Sensors

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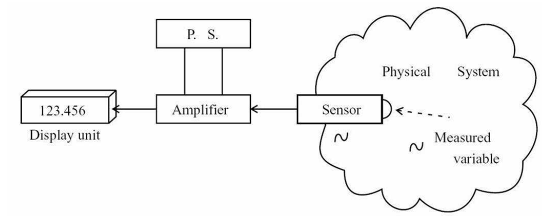
ME 475: Mechatronics

3 Basic Phenomenon in Effect in Sensor Operation



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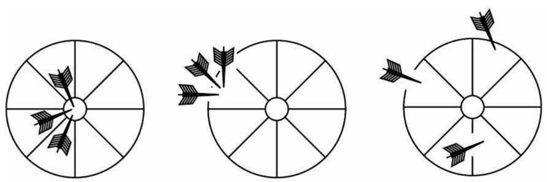
1. Change (or the absolute value) in the measured physical variable (i.e. pressure, temperature, displacement) is translated into change in sensor property (resistance, capacitance, magnetic coupling). This is called the *transduction*.
2. Change in the sensor property is translated into low-power-level 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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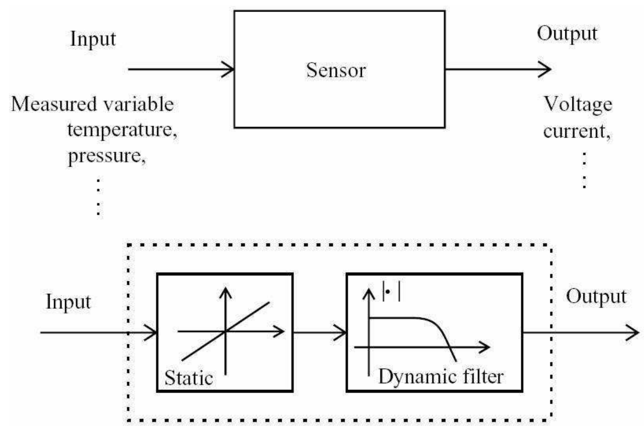
(a) Accurate
(b) Repeatable but not accurate
(c) Not repeatable not accurate

Input-Output Model of Sensors



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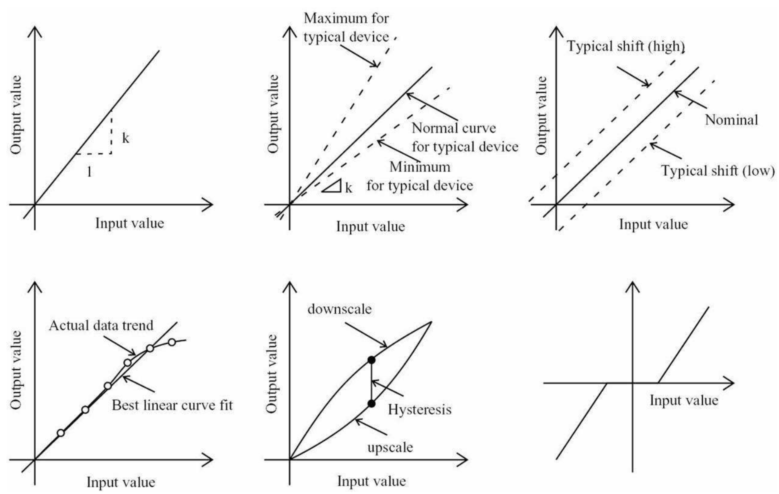
Dynamic response of a sensor can be represented by its frequency response or by its bandwidth specification

Non-linear Variation of Input-Output Relationship



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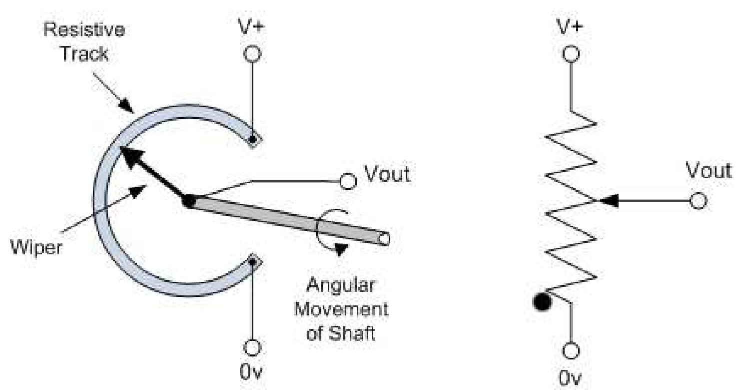
Sensor Calibration

