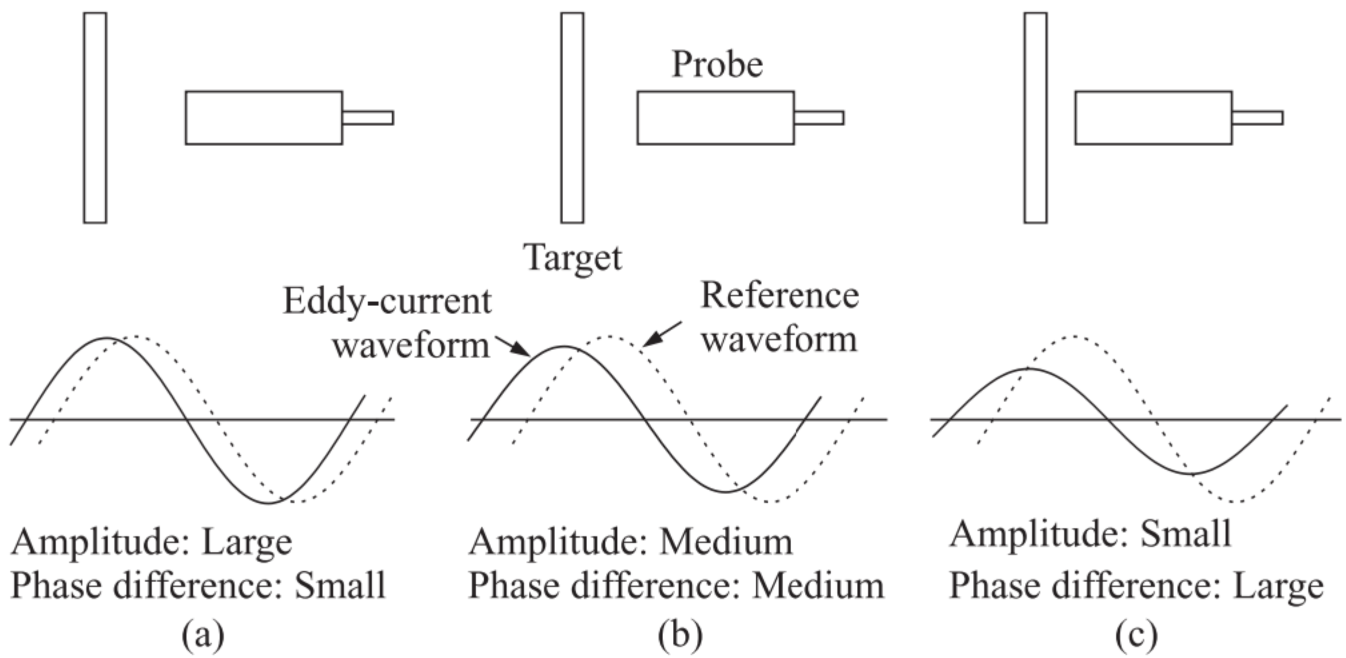


Fig. 6.59 Reference and eddy-current waveforms when the distance between the target and probe is (a) large, (b) medium, and (c) small.

Inductive Proximity Sensor

❑ Eddy-current proximity sensor

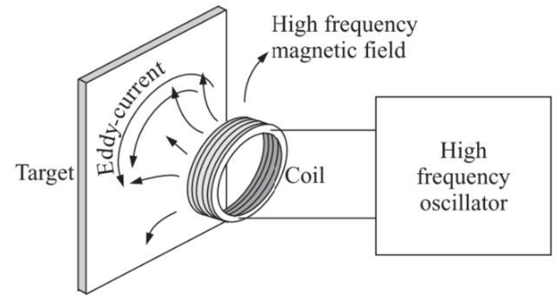


Fig. 6.57 Eddy-current generation.

Advantages and disadvantages. The advantages and disadvantages of an eddy-current transducer are given in Table 6.12.

Table 6.12 Advantages and disadvantages of eddy-current proximity sensors

Advantages	*Disadvantages*
1. Non-contacting measurement.	1. The displacement vs. the impedance characteristic is nonlinear and temperature dependent. Though a balance coil can compensate for the temperature effect, the nonlinearity has to be appropriately taken care of.
2. High resolution.	2. Works only on conductive materials with sufficient thickness. Cannot be used for detecting the displacement of nonconductive materials or thin metal foils.
3. High frequency response.	

Proximity Sensor

- Detect and measure distance of nearby objects without physical contact.
  - **Types**
    1. **Inductive**
    2. **Capacitive**
    3. **Hall effect**
    4. **Optical**
    5. **Ultrasonic**

Capacitive Proximity Sensor

- Target detection using the alteration in the electrostatic field set-up by the sensor
  - the capacitive proximity sensor is capable of detecting any dielectric target like plastic or paper over and above metallic targets
  - Sensing surface: The sensing surface of a capacitive sensor is formed by two concentrically shaped metal electrodes

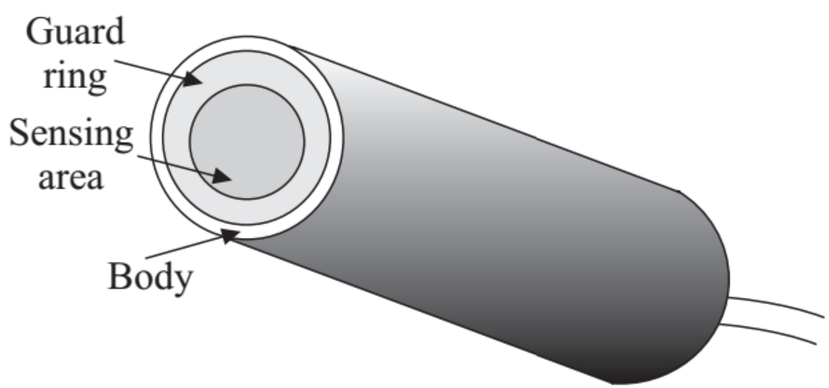


Fig. 6.60 Components of the capacitive proximity sensor probe.

