Sensors

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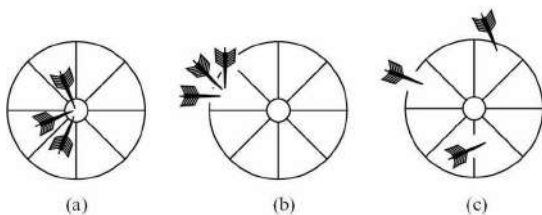http://teacher.buet.ac.bd/zahurul/

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ME 361: Instrumentation & Measurement

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3 Basic Phenomenon in Effect in Sensor Operation

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1. Change (or the absolute value) in the measured physical variable (i.e. pressure, temperature, displacement) is translated into change in sensor property (resistance, capacitance, magnetic coupling). This is called the *transduction*.
2. Change in the sensor property is translated into low-power-level electrical signal in the form of electrical voltage or current.
3. Low-level-power sensor signal is conditioned and transmitted for processing i.e. display or for use in control systems.

Measurement Specification

- **Resolution** refers to the smallest change in the measured variable that can be detected by the sensor.
- **Accuracy** refers to the difference between the actual value and the measured value.
- **Repeatability** refers to the average error between consecutive measurements of the same value.
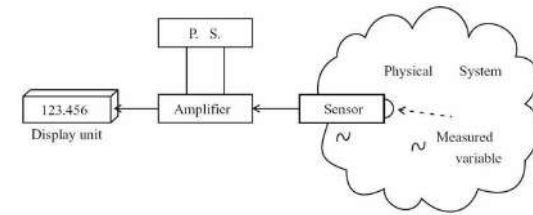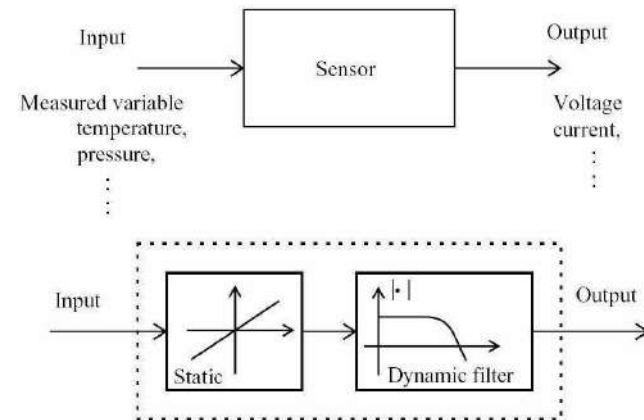

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(a) Accurate
(b) Repeatable but not accurate
(c) Not repeatable not accurate

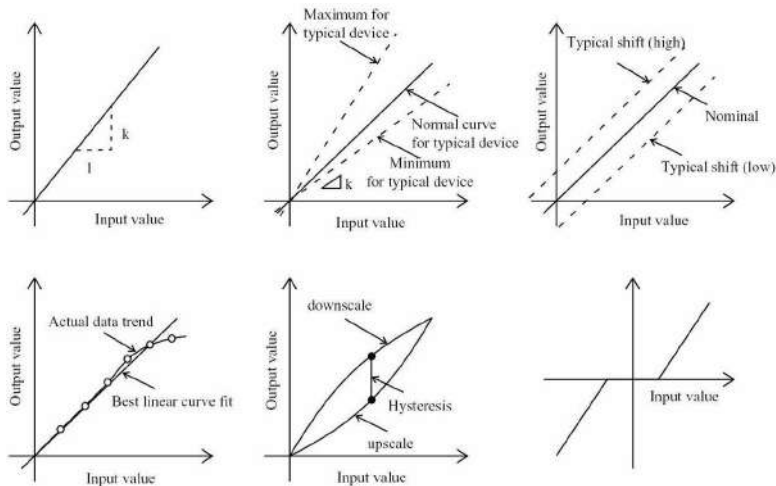
Input-Output Model of Sensors

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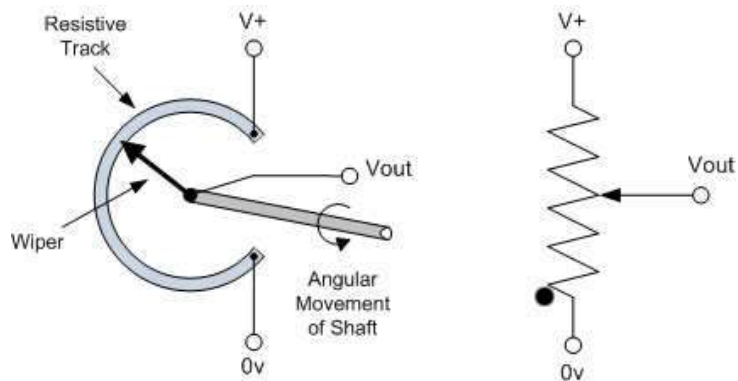*Dynamic response of a sensor can be represented by its frequency response or by its bandwidth specification*

