Lecture 5

Sensors

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ECE 6095/4121
Digital Control of Mechatronic Systems

Sensors and Interfacing

1. Analog and Digital Sensors
   - Position, Velocity and Acceleration
   - Temperature
   - Strain, Stress, Force and Torque
   - Pressure and Flow (Not discussed)
2. Interfacing
   - Micro-controllers
   - PC/Network

Transducers, Sensors, Actuators

- Sensors and actuators are examples of **Transducers**
  - Transducer is a device that converts one physical quantity into another
  - Examples include:
    - Mercury-in-glass thermometer converts temperature into displacement of a column of mercury
    - a microphone converts sound into an electrical signal
- American National Standards Institute (ANSI) Definition of a sensor
  - A device which provides a usable output in response to a specified measurand
  - A sensor acquires a physical parameter and converts it into a signal suitable for processing (e.g., optical, electrical, mechanical)
  - Active sensors require external source of excitation (Resistance Temperature Detectors (RTDs, R), thermistor (R), strain gages (R), Accelerometer (C), LVDT (AC voltage),…)
  - Passive sensors do not (Thermocouples (V), photodiodes (I), piezoelectric (V),.)
- Actuator
  - A mechanical device for moving or controlling something
  - Converts electrical/fluid/pneumatic/fuel energy into mechanical energy

Detectable Phenomenon

- Any physical property of a material that changes in response to some excitation can be used to produce a sensor: resistive, inductive, capacitive, piezoelectric, photoresistive, elastic, thermal,..

Stimulus	**Quantity**
Acoustic	Wave (amplitude, phase), Spectrum, Wave Velocity
Biological & Chemical	Fluid Concentrations (Gas or Liquid)
Electric	Charge, Voltage, Current, Conductivity, Capacitance
Magnetic	Inductance, Flux
Optical	Refractive Index, Reflectivity, Absorption
Thermal	Temperature, Flux, Specific Heat, Thermal Conductivity
Mechanical	Position, Velocity, Acceleration, Force, Strain, Stress, Pressure, Torque

Some of the Key Principles Used

- Amperes’s Law
  - A current carrying conductor in a magnetic field experiences a force (e.g., galvanometer)
- Faraday’s Law of Induction
  - A coil resists a change in magnetic field by generating an opposing voltage/current (e.g., transformer, DC motor)
- Piezoelectric Effect
  - In certain solid materials (notably crystals, certain ceramics), electric charge accumulates in response to applied mechanical stress (e.g., accelerometers)
- Photoconductive Effect
  - When light strikes certain semiconductor materials, the resistance of the material decreases (e.g., photo-resistor)

List of Sensors

- Accelerometer
- Active pixel sensor
- Air flow meter
- Alarm sensor
- Bedwetting alarm
- Bhangmeter
- Biochip
- Biosensor
- Breathalyzer
- Capacitance probe
- Carbon paste electrode
- Carbon monoxide detector
- Catadioptric sensor
- Catalytic bead sensor
- Cationic sensor
- Charge-coupled device
- Chemical field-effect transistor
- Carbon dioxide sensor
- Colorimeter
- Crank sensor
- Curb feeler
- Current sensor
- Defect detector
- Displacement receiver
- Electrolyte–insulator–semiconductor sensor
- Electromechanical film
- Electronic nose
- Electro-optical sensor
- Ethanol sensor
- Fish counter
- Flow sensor
- Force-sensing resistor
- Gas detector
- Geophone
- Hall effect sensor
- Hall probe
- Heat flux sensor
- Hydrogen microsensor
- Hydrophones
- Hygrometer
- Image sensor
- Inclinometer
- Inductive sensor
- Inertial Reference Unit
- Infrared point sensor
- Infrared thermometer
- Intelligent sensor
- Lab-on-a-chip
- Lace Sensor a guitar pickup
- Laser distance measurement sensor
- Level sensor
- Light-addressable potentiometric sensor
- Linear encoder
- Linear variable differential transformer
- Liquid capacitive inclinometers
- Machine vision
- Magnetic anomaly detector
- Magnetic level gauge
- Magnetometer
- MAP sensor
- Mass flow sensor
- Metal detector
- MHD sensor
- Microbolometer
- Microphone
- Microwave chemistry sensor
- Microwave radiometer
- Molecular sensor
- Motion detector
- Net radiometer
- Nitrogen oxide sensor
- Optode
- Oxygen sensor
- Parktronic
- Parking sensors
- Passive infrared sensor
- Pellistor
- Photodiode
- Photoelectric sensor
- Photoionization detector
- Photomultiplier
- Photoresistor
- Photoswitch
- Phototransistor
- Phototube
- Piezoelectric sensor
- Potentiometer
- Potentiometric sensor
- Position sensor
- Pressure sensor
- Proximity sensor
- Pyranometer
- Pyrgeometer
- Quantum sensor
- Rain sensor
- Rain gauge
- Reed switch
- Resistance thermometer
- Rotary encoder
- Scintillation counter
- Seismometers
- Sensor array
- Sensor node
- Shack-Hartmann
- Smoke detector
- Sniffer coil (detects electromagnetic fields)
- Soft sensor
- Speed sensor
- Staring array
- Strain gauge
- Stud finder
- Sulphur dioxide sensors
- Thermal sensor
- Thermistor
- Thermocouple
- Throttle position sensor
- Tilt switch
- Torque sensor
- Touch pad
- Touch sensor
- Transducer
- Touch screen
- Triangulation sensor
- Ultrasonic sensor
- Variable reluctance sensor
- Variometer
- Video sensor
- Velocity sensor
- Vibrating structure gyroscope
- Viscosity sensor
- Wavefront sensor
- Wheel speed sensor
- Wired glove
- Yaw rate sensor
- Magnetic reed sensor