Capacitive Proximity Sensor

Single-Probe Capacitive Position Gauge for Nanometrology Applications

The D-510 family of PISeca™ single-electrode capacitive displacement gauges performs high-precision, non-contact measurements of geometric quantities representing displacement, separation, position, length or other linear dimension against any kind of electrically conductive target. These single-probe nanometrology sensors combine superior resolution and linearity with very high bandwidth for dynamic measurements.

>> D-510 Single-Probe Capacitive Position Gauge for Nanometrology Applications

Features & Advantages

- Sub-Nanometer Resolution, Measuring Ranges to 500 μm
- Absolute, Non-Contact Measurement of Distance / Motion / Vibration
- Multi-Axis Measurements Possible
- Excellent Measuring Linearity to 0.1 %
- Plug & Play: Easy Setup and Integration
- Very Temperature Stable
- Bandwidth to 10 kHz
- Guard-Ring Electrode Design for Better Sensor Linearity
- ILS Linearization System in the Signal Conditioner Electronics Improves Output Signal Linearity
- All Systems Factory Calibrated for Highest Possible Linearity / Accuracy

❑ **They are in the market**

Capacitive Proximity Sensor

- As the target enters the electrostatic field of the electrodes, the capacitance changes causing oscillation in the oscillator circuit
- The trigger circuit reads the amplitude of oscillation and, when it reaches a specific level, the output state of the sensor changes

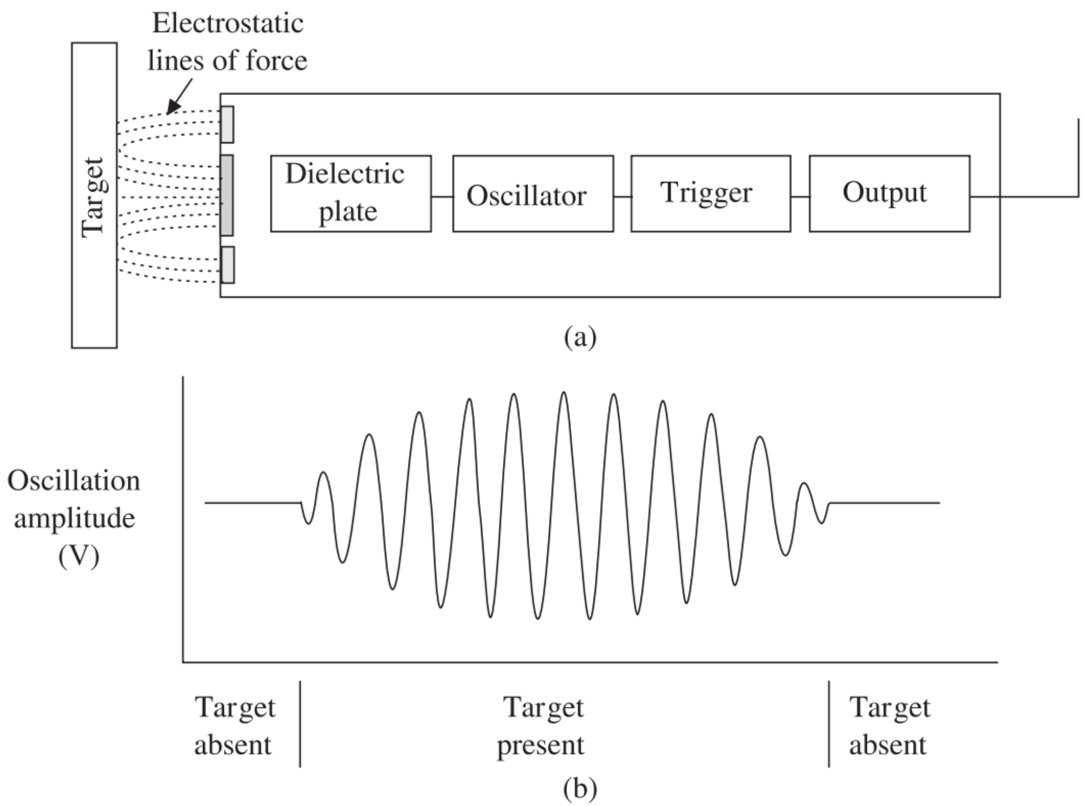


Fig. 6.61 (a) Block diagram of the electronic circuit, and (b) the oscillation generation.

Capacitive Proximity Sensor

- Focusing the field
- For accurate measurements, the electrostatic field from the sensing area needs to be restricted within the space between the probe and the target.