# Non-linear Variation of Input-Output Relationship

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Sensor Calibration

- Calibration afford the opportunity <u>to check</u> the instrument against a known standard and subsequently <u>to reduce errors</u> in accuracy.
- Calibration process involves adjustment to compensate for the variation in:
  - Gain
  - Offset
  - Saturation
  - Hysteresis
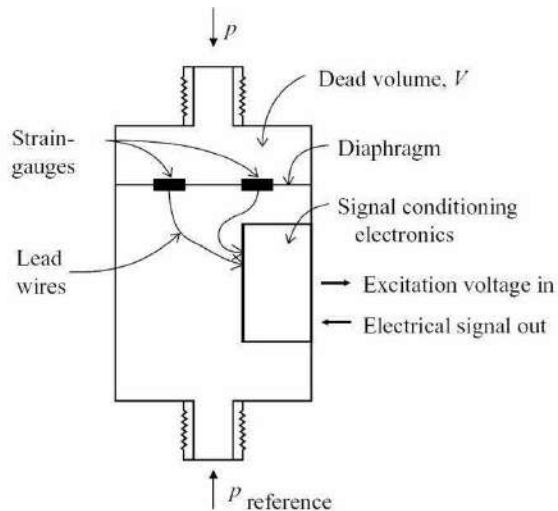 - Dead band
  - Drift in time

Resistive Sensors

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Change is measured physical variable (e.g. pressure, load, torque, position etc.) results in resistance of resistive sensors.
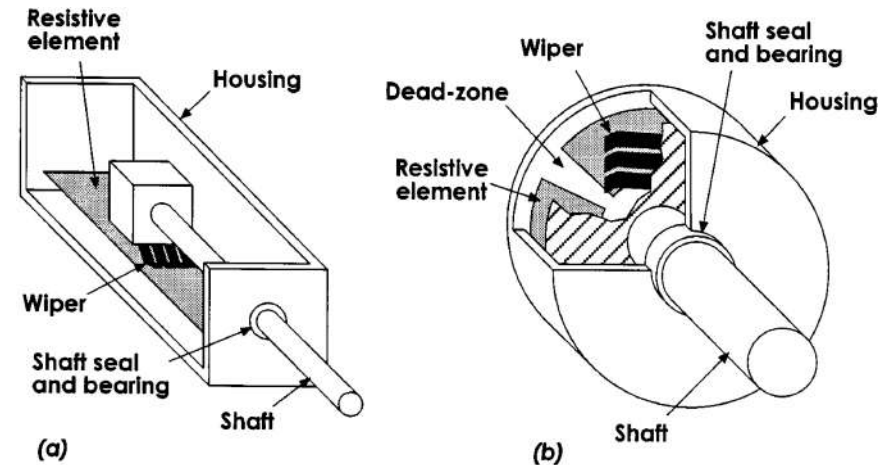
e663.eps

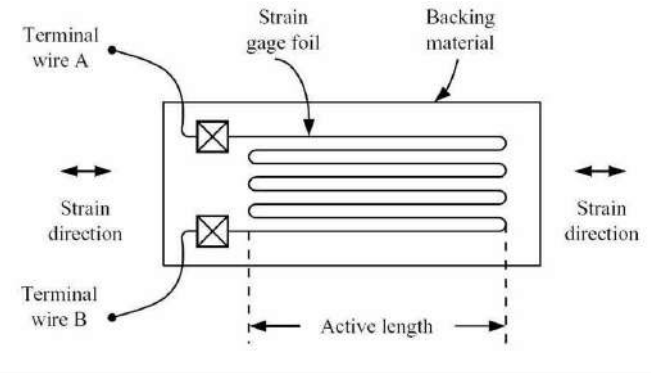*Typical linear and rotary potentiometers*