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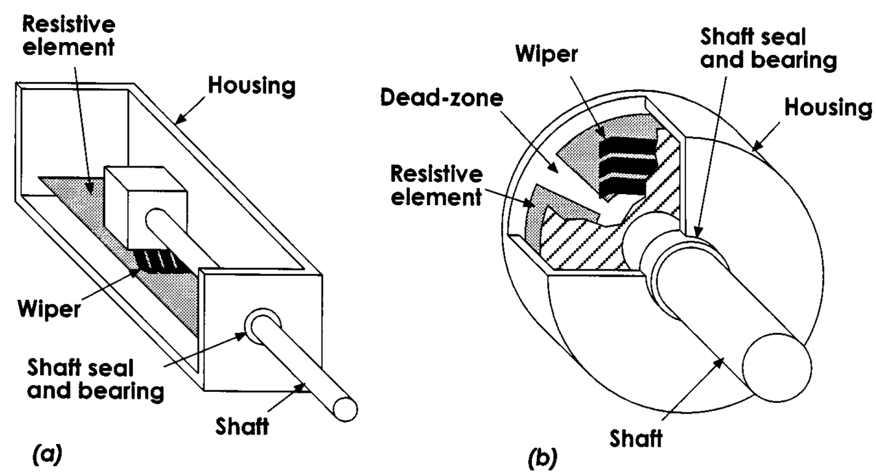
Change is measured physical variable (e.g. pressure, load, torque, position etc.) results in resistance of resistive sensors.



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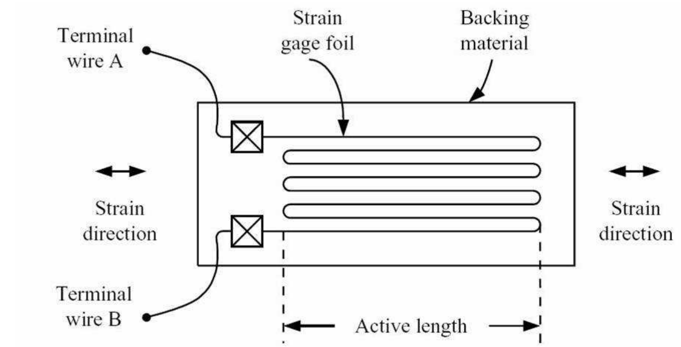
Typical linear and rotary potentiometers

Characteristics of Resistive Sensors

- Very simple device, also known as potentiometer or rheostat.
- 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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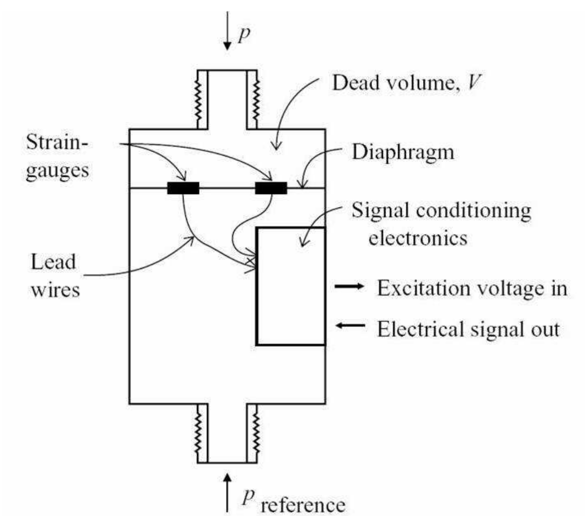
In strain gauge,

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

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



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Pressure gauge using diaphragm and strain gauge

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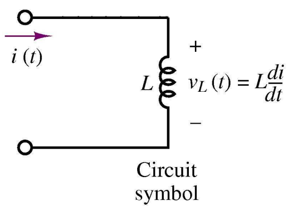
Various load cells using strain gauges for force and torque measurements

Inductive Sensors

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



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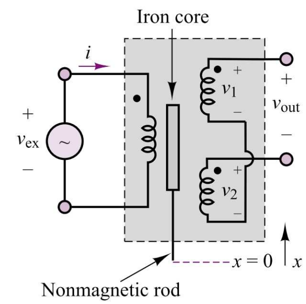
- Flux linkage, $\lambda = N\phi = Li$: amount of flux linking the N turns of coils, ϕ is the flux passing through the coil.
- Self inductance, L measures the voltage induced by the magnetic field generated by a current flowing in the circuit.