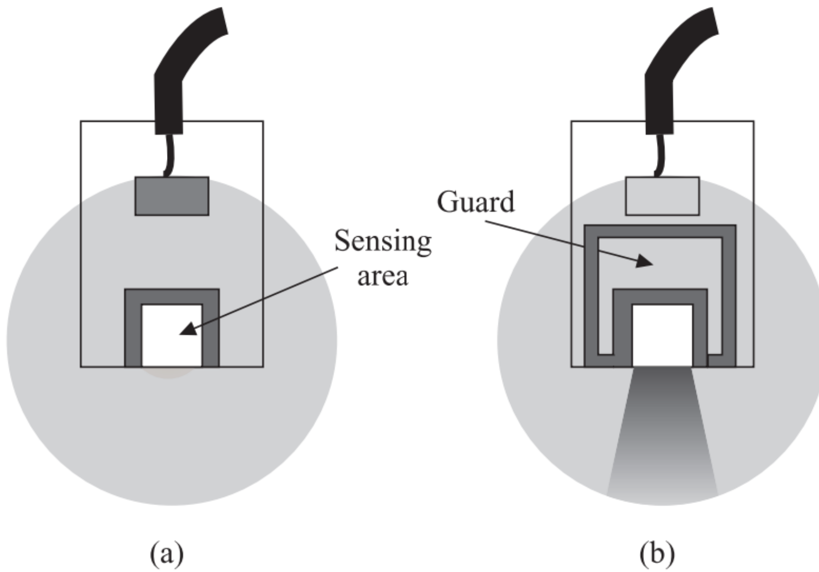


Fig. 6.62 Schematic diagrams showing electrostatic fields, through shading, of (a) unguarded, and (b) guarded capacitive proximity sensors.

- *Fringing*
- *Guarding:* the back and sides of the sensing area are surrounded by another conductor that is kept at the same voltage as the sensing area

Capacitive Proximity Sensor

Target size. The target size is important when selecting a probe for a specific application. A slightly conical field that is a projection of the sensing area, is produced when the sensing electrostatic field is focussed by guarding. The minimum target diameter for standard calibration is

$$\text{Target diameter} = 1.3 \times (\text{Sensing area diameter})$$

If the target size is too small, the electrostatic field will wrap around the sides of the target which means the field will extend further than it did while it was calibrated. As a result, it will measure the target further away.

Range. The range in which a probe is useful is a function of the size of the sensing area. The greater the area, the larger the range. Therefore, a smaller probe should be closer to the target. Although it is adjustable, but there is a limit to the range of adjustment. In general,

$$\text{Maximum gap} = 0.4 \times (\text{Sensing area diameter})$$

Proximity Sensor

- ❑ Detect and measure distance of nearby objects without physical contact.
  - ❑ **Types**
    1. **Inductive**
    2. **Capacitive**
    3. **Hall effect**
    4. **Optical**
    5. **Ultrasonic**

Hall-Effect Sensors

❑ Hall-Effect

- The charges (electrons or holes) flowing in a perpendicular magnetic field experience a force that produce the charges deflection and, so, a transverse voltage

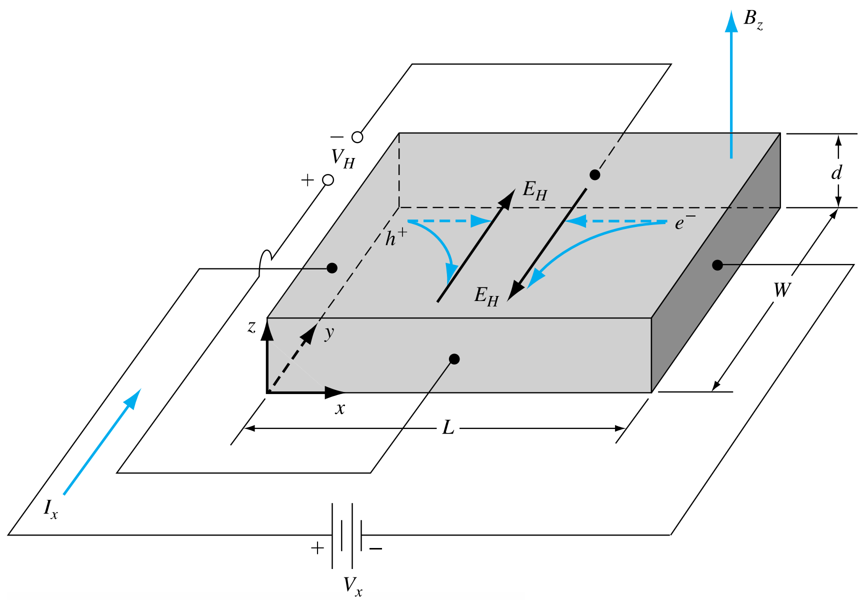
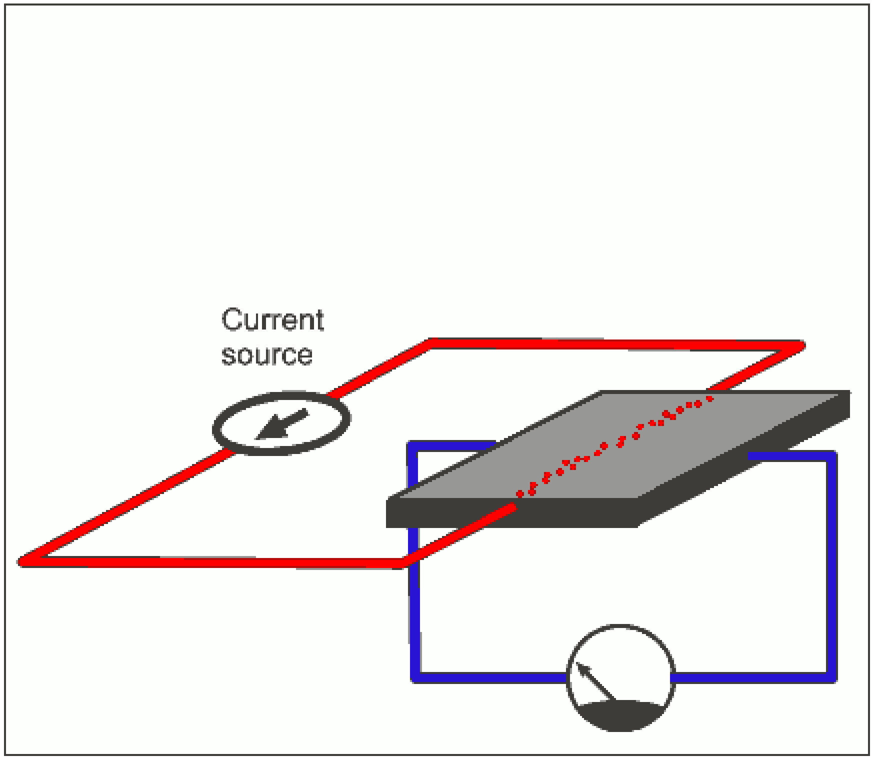
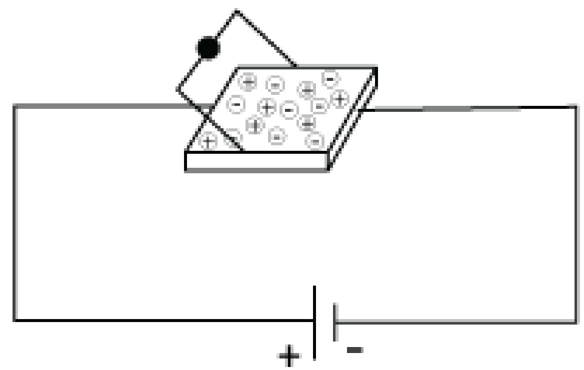