Characteristics of Resistive Sensors

- Very simple device, also known as <u>potentiometer</u> or <u>rheostat</u>.
- Contains a resistance element that is contacted by a movable contact (or slide or wiper) to measure linear or angular displacement.
- Available commercially in many sizes, designs, ranges and prices.
- May be used to measure pressure, torque or force as it is possible to convert these to displacement by mechanical means.
- Electrical efficiency is very high and may provide sufficient output to permit control without any amplification.
- May be ac- or dc- excited.
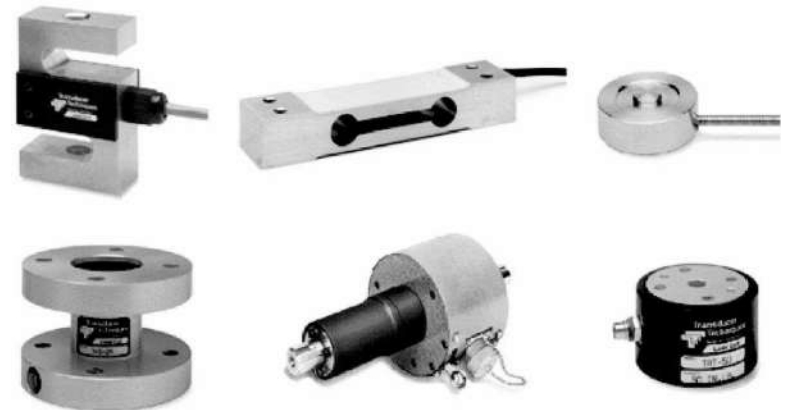- Because of friction life is limited and may generate noise.

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In strain gauge,

$$\frac{\Delta R}{R} = G\frac{\Delta L}{L} = \epsilon\, G$$

$$V_{out} = k_1 \frac{\Delta R}{R} = k_2\, G$$

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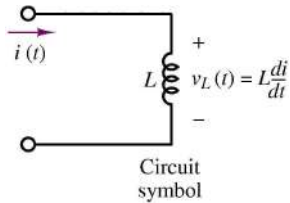*Pressure gauge using diaphragm and strain gauge*

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Various load cells using strain gauges for force and torque measurements

Inductive Sensors

$$v_L(t) = -L\frac{di}{dt} = -\frac{d\lambda}{dt} = -N\frac{d\phi}{dt}$$

e436.eps

Circuit symbol

- Flux linkage, $\lambda = N\phi = Li$: amount of flux linking the N turns of coils, ϕ is the flux passing through the coil.
- Self inductance, L measures the voltage induced by the magnetic field generated by a current flowing in the circuit.

Electromagnetic induction is the creating of an emf in a conductor which is moving in a magnetic field, or is placed in a changing magnetic field. *Faraday's Law of Induction* states that an emf is induced on a circuit due to changing magnetic flux and the induced voltage opposes the change in the magnetic flux (*Lenz's Law*).

LVDT: Linear Variable Differential Transformer

e637.eps

$$iR_p + L_p\frac{di}{dt} = V_{ex}$$

$$v_1 = M_1\frac{di}{dt} \qquad v_2 = M_2\frac{di}{dt}$$

$$v_{out} = v_1 - v_2 = (M_1 - M_2)\frac{di}{dt}$$

M_1 & M_2 : mutual inductances

- Ferromagnetic core determines the magnetic coupling between primary and secondary coils.
- If core $\Uparrow\rightsquigarrow$ more coupling between with top coil $\to v_{out} > 0$. At null position: $M_1 = M_2 \mapsto v_{out} = 0$. In LVDT, $M_1 - M_2$ is linearly related to the core displacement.
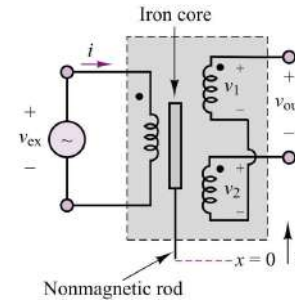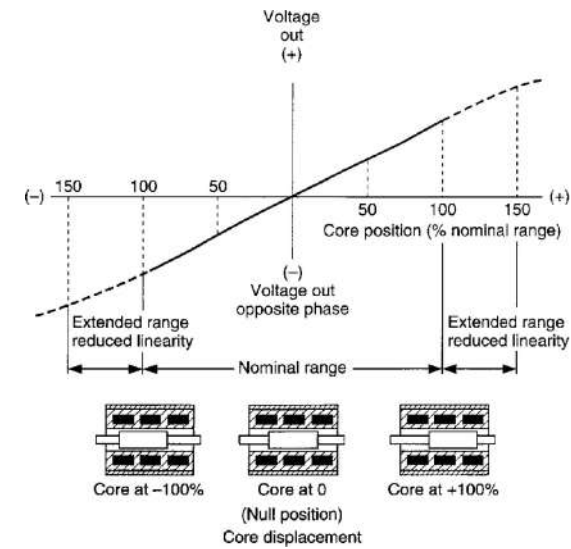