http://www.authorstream.com/Presentation/aSGuest40984-352482-Data-Acquisition-Signal-Conditioning-acquisitio-Education-ppt-powerpoint/

Motion Transducers

- Motion
  - Displacement (position, distance, proximity, size, gage,..)
  - Velocity
  - Acceleration
  - Jerk
- In principle, a force sensor can be used to measure acceleration, velocity or position.

$$\text{Recall } F = ma;\ F = Bv;\ F = Kx$$

- Also, can exploit relations among *a*, *v*, *x*. Beware of differentiation!

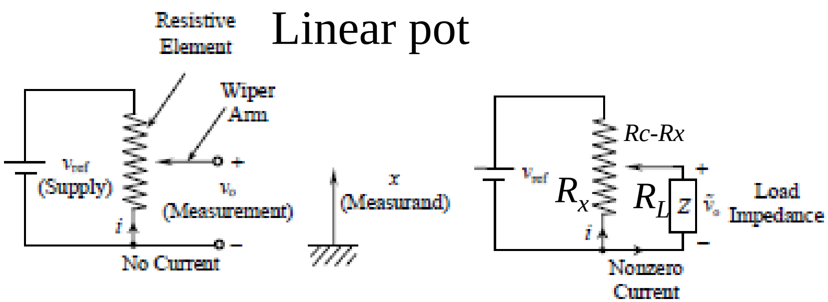
$$\text{Recall } v(t) = v(0) + \int_0^t a(\tau)d\tau;\ x(t) = x(0) + \int_0^t v(\tau)d\tau$$

- Rule of Thumb: Use displacement measurement for low-frequency applications (~ 1Hz); velocity measurement for intermediate frequencies (~ 1kHz); acceleration measurement for higher frequency measurands with high noise

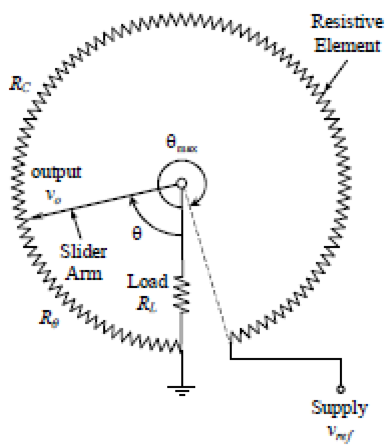
Potentiometer

- Angular and linear resistance potentiometers ("pots") are widely used for position sensing
  - Resistive material with a sliding contact onto the resistive track (10Ω -100k Ω)
  - Voltage is applied across the two ends and the voltage on the sliding contact is a measure of position

Linear pot



Rotary pot



For finite resistive impedance, $Z = R_L$

$$Let\ \alpha = \frac{R_L}{R_c};\ \frac{R_x}{R_c} = \frac{x}{x_{\max}};\ k = \frac{v_{ref}}{x_{\max}}$$