Figure 5.13 | Geometry for measuring the Hall effect.

Ref: Semiconductor Physics and Devices: Basic Principles by Donald A. Neamen

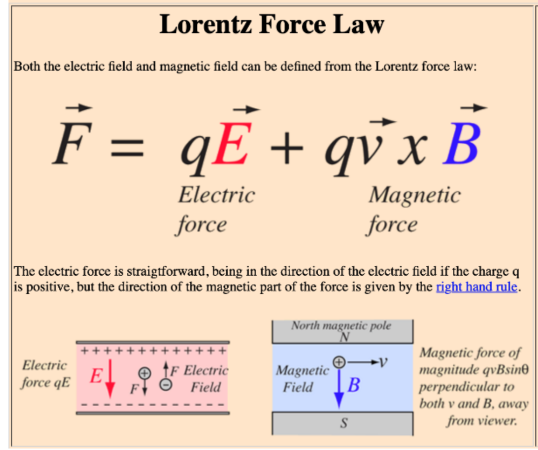
Recall Ch. 5 Hall Effect?





Recall Ch. 5 Hall Effect?

- ❑ **Why?**
  - ❑ Lorentz force law

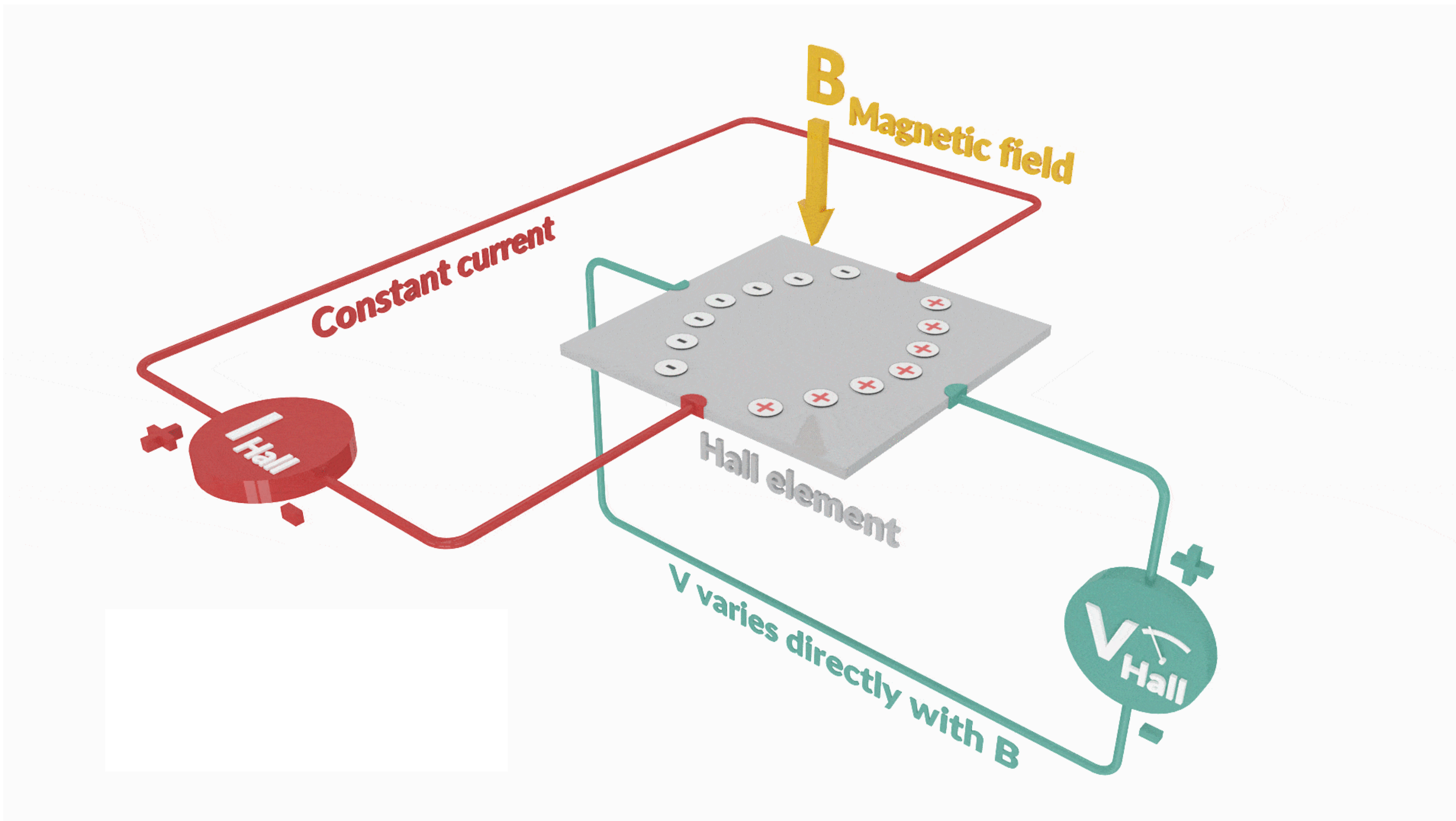


Lorentz Force Law

Both the electric field and magnetic field can be defined from the Lorentz force law:

$$\vec{F} = \underbrace{q\vec{E}}_{\text{Electric force}} + \underbrace{q\vec{v} \times \vec{B}}_{\text{Magnetic force}}$$

The electric force is straigtforward, being in the direction of the electric field if the charge q is positive, but the direction of the magnetic part of the force is given by the right hand rule.



