SENSORS and TRANSDUCERS

Tadeusz Stepinski, Signaler och system

- The Magnetic Energy Domain
  - Physics
    - » Magnetism
    - » Hall effect
    - » Superconductivity
    - » Magnetoresistivity
  - Variable inductance sensors
  - Variable reluctance sensors

Magnetic Energy Domain - Physics

- We are considering transduction information into and from the magnetic energy domain.

- Basic mechanisms relevant for our discussion:
  - Hall effect in conductors
  - Hall effect in semiconductors
  - Superconductivity
  - Magnetoresistivity

Magnetic Energy Domain - Physics

- Survey of types of magnetism and related forces

Lorentz force law

Charge carriers moving in magnetic field are exerted to forces described by

$$\underline{F} = -q \cdot (\underline{v} \times \underline{B})$$

where: B - magnetic induction
v - electron velocity
q - elementary charge

Type of magnetic material	Examples	Resulting force as a function of current in a magnetic field with gradient (N)	Resulting magnetic dipole moment when $H_{utw} = 0$ A m^{-1}
Diamagnetic	Cu, salt, water	F quadratic (I^2); repulsive	0
Paramagnetic	Al, Na, liquid oxygen	F quadratic (I^2)	? 0
Ferromagnetic	Ni, Fe	F linear (I)	>> 0
Ferrimagnetic	Fe_3O_4	F linear (I)	>> 0

Magnetic Energy Domain - Physics

- In the microscopic (atomic) scale we distinguish three possible contributions from the moving charges to the magnetic field:
  - The magnetic orbital moment - due to the movement of the electrons in their orbitals
  - The magnetic spin moment - the electrons are spinning around their axes, so-called Bohr magnetons
  - The magnetic core moment - the core, with its positive charge also spins around an axis
- Diamagnetic materials - net magnetic moment is zero and the force acting in a strong magnetic field is repulsive (it is quadratic with the current above certain field strength)

Magnetic Energy Domain - Physics

- Paramagnetic materials - in materials with unpaired electrons (the orbital magnetic moments are not balanced) there is a net magnetic moment per atom.
- Langevin function (1905) - defines how the magnetic moment depends on magnetic field and temperature

$$M = N \cdot p \cdot \left[\coth\left(\frac{\mu_0 pH}{kT} \right) - \frac{kT}{\mu_0 pH} \right] = N \cdot p \cdot \mathcal{L}\left(\frac{\mu_0 pH}{kT} \right)$$

where: $-1 < \mathcal{L}(x) < 1$ - *Langevin function*

M (A m^{-1}) - *total magnetic moment per unit volume*

N (m^{-3}) - *total number of magnetic dipoles per unit volume*

p (A m^2) - *magnetic dipole moment of the atom*

μ_0 = 1.256 637 10^{-6} (A m^{-1})

k = 1.38 10^{-23} (J K^{-1})

Magnetic Energy Domain - Physics

- Ferromagnetic materials
  - Remanent magnetism occurs
  - Weiss field H_{Weiss} is present in magnetic domains $H_{weiss} = \lambda M$

$$M = N \cdot p \cdot \mathcal{L}\left(\frac{\mu_0 p H_a + \lambda M}{kT}\right)$$

where: $-1 < \mathcal{L}(x) < 1$ *Langevin function*

H_a (A m^{-1}) - *total external applied field*

$$\chi = \frac{M}{H}$$

magnetic susceptibility - represents magnetization caused by the external applied field strength, H_a

Magnetic Energy Domain - Physics

- Summary - diamagnets, paramagnets and ferromagnets

$$M = \chi \cdot H$$

$$B = \mu_0 (1 + \chi) H = \mu_0 \mu_r H$$

Classification	Material	Susceptibility χ
Diamagnets	- copper, silver, gold, bismuth	Small and negative $\chi = -10^{-5}$
	- superconductors	$\chi = -1$
Paramagnets	Aluminum, platinum	Small and positive $\chi = 10^{-3}$ to 10^{-5}
Ferromagnets	Iron, cobalt, nickel and rare earth metals	Large and positive $\chi = 50$ to 10^{4}
Ferrimagnets	Magnetic ferrites, Fe_3O_4, BaO $6(Fe_2O_3)$,	Large and positive

Magnetic Energy Domain - Physics

- *Curie temeprature* T_C - the magnetic polarization is completely randomized and magnetism in ferromagnets vanishes