$$v_0 = \frac{R_x \| R_L}{R_c - R_x + R_x \| R_L} v_{ref}$$

$$= \frac{R_x . R_L}{R_c R_x - R_x^2 + R_c . R_L} v_{ref}$$

Divide by $R_c\, R_L$

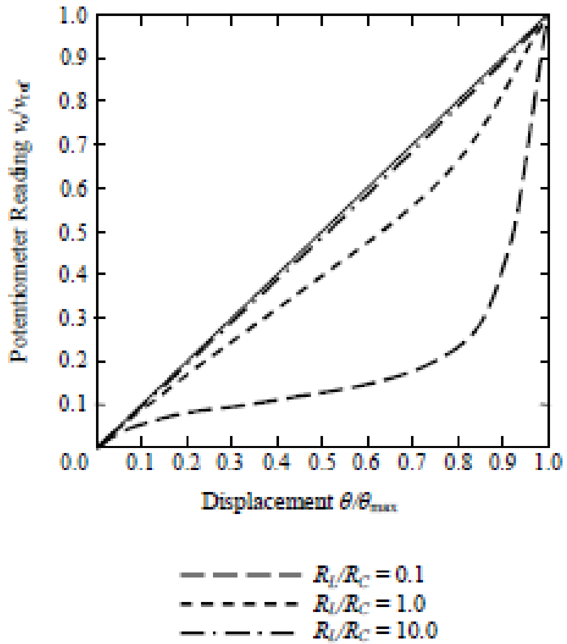
$$v_0 = \frac{kx}{1 + \left(\frac{x}{x_{\max}}\right)\frac{1}{\alpha}\left(1 - \frac{x}{x_{\max}}\right)}$$

If load impedance is high $\Rightarrow \alpha \to \infty$

$v_0 = kx$. For rotary, replace x by θ.

Loading Nonlinearity

- Electrical loading induces nonlinear dependence of v_0 on θ



$$v_0 = \frac{k\theta}{1+\left(\frac{\theta}{\theta_{max}}\right)\frac{1}{\alpha}\left(1-\frac{\theta}{\theta_{max}}\right)};$$

$$\alpha = \frac{R_L}{R_c}; k = \frac{v_{ref}}{\theta_{max}}; \frac{R_x}{R_c} = \frac{\theta}{\theta_{max}}$$

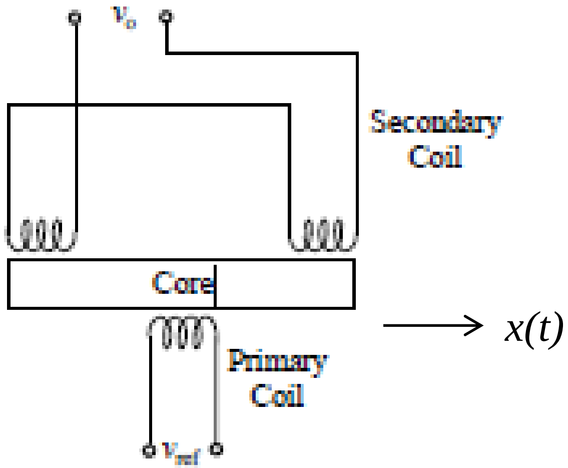
- Advantages
  - Cheap
  - No need for amplification

∃ Optical potentiometers as well

- Limitations
  - Mechanical loading: Force is needed to move the slider
  - only low frequency (slider bounce, friction,…)
  - Variations in v_{ref}
  - Electrical loading, α
  - Resolution limited by number of turns in the coil
  - Wear out and heating up

Linear Variable Differential Transformer

- Mechanical motion of a ferromagnetic material (called core) within the flux-path between the primary coil and two secondary coils (which oppose each other!) induces changes in flux linkage in the secondary coil. Also called a variable reluctance transducer or more specifically, mutual induction transducer
- Core at the centre induces zero voltage (*null position*)
- Precise measurement of movements is possible (sub-millimeter accuracy). Typically used to measure from ± 1mm to ± 50cm; Rotary (RVDT): $\pm 30\text{-}40^0$



$$v_{ref}(t) = v_p \sin \omega_c t$$

v_p = peak primary voltage amplitude;