Hall Effect Proximity Sensor

- Non-contact electronic sensor
  - A permanent magnet or ferromagnetic part as trigger intermediary and a Hall effect sensor IC
  - The Hall sensor IC detects the change of the magnetic field when the permanent magnet comes in the close proximity to it and generates an electric signal.

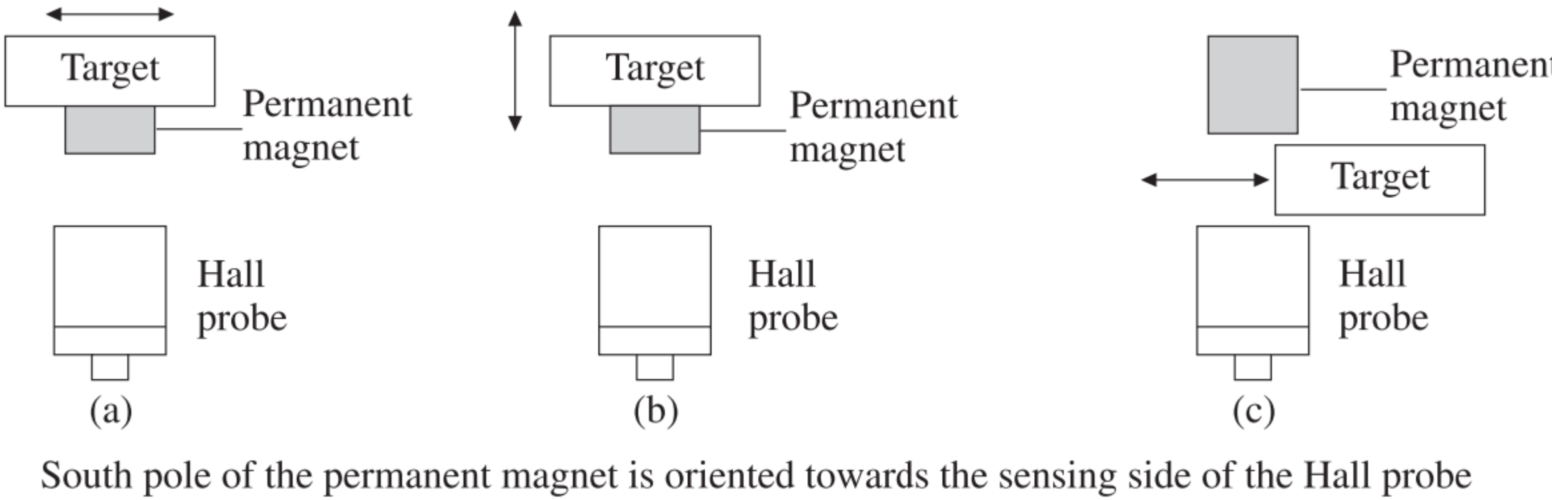


Fig. 6.63 Hall proximity measurement: (a) horizontal, (b) vertical, and (c) interception modes. The double-edged arrow indicates the direction of movement of the target.

Figure 6.64 depicts the dimensions of a typical Hall proximity probe.

Hall Effect Proximity Sensor

Advantages and disadvantages. The advantages and disadvantages of Hall proximity sensors are given in Table 6.13.