Curie-Weiss law

$$\chi = \frac{C}{T - T_C}$$

$$C = \frac{N\mu_0 m^2}{3k}$$

where: *m - atomic magnetic moment*

N - number of moments per unit volume

Magnetic Energy Domain - Physics

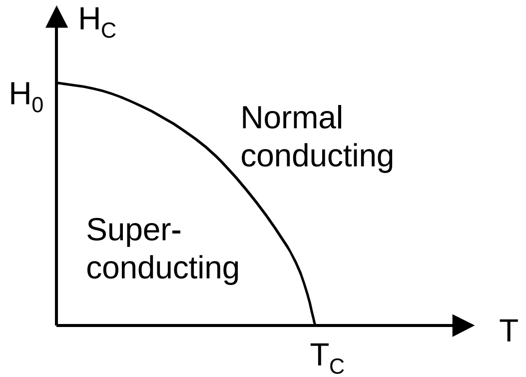
- Superconductivity - infinite conductivity below certain temperature T_C

  However, a critical field strength H_C also exists at which the magnetic polarization vanishes

$$H_C(T) = H_0\left(1 - \frac{T^2}{T_C^2}\right)$$

where: *H_0 - critical field strength at $T = 0$ K*

T_C - critical temperature at which superconductivity disappears

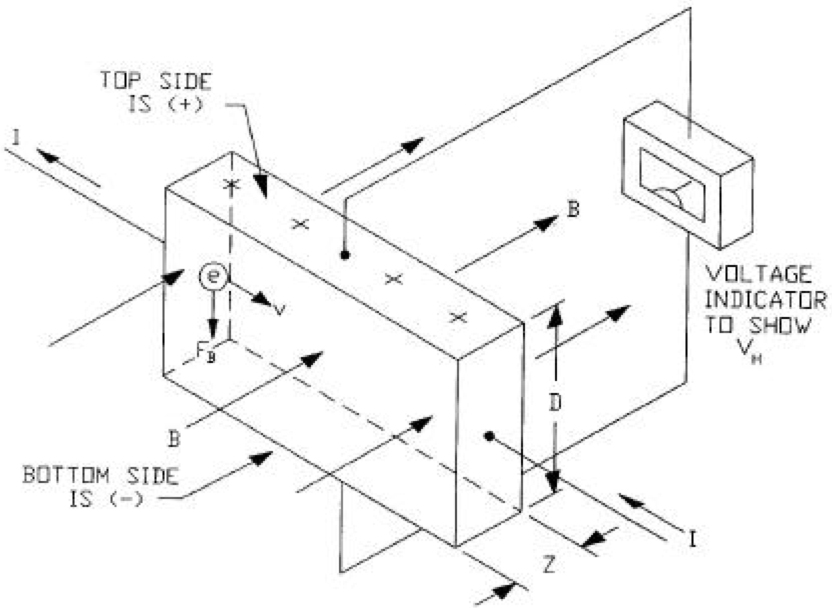


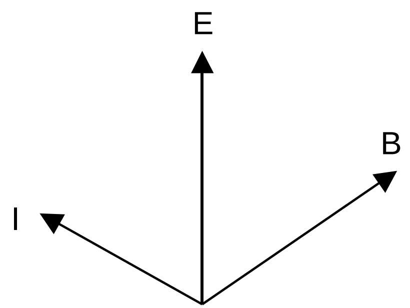
Magnetic Energy Domain - Physics

- Hall effect

  Discovered by Edwin Hall in 1879.

  When a current is flowing in a (semi)conductor which is placed in magnetic field, not parallel with the current direction, an electric field will be generated perpendicular with respect to the current and the field direction





Magnetic Energy Domain - Physics

– Hall effect in conductors

Hall voltage can be described by

$$V_H = \frac{R_H I_x B_z}{d}$$

where: R_H (m^3C^{-1}) - *Hall constant*

I_x (A) - *current in x-direction*

B_z (Vsm^{-2})- *magnetic induction in z-direction*

d (m) - *plate thickness*

Material	Hall coefficient (m^3C^{-1})
InSb	$-116\ 10^{-6}$
InAs	$-112\ 10^{-6}$
InP	$-1.4\ 10^{-3}$

Magnetic Energy Domain - Physics

– Hall effect in semiconductors

Hall constant can be described by

$$R_H = \frac{p\mu_p^2 - n\mu_n^2}{q\left(p\mu_p + n\mu_n\right)^2}$$

where: n, *p* (m^{-3}) - *electron and hole density per unit volume, respectively*

$\mu_{n,p}$ ($m^2V^{-1}\ s^{-1}$) -*mobility of electron and holes, respectively*

» For n-type material $n >> p$ and Hall coefficient becomes $R_H = -1/nq$

» For p-type material $p >> n$ and Hall coefficient becomes $R_H = 1/pq$

» Product of Hall coefficient and the specific density defines Hall mobility

$$R_H\sigma = \mu_H(n) \qquad R_H\sigma = \mu_H(p)$$

Magnetic Energy Domain - Physics

– Magnetoresistivity

Increase of resistance due to magnetic field which exerts a force on the charge carriers

Magnetoresistivity in magnetic layers is much larger than in semiconductors.