ω_c = carrier frequency

r = transformer ratio

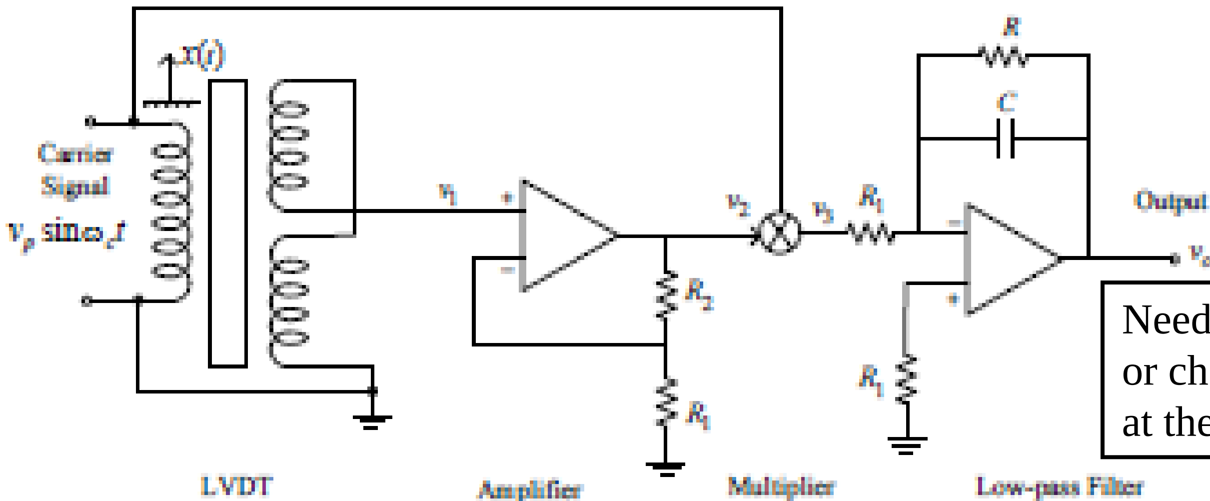
$x(t)$ = displacement from null

$$v_0(t) = v_p r\, x(t) \sin \omega_c t$$

- Modulated signal needs to be amplified, demodulated and filtered. Usually, it is packaged with the LVDT.
- Other mutual-induction transducers : proximity sensor, resolver, synchro transformer

http://www.rdpe.com/displacement/lvdt/lvdt-principles.htm

LVDT Signal Conditioning



Need to invert at the output or change phase by 180^0 at the input

Output of Amplifier

$$v_1(t) = v_p r\, x(t) \sin \omega_c t$$

$$v_1(t) = \frac{R_1}{R_1 + R_2} v_2(t)$$

$$\Rightarrow v_2(t) = \underbrace{\left(1 + \frac{R_2}{R_1}\right)}_{g} v_1(t)$$

$$So,\ v_2(t) = v_p r\, g\, x(t) \sin \omega_c t$$

Demodulation

$$v_3(t) = v_2(t) v_p \sin \omega_c t$$
$$= v_p^2 r\, g\, x(t) \sin^2 \omega_c t$$
$$= \frac{v_p^2 r\, g}{2} x(t) \left(1 - \cos 2\omega_c t\right)$$