Table 6.13 Advantages and disadvantages of Hall proximity sensors

Advantages	*Disadvantages*
1. Good output wave shape.	1. Maximum sensing distance is about 10 cm with strong magnets.
2. High stability	2. Affected by temperature variation because mobilities of carriers are temperature dependant.
3. Low cost.	3. Presence of an offset voltage. This occurs even with well centred electrodes. It can be as high as 100 mV for a 12 V source[a].
4. Unaffected by oil, dirt and vibration.	
5. High suitability for integrating to PC systems and various kinds of industrial control equipment	
6. Adaptability as optimal switches for position control, speed measurement, counting, direction detection and automatic protection	

Proximity Sensor

- ❑ Detect and measure distance of nearby objects without physical contact.
  - ❑ **Types**
    1. **Inductive**
    2. **Capacitive**
    3. **Hall effect**
    4. **Optical**
    5. **Ultrasonic**

Optical Proximity Sensor

- ❑ **Working**

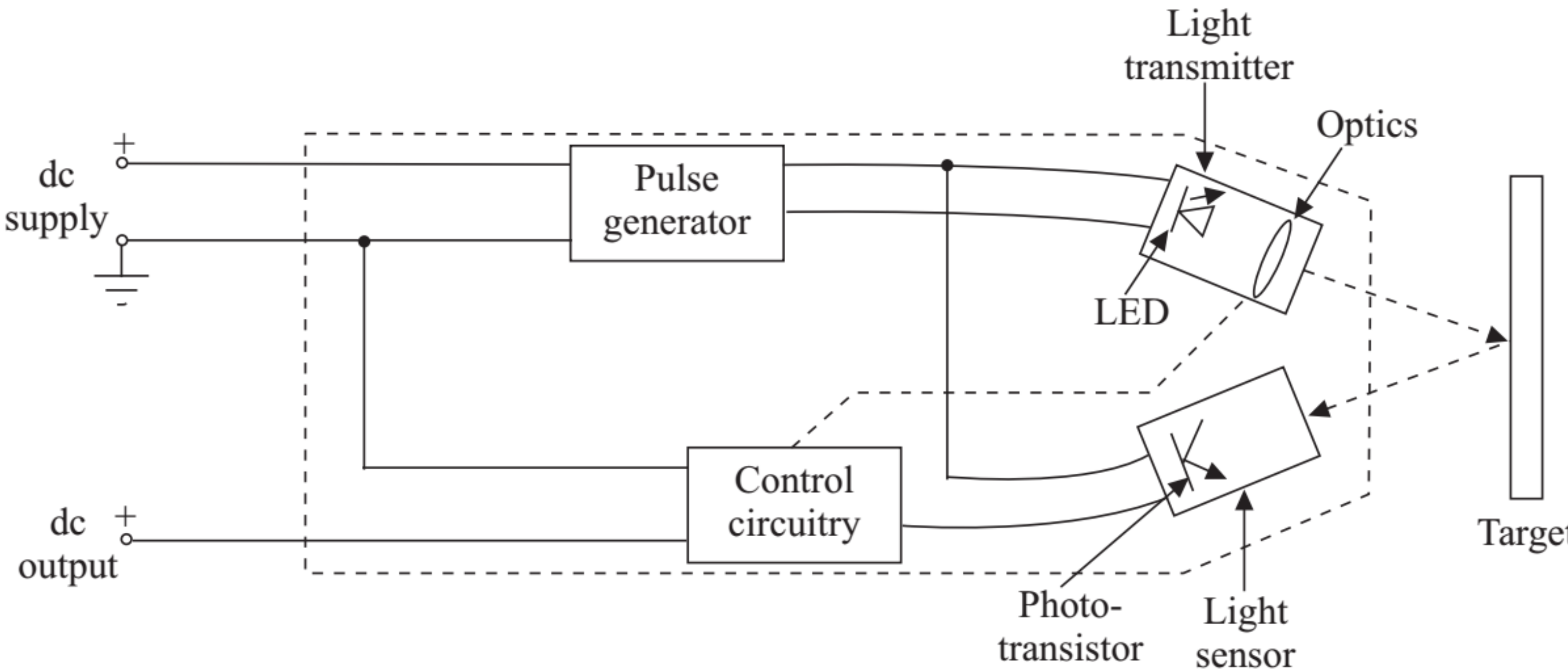


Fig. 6.65 Simple optical proximity sensor.

Optical Proximity Sensor

Optical proximity sensors can be of three types, namely:

1. Through beam
2. Diffuse scan
3. Retro-reflective

Through beam. This type of sensors consist of separate transmitter and receiver. The target is sensed when the beam is interrupted.

Diffuse scan. This type of sensors have both transmitter and receiver in the same enclosure. The closely focussed beam is reflected back by the target.

Retro-reflective. This type of sensors use a special reflector to reflect the beam back. When the target interrupts the beam, an output signal is generated. The sensing distance of retro-reflective types is greater than the diffuse scan types. The receiver rejects reflections from all other sources or objects other than the special reflector.

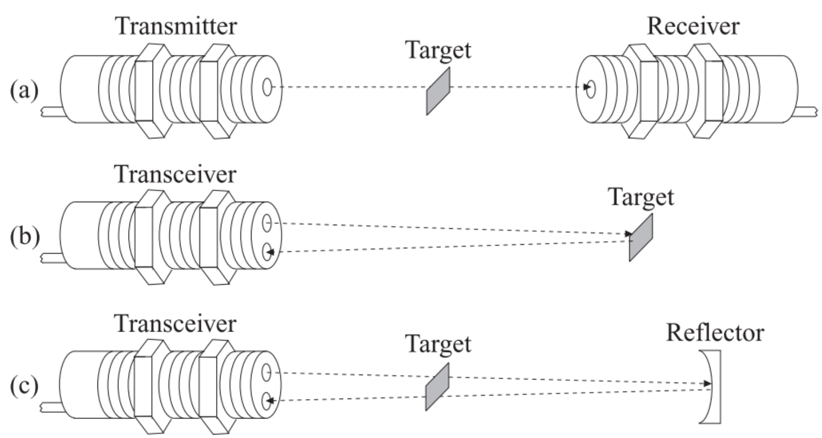


Fig. 6.66 Different types of optical proximity sensing: (a) through beam, (b) diffuse scan and (c) retro-reflection.