Resistance of a magnetic resistor, when B is perpendicular to current

$$\rho = \rho_0 (1 + k_m B^2)$$

where: ρ (Ω m) -*specific resistivity*

ρ_0 (Ω m) -*specific resistivity when* $\boldsymbol{B}=0$

k_m - *magnetic resistivity factor*

Example: for InSb $k_m = 38\ T^2\ \Omega^{-1}\ m^{-1}$ at B= 1T

Magnetic Energy Domain - Physics

- Magnetoresistivity

  Resistance of a magnetic film is a function of angle between magnetic field and current

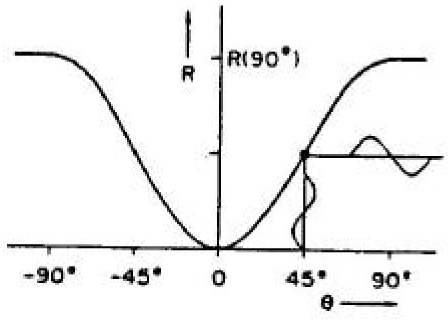
$$R(\Theta) = R(0) - [R(0) - R(90)]\sin^2(\Theta)$$

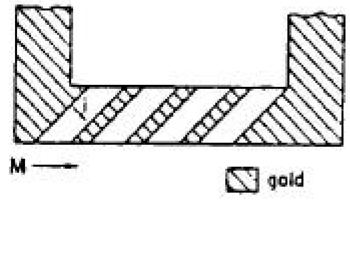
where: R(0) - *resistance of magnetic layer for field parallel to current*

R(90) - *resistance of magnetic layer for field perpendicular to current*

Θ - *angle between field and current*

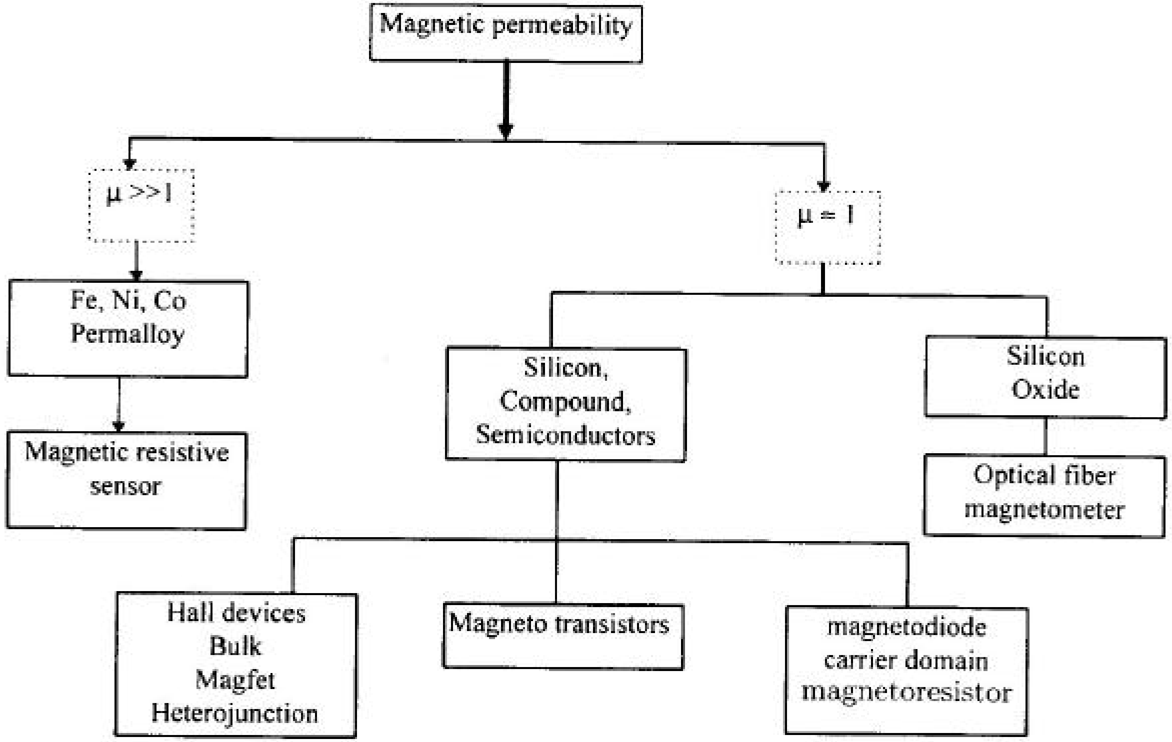
Highest efficiency when the current and the field are perpendicular - *barber-pole* structure





Magnetic Energy Domain - Physics

- Magnetic sensors - a survey

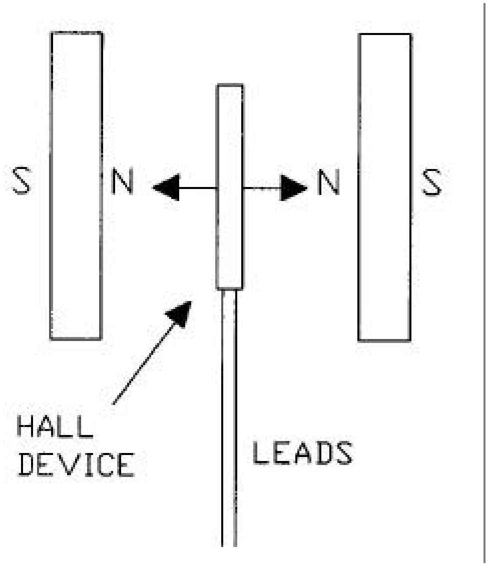


Survey of magnetic sensors.