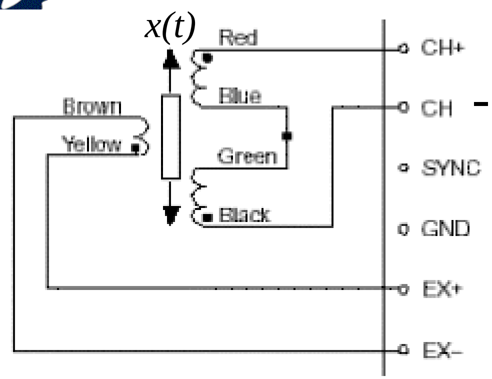
Output

$$\frac{v_0(s)}{v_3(s)} = -\frac{R}{R_1(1 + RCs)};$$
$$RC\omega_c > 10$$

Useful radian frequency range of *x(t)* for measurement : 0.1/RC

http://www.rdpe.com/displacement/lvdt/lvdt-principles.htm

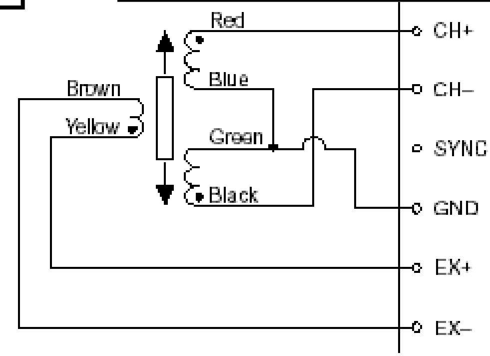
Connecting LVDTs and Advantages



$$v_1(t) = (v_{CH+} - v_{CH-})x(t)$$

4-wire connection of an LVDT

$$v_1(t) = \frac{(v_{CH+} - v_{CH-})}{(v_{CH+} + v_{CH-})} x(t)$$

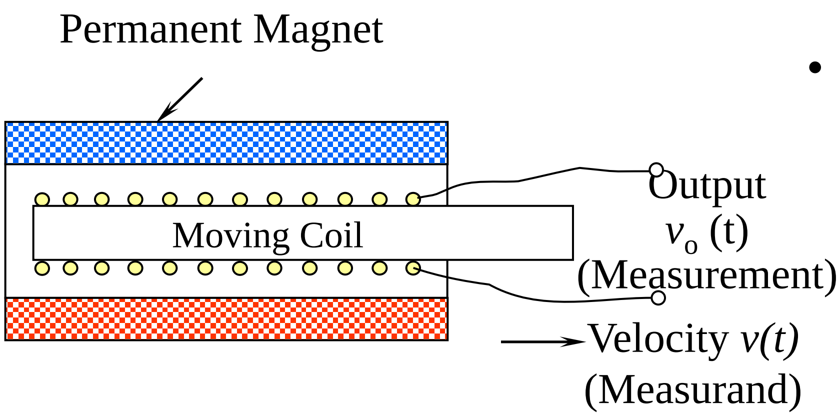


5-wire connection of an LVDT

- Advantages
  - Non-contacting device with no frictional resistance
  - Hysteresis (both magnetic hysteresis and mechanical backlash) is negligible
  - Low output impedance (≈ 100Ω)
  - Directional measurements (positive/negative) are obtained
  - Available in small sizes
  - Inexpensive and durable
  - Fine resolutions are possible. Much better than a coil potentiometer. (sub-millimeter accuracies)
  - Rotary

Permanent Magnet Transducers

- Rectilinear

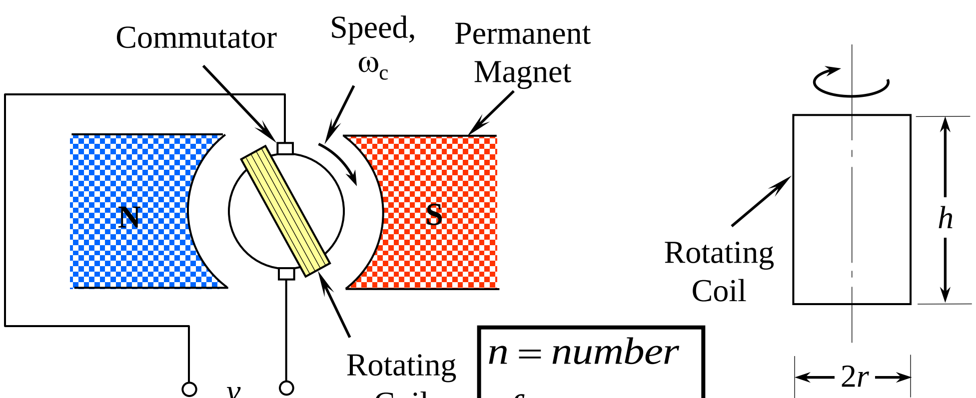


- Relative motion between the magnetic field generated by the permanent magnet and the moving coil induces a voltage

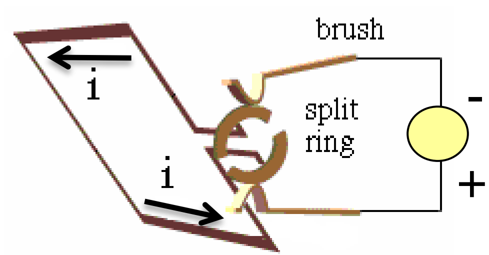
$$v_0(t) \propto \text{velocity of coil, } v(t)$$

- Rotary (DC Tachometer ⇒ tachogenerator)

$$v_0 = |2nhrB\omega_c| = K\omega_c$$
$$B = \textit{flux density}$$

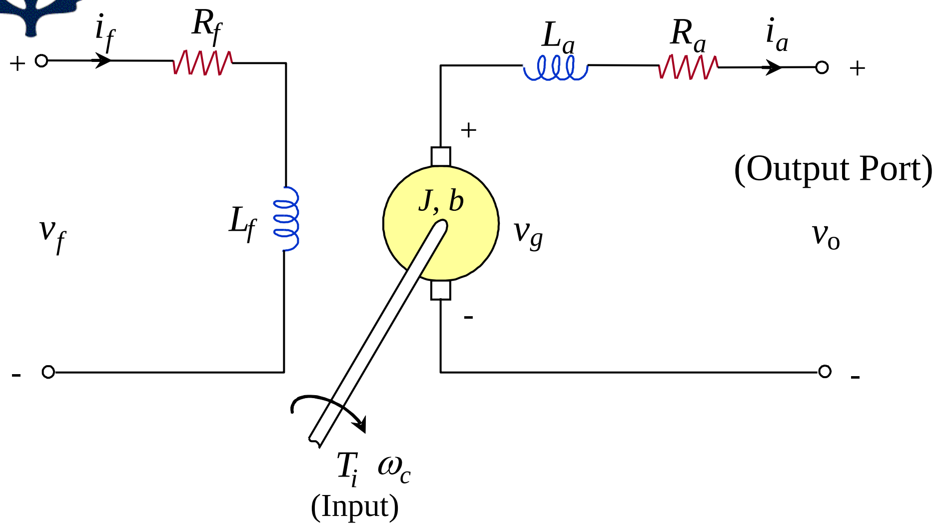


$n = \textit{number of turns}$

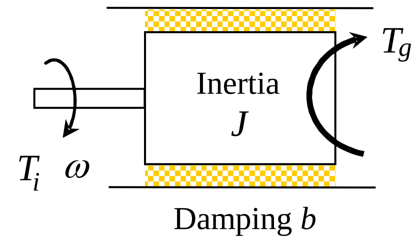


- Induced voltage at the rotating coil is picked up using a commutator device (consists of low resistance carbon brushes that make contact with coil thru slip rings)