- In inductive transducers, a core moves linearly inside a transformer consisting of a center primary coil & two secondary coils.
- The secondary coils have equal number of turns & are connected in series opposing so that the emfs induced in the coils oppose each other. When core is centred voltage output is zero.
- When the core is moved off center, net voltage output varies linearly with core's position. When operating within linear range, it is known as *Linear Variable Differential Transformer (LVDT)*.

Applications:
Used to measure position, pressure, liquid level, vibration, acceleration & shock. May be configured to many kinds of specialized applications. The list includes standard, long-travel & miniature types, rotary variable differential transformers (RVDTs), high-temperature & cryogenic types, LVDTs designed for hostile environments, hermetically sealed, high-pressure, large-bore & nuclear-rated units.

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LVDT voltage & phase as a function of core position

LVDT Characteristics
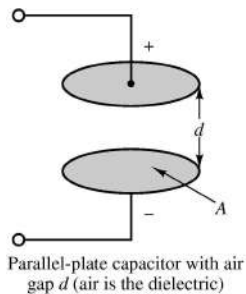
Input

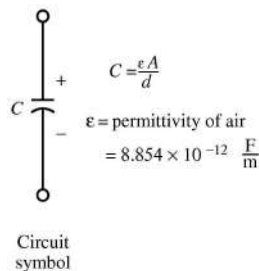|		
⊙	type	: Linear displacement.
⊙	range	: $\pm 0.1 - \pm 75$mm.
⊙	impedance char.	: Require $10^{-3} - 3 \cdot 10^{-3}$N force.
⊙	sensitivity	: 0.5% of total input range.

Output

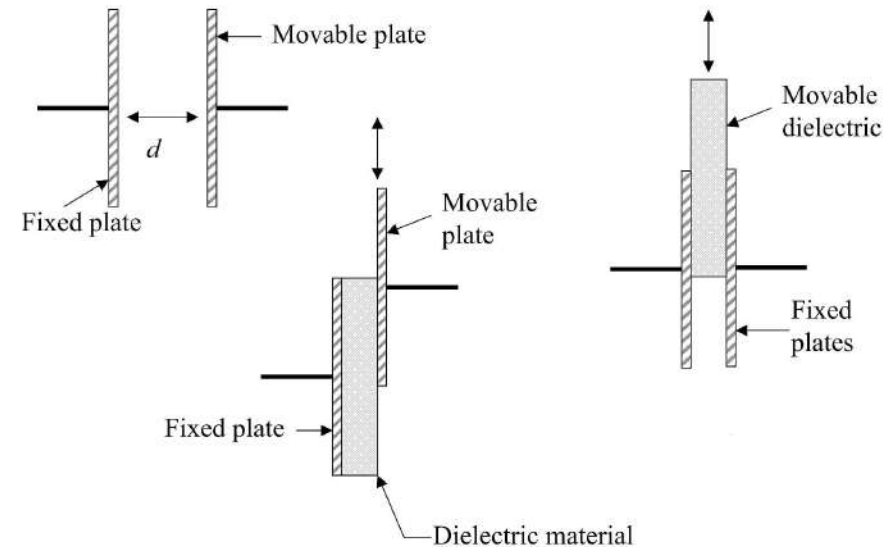|		
⊙	type	: Voltage $\propto$ input displacement.
⊙	range	: $16 - 160$ mV/mm; $f \uparrow \rightarrow$ output $\uparrow$.
⊙	impedance char.	: Mainly resistive; as low as 20 Ω.
	Frequency response	: 50 Hz to 20 kHz. Applied frequency must be 10 times desired response.
	Temperature effects	: Small influence; use thermistor to reduce.
	Error	: Deviation from linearity is about 0.5%; generally accurate to 1.0%.

Advantages:
- Good accuracy, sensitivity and linearity
- Frictionless operation
- Ruggedness
- Physical, electrical and environmental isolation
- Cross-axis rejection
- Infinite resolution.