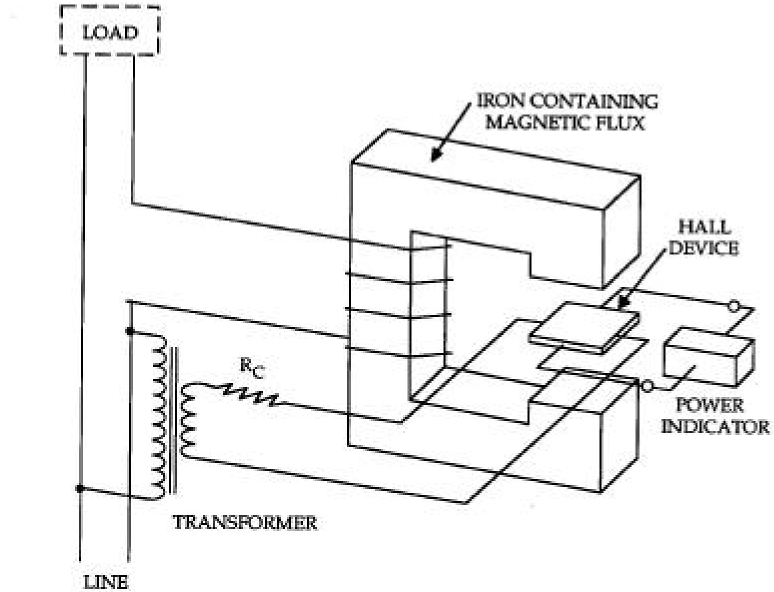
Magnetic Field Sensors

- Hall element applications

Linear displacement measurements

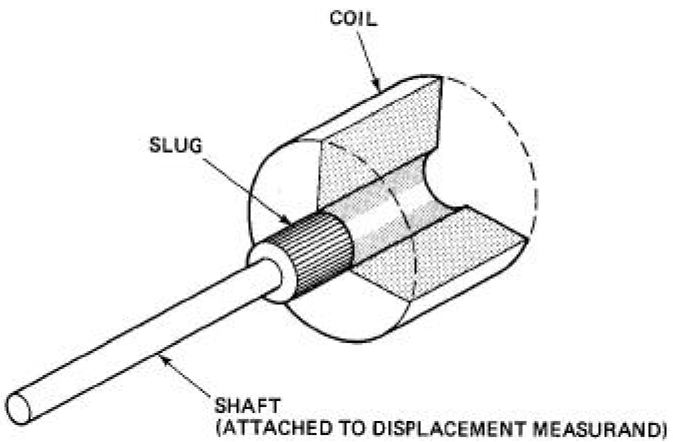


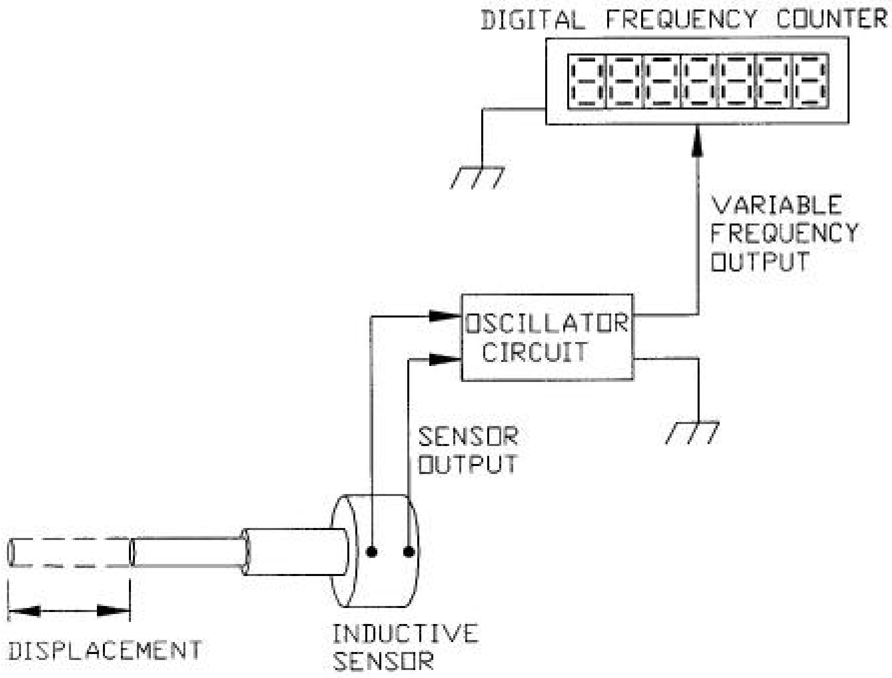
Wattmeter



Variable-inductance Sensors

- Coil with movable slug as linear motion inductor





Variable-reluctance Sensors

- Reluctance and inductance sound alike but refer to different physical variables.