DC Tachometer Model



$$v_g = K\omega_c$$
$$T_g = Ki_a$$



- Dynamic Model

$$v_g = K\omega_c = v_o + R_a i_a + L_a \frac{di_a}{dt}$$

$$T_i = J\frac{d\omega_c}{dt} + b\omega_c + T_g \approx J\frac{d\omega_c}{dt} + b\omega_c + Ki_a$$

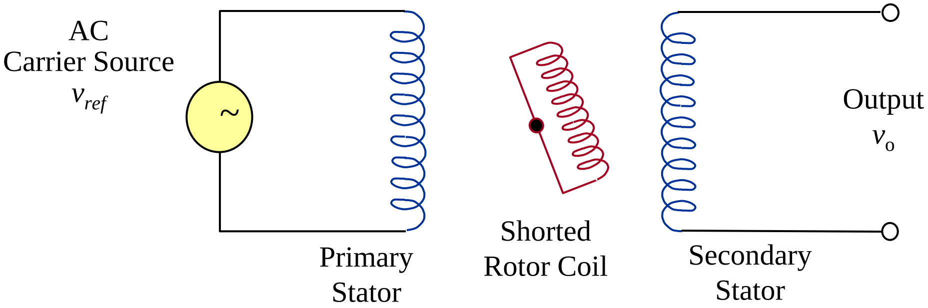
$$\Rightarrow \begin{pmatrix} \frac{di_a}{dt} \\ \frac{d\omega_c}{dt} \end{pmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & \frac{K}{L_a} \\ -\frac{K}{J} & -\frac{b}{J} \end{bmatrix} \begin{pmatrix} i_a \\ \omega_c \end{pmatrix} + \begin{bmatrix} -\frac{1}{L_a} & 0 \\ 0 & \frac{1}{J} \end{bmatrix} \begin{pmatrix} V_0 \\ T_i \end{pmatrix}$$

- Steady State Model

$$\omega_c = \frac{v_o + R_a i_a}{K} \; in\ steady\ state \Rightarrow \omega_c \approx \frac{v_o}{K} \; for\ negligible\ R_a$$

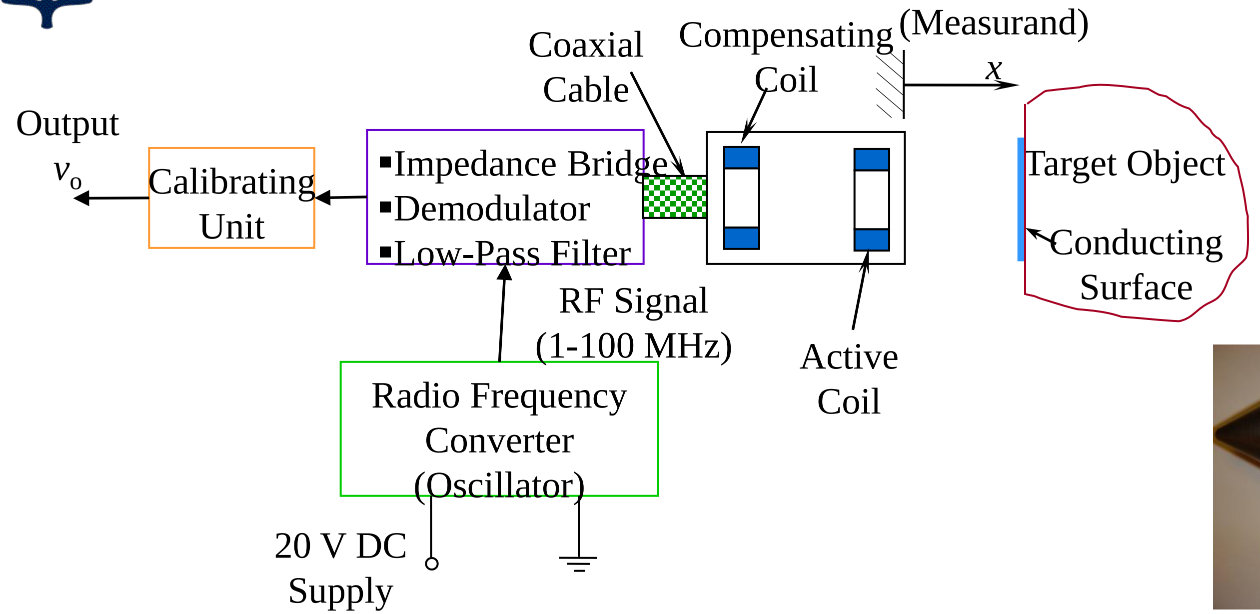
$$T_i = b\omega_c + Ki_a = (K + \frac{bR_a}{K})\, i_a + \frac{b}{K} v_o \Rightarrow T_i \approx Ki_a \;\; for\ negligible\ b$$