Disadvantages:
- Moving mass (inertia)
- Susceptible to stray ac magnetic fields
- Physical size
- Circuit requirements for full rated accuracy.

Capacitive Sensors

$C = \frac{\varepsilon A}{d}$

ε = permittivity of air
$= 8.854 \times 10^{-12} \frac{F}{m}$

Parallel-plate capacitor with air gap d (air is the dielectric)

Circuit symbol

e433.eps   e434.eps

- Physical variable to be measured can be used to change in the capacitance by changing: (1) d, (2) A or (3) ϵ.
- Capacitance may be measured with bridge circuits. High-output impedance requires careful construction of output circuitry.
- Output impedance, Z of a capacitor is given by: $\Longrightarrow$ $\boxed{Z = \frac{1}{2\pi f C}}$

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+5V

Output frequency

555 Timer

Reset V_{cc}
Discharge Output
Threshold
Control
Trigger
Ground

C_S

Larger capacitance

Smaller capacitance
= higher frequency

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Capacitive Transducer Characteristics:

Input

⊙ type : Displacement, area or change in ϵ.
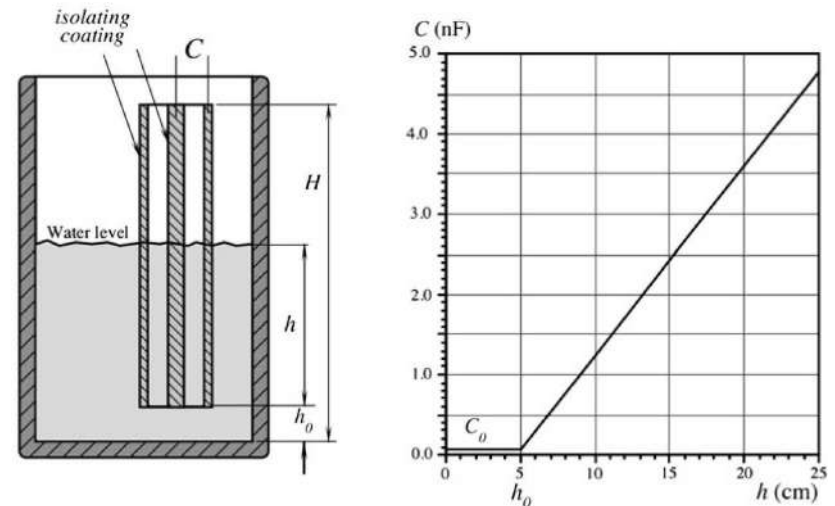⊙ range : Very broad; from $1\mu m$ to several meters.
⊙ impedance char. : Require very small force, few dynes.
⊙ sensitivity : Highly variable; can obtain 400 pF/mm.

Output

⊙ type : Capacitance.
⊙ range : Usually $10^{-3} - 10^3$ pF.
⊙ impedance char. : Usually $10^3 - 10^7 \Omega$.
Frequency response : Depends on construction; up to 50 kHz.
Temperature effects : Not strong if design allows for effects.

Applications:

⊙ Pressure & force measurement ⊙ Level measurements & switches
⊙ Displacement measurement ⊙ Moisture & humidity measurement
⊙ Proximity detectors ⊙ Tachometers ⊙ Capacitive microphones (
considered capable of the highest performance).

Fixed metal plate

p_1

E_o

High-gain amplifier

Capacitor, C

t

Thin metal diaphragm

C

E_i

p_2

e474.eps

$$\Delta P \rightarrow t \rightarrow C \rightarrow E_o$$

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isolating coating
C
H
Water level
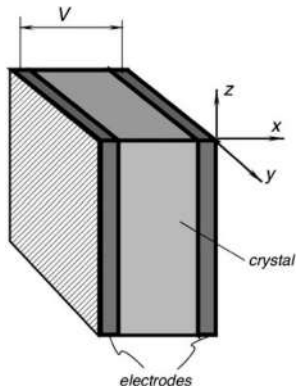h
h_o