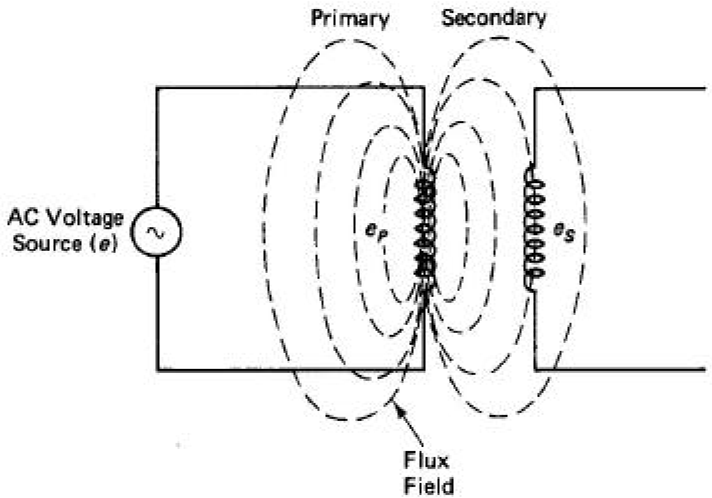
  Reluctance is the “opposite” of permeability

$$R = \frac{l}{\mu A}$$

where: R - *reluctance*

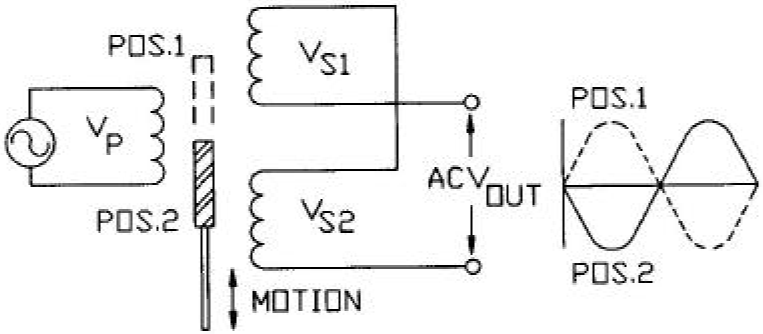
l - length of magnetic circuit

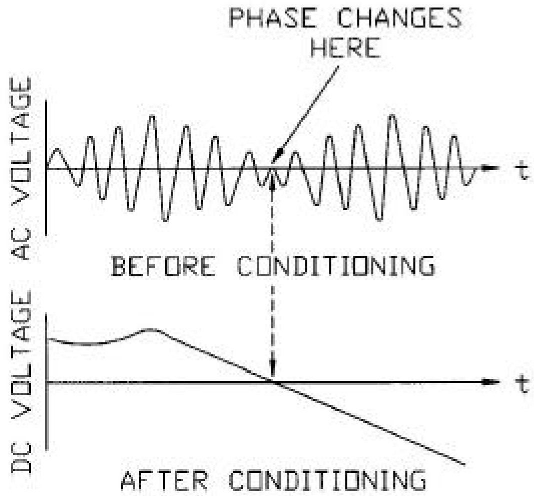
A - cross-sectional area

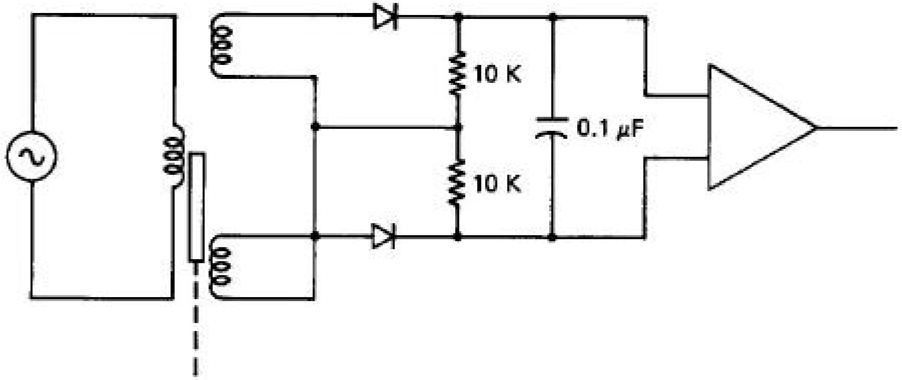


Variable-reluctance Sensors

- Linear Variable Differential Transformer (LVDT)