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



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

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

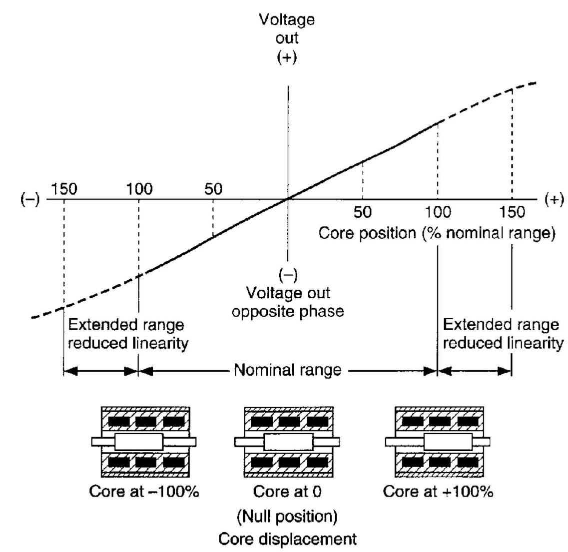
$$v_{out} = v_1 - v_2 = (M_1 - M_2)\frac{di}{dt}$$

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 $\rightarrow v_{out} > 0$. 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%.

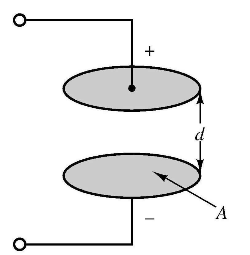
Advantages:

- 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



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

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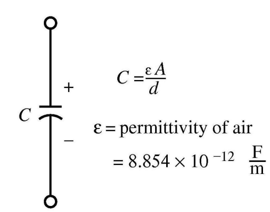

Circuit symbol

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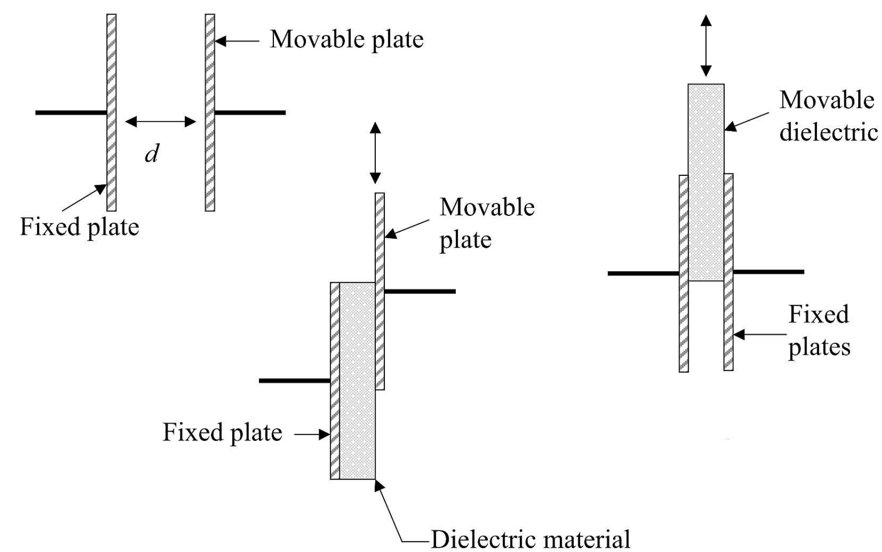
- Physical variable to be measured can be used to change in the capacitance by changing: (1) d, (2) A or (3) ϵ.
- Capacitance may be measured with bridge circuits. High-output impedance requires careful construction of output circuitry.
- Output impedance, Z of a capacitor is given by: $\Longrightarrow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