C (nF)
C_o
h_o
h (cm)

e664.eps

Capacitive water level sensor & typical capacitance as a function of water level
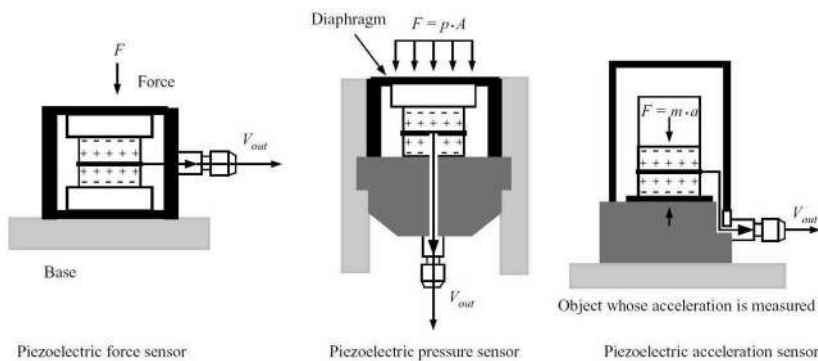
Piezoelectric transducers

Piezoelectric transducers involve a class of materials which, when mechanically deformed, produce an electric charge. The effect is *reversible* and applied usefully in both directions.
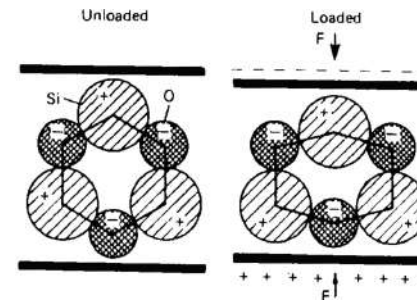

$$V = gtP = \left[\frac{d}{\epsilon}\right] tP$$

V = Output voltage [V]
g = Voltage sensitivity [V/N]
d = Piezoelectric constant [C/N]
F = Applied force [N]
P = Applied pressure [Pa]
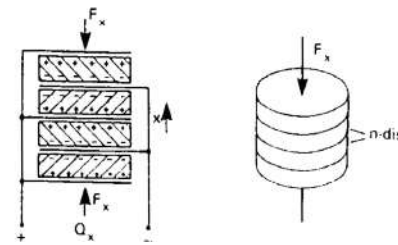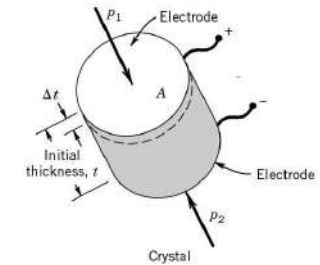
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Applications: Used to measure: ⊙ Surface roughness ⊙ Strain ⊙ Force & torque ⊙ Pressure ⊙ Motion ⊙ Sound & noise.
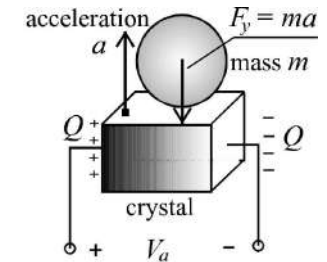Also used in: ⊙ Ultrasound NDT equipments ⊙ Sonar system ⊙ Ultrasound flow-meters ⊙ Small vibration shakers ⊙ Pumps for ink-jet printers ⊙ Micro-motion actuators.

Piezoelectric materials: natural (quartz, rochelle salt) & synthetic crystals (lithium sulphate, ammonium dihydrogen phosphate), polarized ferroelectric ceramics (barium titanate & some polymer films).

Transducer Characteristics:

  Input
   ⊙   type   : Force or stress.
   ⊙   range   : Varies widely with crystal material.
   ⊙   impedance char.   : Input force required are relatively large.
   ⊙   sensitivity   : Varies with material:
                           $\rightarrow$ Quartz ~ 0.05 Vm/N.
                           $\rightarrow$ Rochelle salt ~ 0.015 Vm/N.
                           $\rightarrow$ Barium titanate ~ 0.007 Vm/N.

  Output
   ⊙   type   : Voltage proportional to input.
   ⊙   range   : Wide, depends on crystal size & material.
   ⊙   impedance char.   : High, of the order of $10^3 M\Omega$.
   Frequency response   : 20- 20 kHz, no steady-state response.
   Temperature effects   : Wide variation with temperature.