Optical Proximity Sensor

❑ Working

Table 6.14 Advantages and disadvantages of optical proximity sensor

Advantages	*Disadvantages*
1. Small in size.	1. Alignment, i.e. proper incidence of the light is necessary.
2. Fast switching, no switch bounce.	2. Can be disturbed by ambient light conditions such as arc welding in the proximity.
3. Insensitive to vibration and shock.	3. Dust-free, low moisture and clean environment is necessary.
4. Many configurations are commercially available.	

Applications. In pharmaceutical, food, paper, plastic and automobile industries, some of the uses of optical proximity sensors are:

1. Stack height control or box, bottle, container counting
2. Fluid level control such as bottle filling; level sensing applications for solid, grains, sand, ice and other bulk material
3. Glass sheet position sensing
4. Security and safety, e.g. collision prevention, in machine tools, presses
5. Colour sensing applications
6. Breakage and jam detection in conveyors.

Proximity Sensor

- Detect and measure distance of nearby objects without physical contact.

  - **Types**

    1. **Inductive**
    2. **Capacitive**
    3. **Hall effect**
    4. **Optical**
    5. **Ultrasonic**

Ultrasonic Proximity Sensor

- The distance to an object can be calculated from the time delay between the emitted and reflected sounds

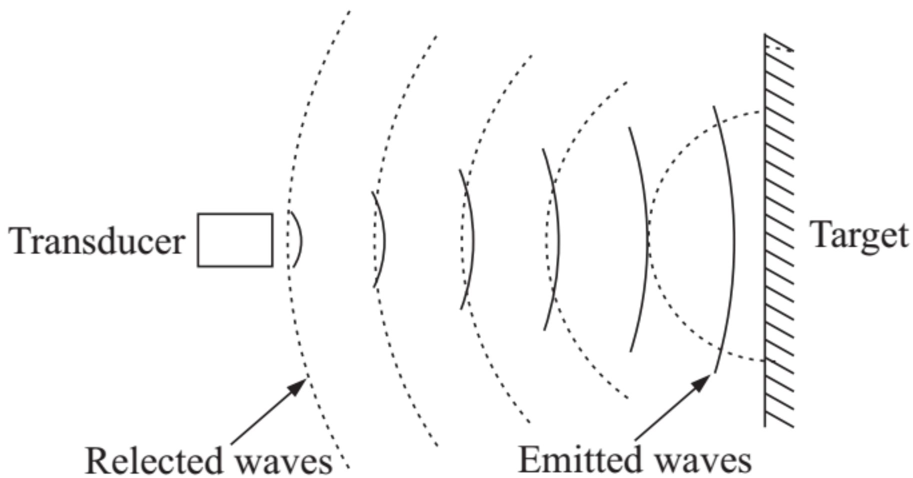


Fig. 6.43 Ultrasonic displacement measurement.

Ultrasonic Proximity Sensor

- The distance to an object can be calculated from the time delay between the emitted and reflected sounds

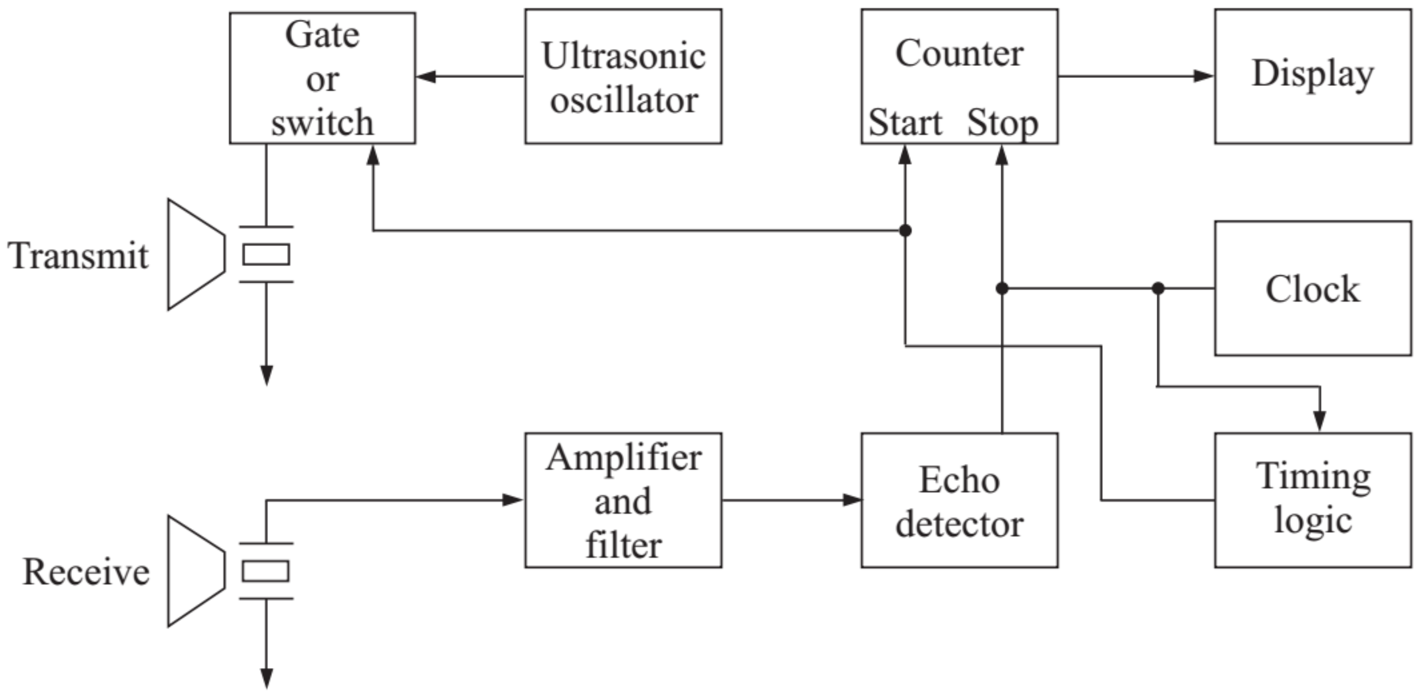


Fig. 6.44 Block diagram of a typical ultrasonic displacement measurement system.