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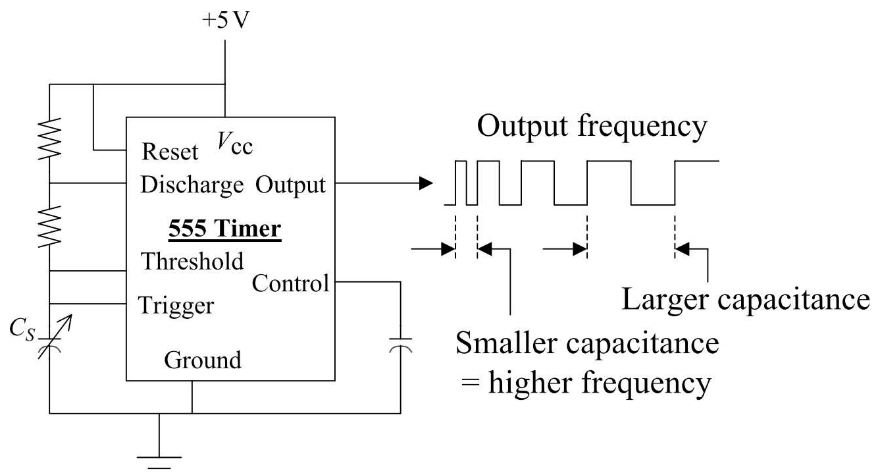

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Capacitive Transducer Characteristics:

Input

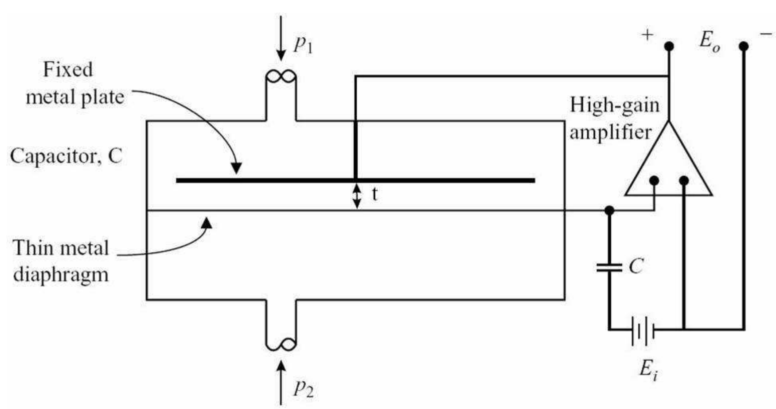
⊙	type	: Displacement, area or change in ϵ.
⊙	range	: Very broad; from 1μm to several meters.
⊙	impedance char.	: Require very small force, few dynes.
⊙	sensitivity	: Highly variable; can obtain 400 pF/mm.

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).



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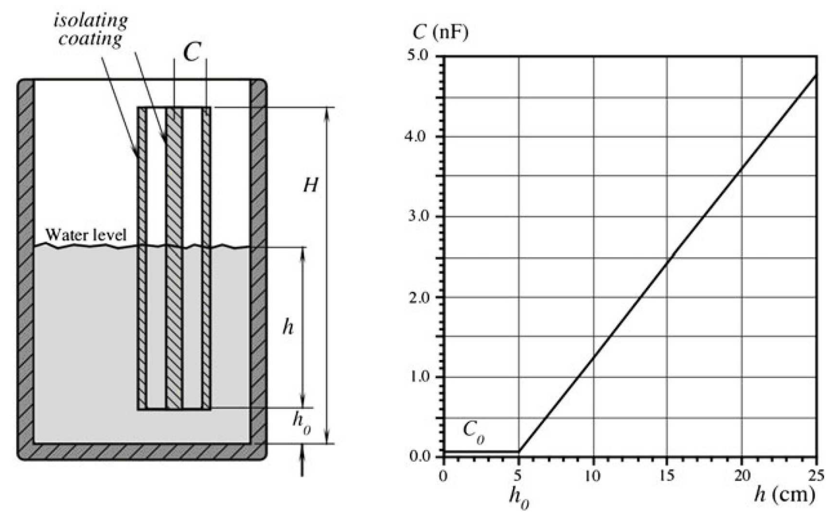
$$\Delta P \rightarrow t \rightarrow C \rightarrow E_o$$



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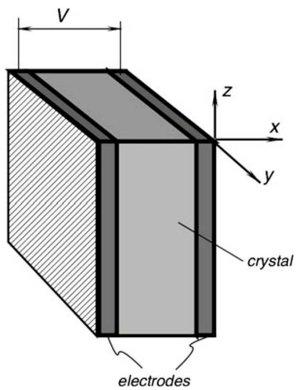
Capacitive water level sensor & typical capacitance as a function of water level

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.