Photoemissive & Photoelectric Transducers

- Photoemissive transducers consist of a cathode-anode combination enclosed in a glass or quartz envelope, which is either evacuated or filled with an inert gas.
- In the proper circuit (usually a d.c. source from 100 - 200 V), light impingement on the cathode frees electrons to flow, thereby providing a small current given by: $\Longrightarrow$ $\boxed{I = S\Phi}$

$$
\begin{aligned}
I &= \text{photoelectric currents} \\
\Phi &= \text{illumination on cathode} \\
S &= \text{sensitivity.}
\end{aligned}
$$

- Photoelectric-tube response in different wavelength depends on:
  1. Photo-emissivity of the cathode material ($0.2 - 0.8\mu$m).
  2. Transmissivity of the glass-tube envelope.
     - Most glasses do not transmit light below about 0.4μm.
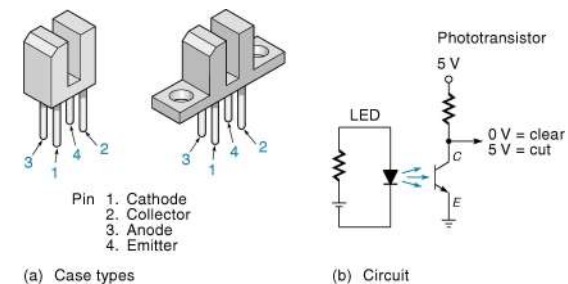   - Quartz transmits down to 0.2μm.

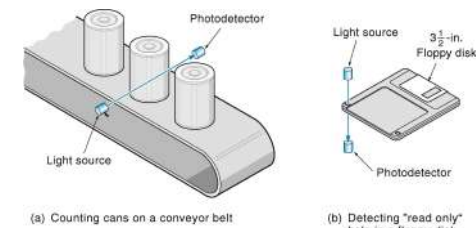# Photo-conductive/Photo-resistive Transducers

- Photo-conductive cells are elements whose conductivity is a function of the incident electromagnetic radiation. Commercially important materials are cadmium sulphide, germanium, and silicon.
- The essential elements of a photo-conductive cell are the ceramic substrate, a layer of photo-conductive material, metallic electrodes and a moisture-resistant enclosure.
- Lead-sulphide cell is widely used for detection of thermal radiation in the wavelength band of $1 - 3\mu$m. By cooling the detector higher wavelength ($= 4 - 5\mu$m) can be achieved.
- The spectral response of CdS cell closely matches that of human eye, and the cell is often used in applications where human vision is a factor.
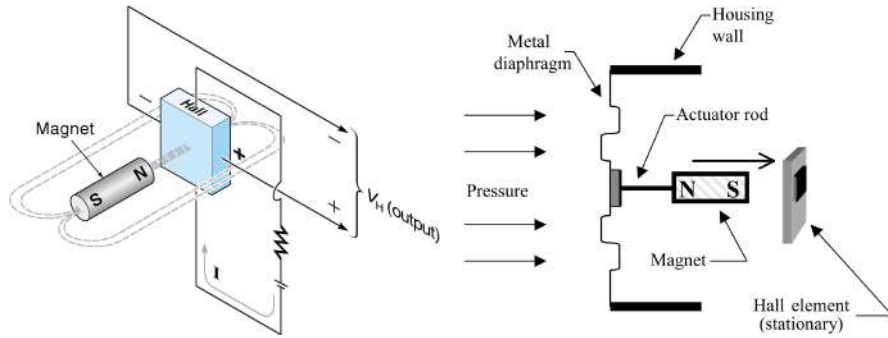
Photovoltaic Cells

- Photovoltaic-cell (solar cell) consists of a metal base plate, a semiconductor material, and a thin transparent metallic layer. When light strikes the barrier between the transparent metal layer and the semiconductor material, a voltage is generated.
  - Si cells cover the visible & near-infra-red spectrum, intensities between $10^{-3} - 10^3 mW/cm^2$.
  - Se cells accepts a spectrum of near-infra-red to ultraviolet, intensities between $10^{-1} - 10^2 mW/cm^2$.
- The output of the device is strongly dependent on the load resistance R.
- The logarithmic behaviour of the cell is a decided advantage in such applications because of its sensitivity over a broad range of light intensities.
- Most widely used applications of the PVC include the light exposer meter in photographic work and solar radiation measurement.

Phototransistor Sensors

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Hall Effect Sensor

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e657.eps

$$V_H = K_H \frac{IB}{t}$$

V_H	= Hall-effect voltage	K_H	= constant
B	= magnetic flux-density	I	= current
t	= thickness constant		

(a) Head-on

(b) Slide-by

(c) Notch sensor (notch reduces flux)

(d) Metal detector (ball increases flux)

e457.eps