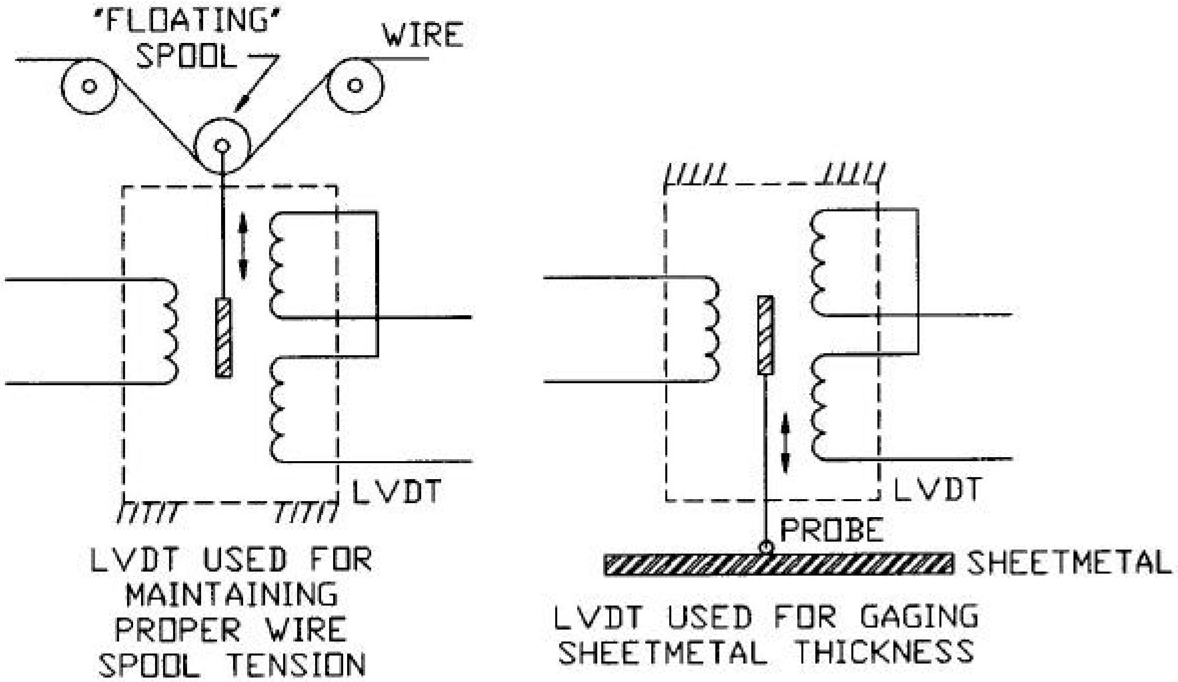






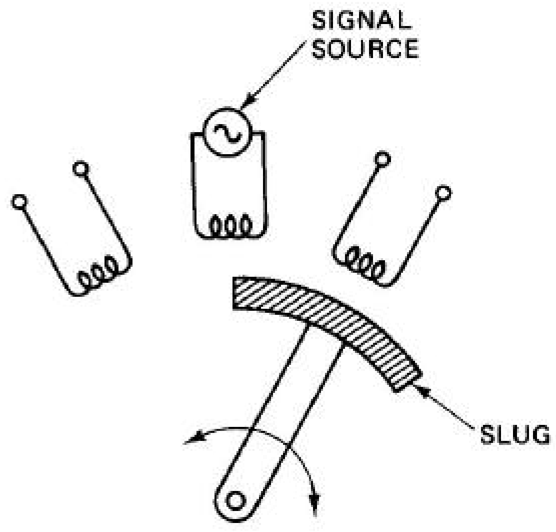
Variable-reluctance Sensors

- LVDT - Applications



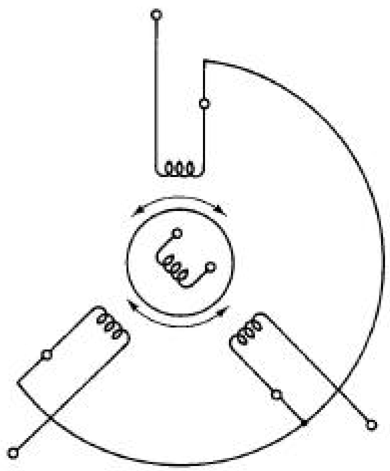
Variable-reluctance Sensors

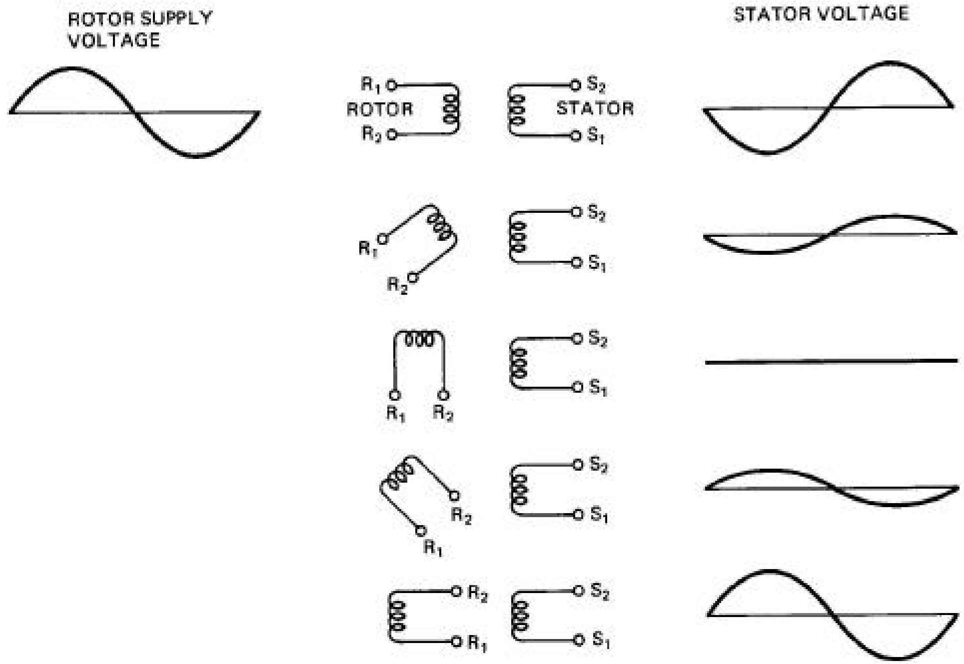
- Rotary motion LVDT



Variable-reluctance Sensors

- Synchromechanism
  - Control synchros - for indicating readings of position
  - Torque synchros - for performing work using remotely transmitted signals