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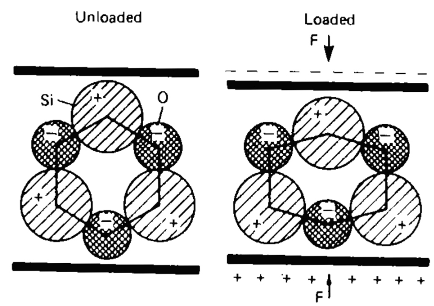
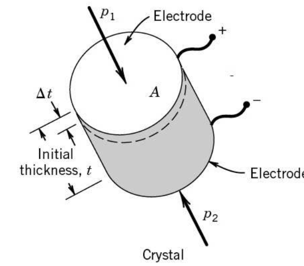
$$V = gtP = \left[\frac{d}{\epsilon}\right] tP$$

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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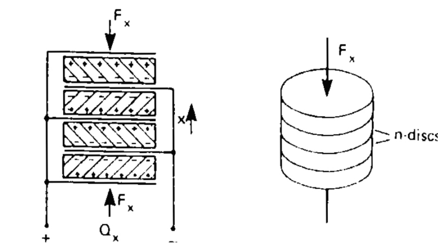

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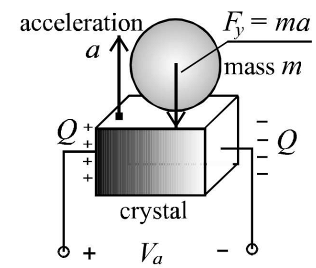

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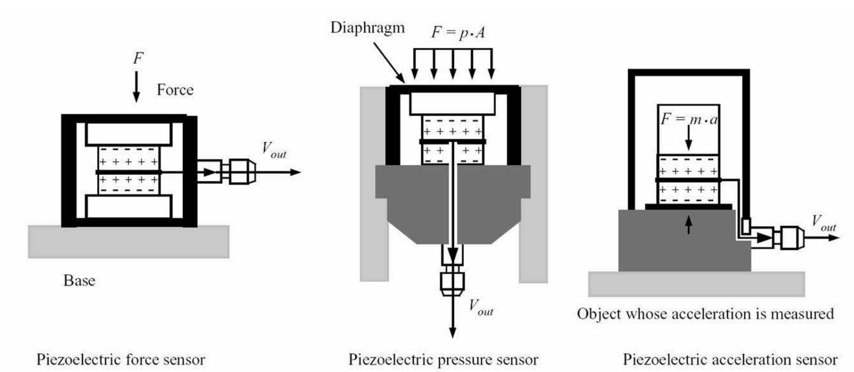

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Applications: Used to measure: ⊙ Surface roughness ⊙ Strain ⊙ Force & torque ⊙ Pressure ⊙ Motion ⊙ Sound & noise.
Also used in: ⊙ Ultrasound NDT equipments ⊙ Sonar system ⊙ Ultrasound flow-meters ⊙ Small vibration shakers ⊙ Pumps for ink-jet printers ⊙ 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:
  - → Quartz ∼ 0.05 Vm/N.
  - → Rochelle salt ∼ 0.015 Vm/N.
  - → 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: $\Longrightarrow \boxed{I = S\Phi}$

I = photoelectric currents
Φ = illumination on cathode
S = sensitivity.

- 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.

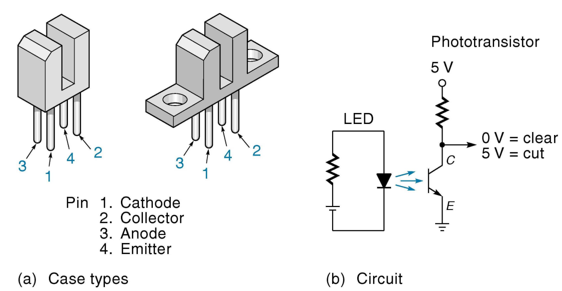
Photo-conductive/Photo-resistive Transducers

- 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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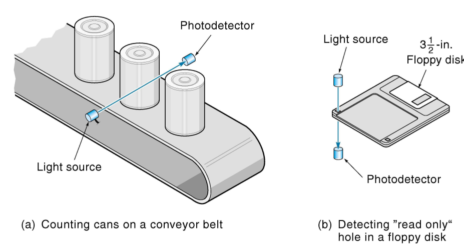