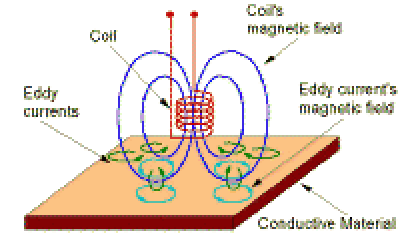
AC Induction Tachometer



- Similar to an induction motor. Rotor windings are shorted.
- Powered by an ac carrier source v_{ref} with radian frequency ω_c
- The induced voltage in the rotor windings is a modulated signal of the supply. Modulation is due to the speed of the rotor.
- The output voltage on the secondary is a result of primary and rotor windings and is supply modulated by the speed
- Main advantage of AC tachometers is that they have no slip rings or brushes

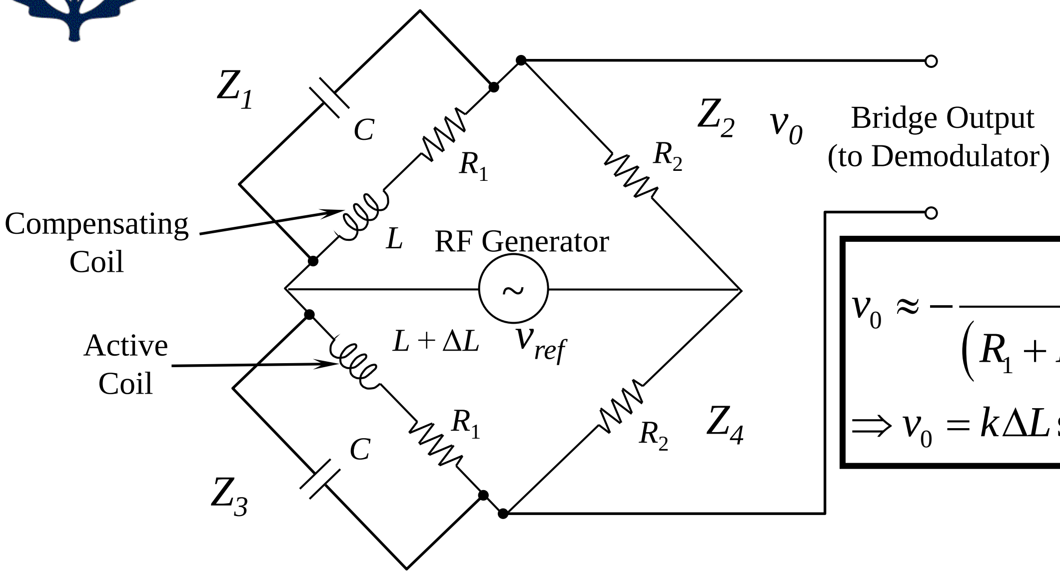
Eddy Current Transducers





- Conducting coils when subjected to a fluctuating magnetic field produce Eddy currents
- When a target object is moved closer to the sensor, the inductance of the active coil changes. Compensating coil compensates for thermal effects.
- The two coils on the probe head form two arms of an inductance bridge
- The output of the bridge is amplitude modulated signal

Impedance Bridge



$$v_0 = \frac{Z_1 Z_4 - Z_2 Z_3}{(Z_1+Z_2)(Z_3+Z_4)} v_{ref}$$

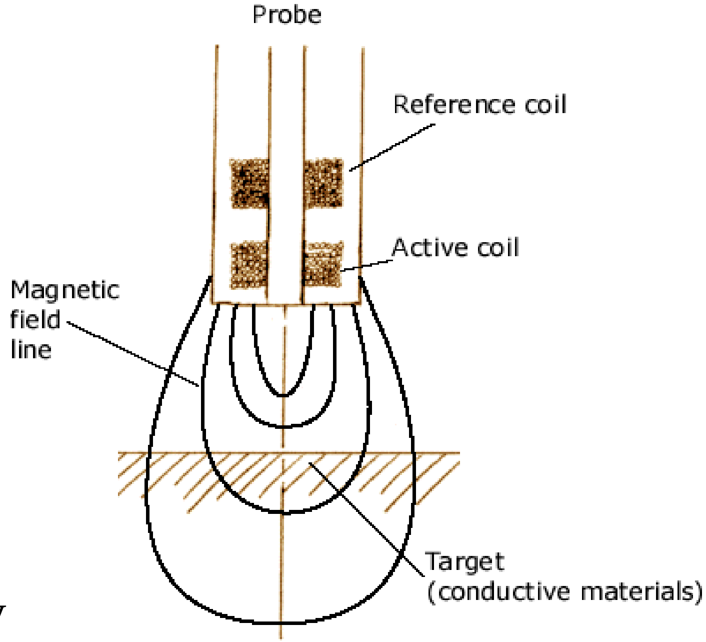
$$v_0 \approx -\frac{R_2(j\omega_{ref})\Delta L}{\left(R_1 + R_2(1 - LC\omega_{ref}^2) + j(R_1 R_2 C + L)\omega_{ref}\right)^2} v_{ref}$$