Ultrasonic Proximity Sensor

- If the velocity of sound propagation is known, the distance to an object can be calculated from the time delay between the emitted and reflected sounds
- Works of TOF principle and Echo Ranging

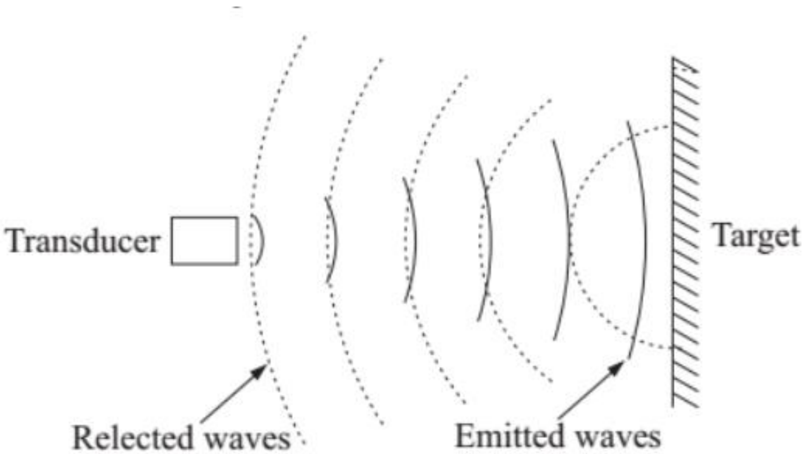


Fig. 6.43 Ultrasonic displacement measurement.

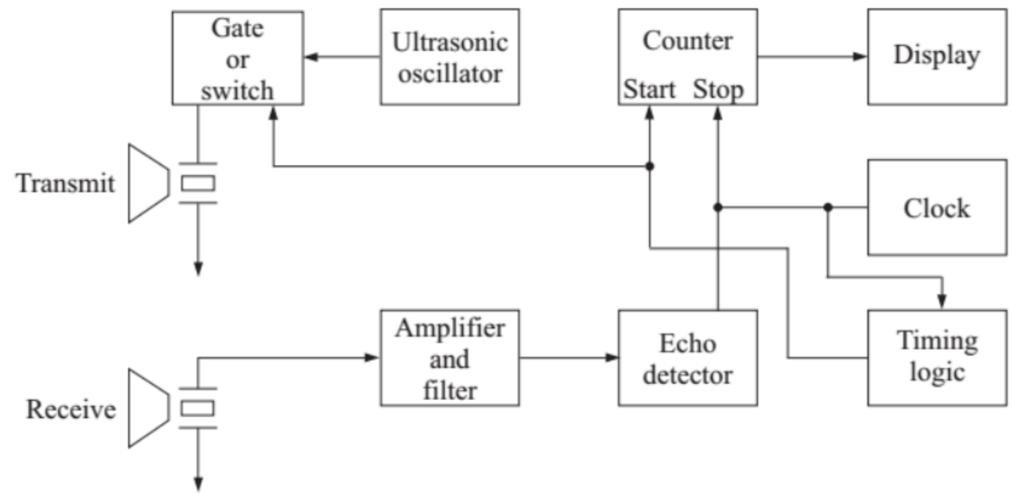


Fig. 6.44 Block diagram of a typical ultrasonic displacement measurement system.

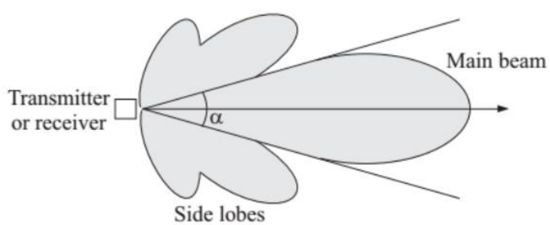
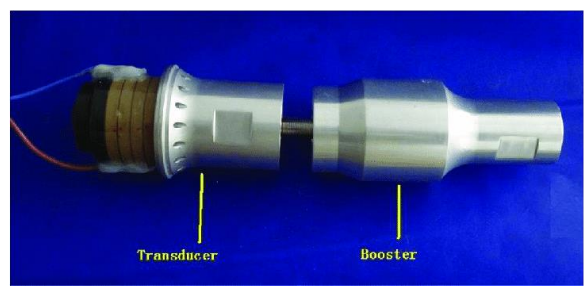


Fig. 6.45 Intensity distribution pattern of ultrasonic beam.



Ultrasonic Proximity Sensor

- **The distance to an object can be calculated from the time delay between the emitted and reflected sounds**

Table 6.9 Advantages and disadvantages of echo ranging

Advantages	*Disadvantages*
1. Non-contact measurement.	1. Moderate accuracy: 0.1 to 2% of the range.
2. Works with almost any surface type.	2. Requires near-perpendicular incidence on the target.
3. Resistant to vibration, radiation, background light, and noise.	3. Affected by dust, dirt, high humidity or air turbulence.
4. Low cost.	4. Limited speed of response.

Queries

Thanks!