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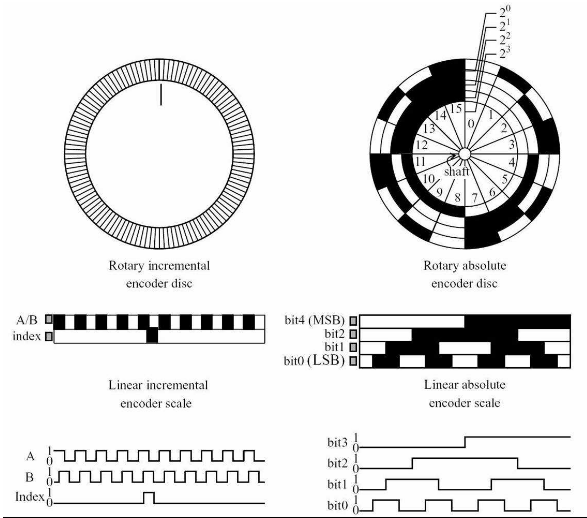
Encoder



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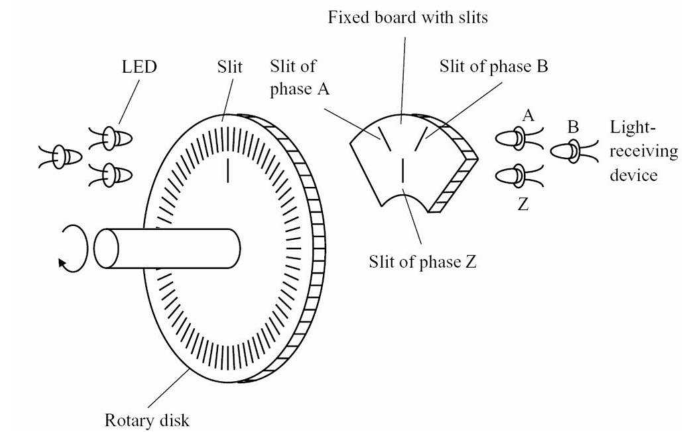

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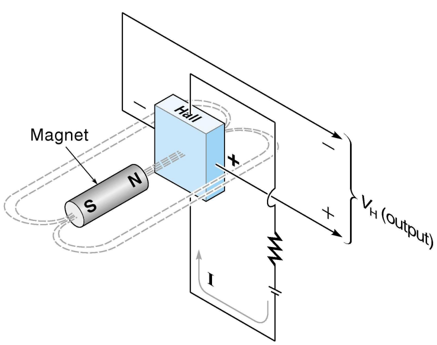
Hall Effect Sensor



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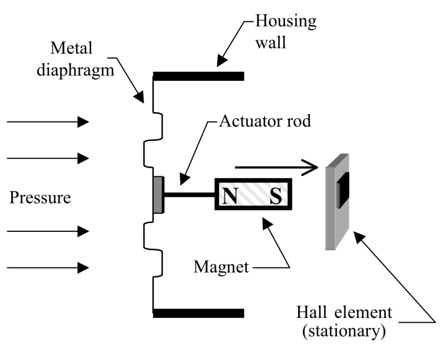

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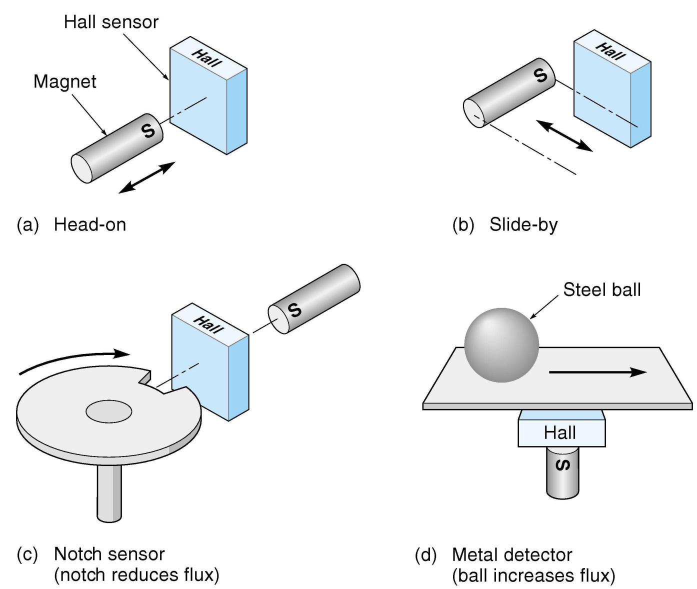
$$V_H = K_H \frac{IB}{t}$$

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



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