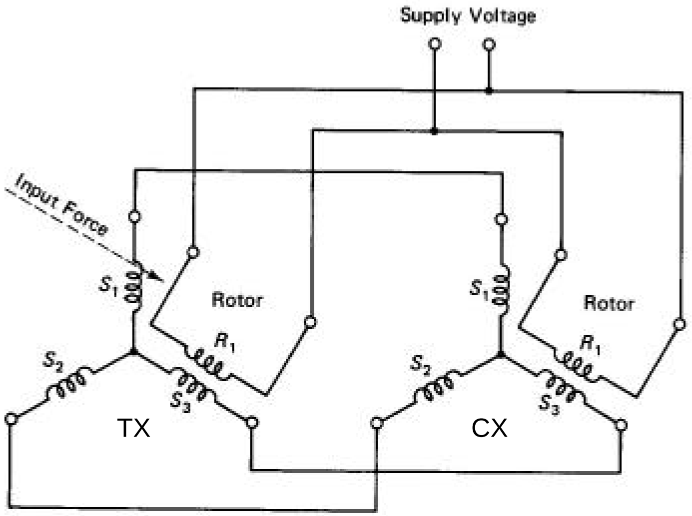


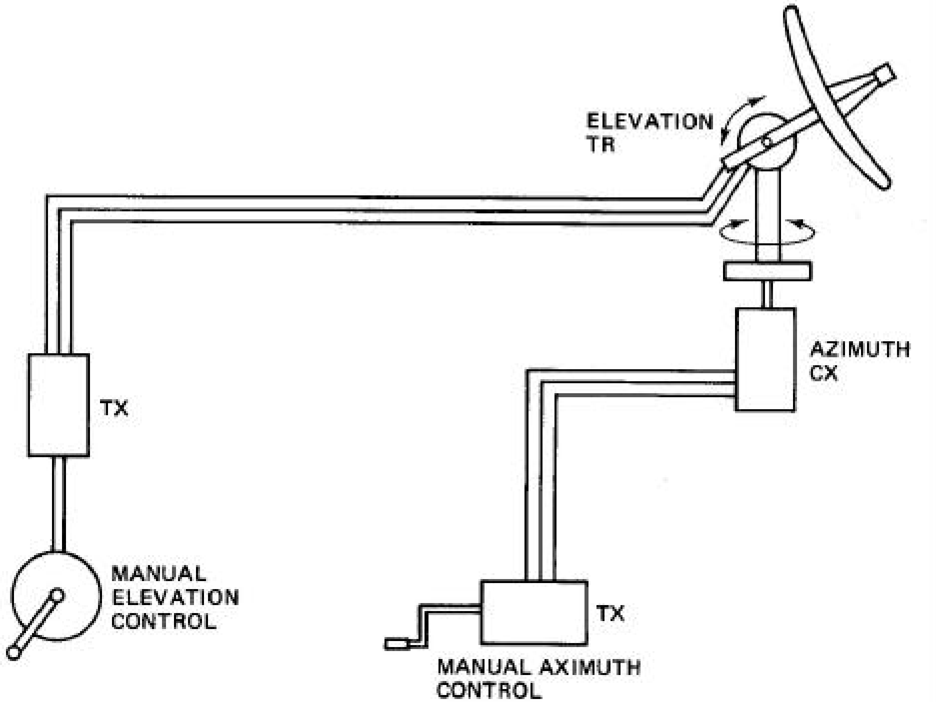


Variable-reluctance Sensors

- Synchromechanism - control transmitter and receiver

Schematic of a synchro pair system



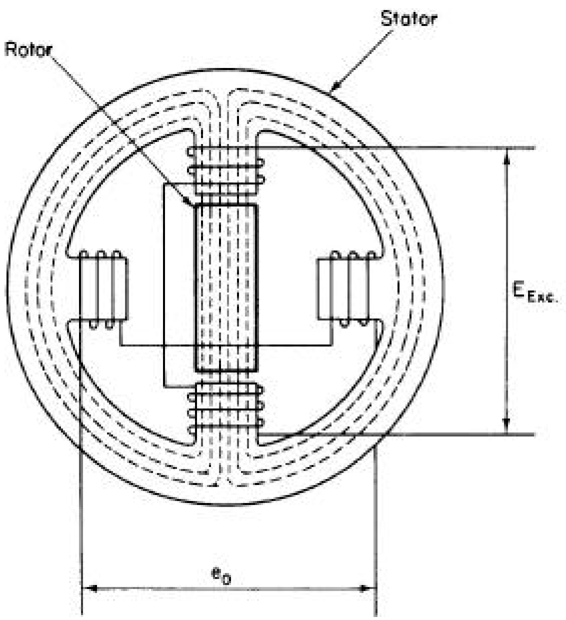


TX -RX synchros in controlling positioning of an antenna

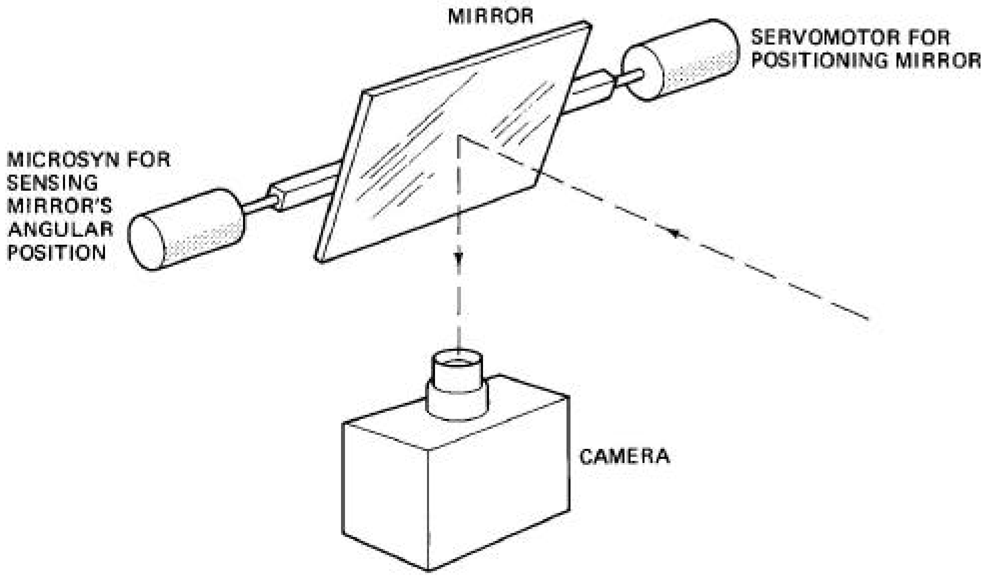
Variable-reluctance Sensors

- Microsyn - rotary reluctance device used when the angular displacements being measured or controlled are very small (few degrees or so)

Microsyn construction



Microsyn used for positioning a mirror in a satellite camera



Review Questions

- Explain what mechanism can be described by Langevin function.
- What role plays magnetic field in superconductivity ?
- Explain the Hall effect in a piece of material.
- Explain how the resistance of a magnetic film depends on the angle between the directions of the magnetic field and current.
- How would you use a Hall effect device to measure electricity consumed by an electrical installation ?
- How would you set up an inductive sensor for the purpose of detecting metal particles in copper wire ?
- How would you set up a circuit for the purpose of sensing variable inductance of an inductive sensor ?
- Explain the difference between reluctance and inductance.
- Explain how the LVDT works. Explain what the differential rectifier does in an LVDT signal-conditioning circuit.
- Explain the operation principle of the synchromechanism.
- Explain how microsyn is constructed.