$$\Rightarrow v_0 = k\Delta L \sin\omega_{ref} t \Rightarrow \text{modulated output}$$

- The bridge is balanced when there is no object $\Rightarrow Z_1 = Z_3$
- The change in inductance creates an imbalance in the circuit and results in the output signal
- The modulated signal needs to be demodulated to determine the displacement
- For large displacements, output is not linearly related to displacement. One term in the denominator is actually $(R_1 + R_2(1-(L+\Delta L)C\omega_{ref}^2) + j(R_1 R_2 C + L + \Delta L)\omega_{ref})$

Typical Characteristics of Eddy Current Transducers

- Typical diameter of the probe is about 2mm (larger ones: 75mm)
- The target object has to be slightly larger than the frontal area of the probe
- Output impedance is about 1 kΩ (medium impedance)
- Sensitivity is around 5V/mm
- Range: .25mm – 30mm
- Suitable for high transients (100 kHz)
- Applications include
  - Displacement
  - Fault detection (e.g., cracks, corrosion)
  - Metal detection
  - Braking
  - Monitoring conductivity & permeability

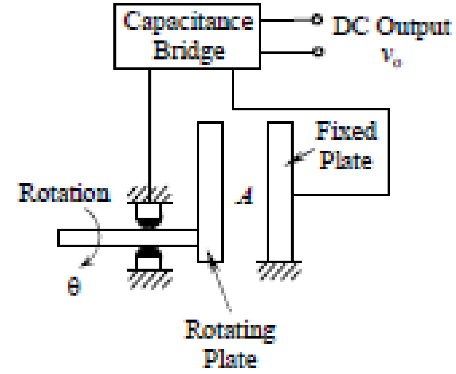


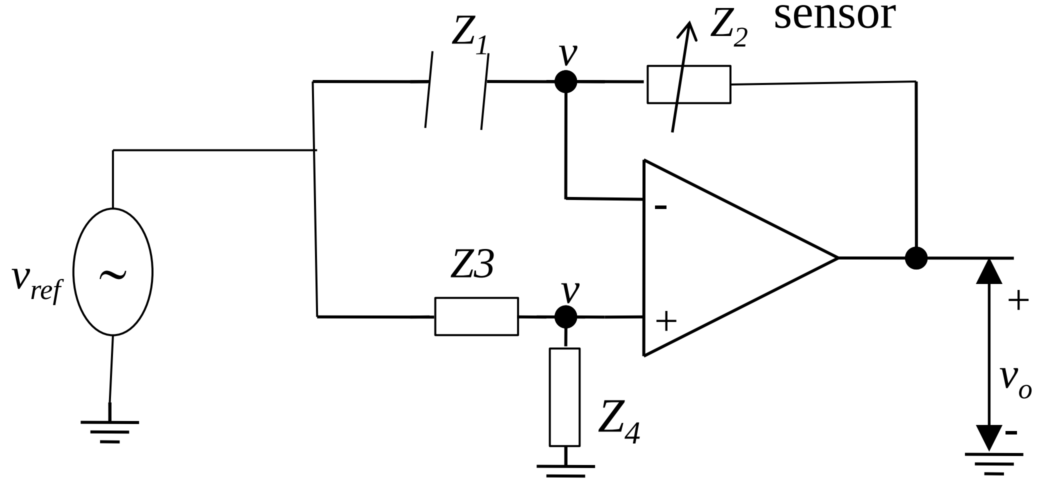
Variable Capacitance Transducers

- Recall the capacitance, C of a two-plate capacitor is given by

  $C = \varepsilon \frac{A}{x}$; ε = dielectric constant (permittivity); A = overlapping area of the two plates; x = gap width between the two plates

- Capacitive Rotation Sensor
  - ∠displacement of one of the plates changes A
  - $A \propto \theta \Rightarrow C = K\,\theta$





Capacitance Bridge Circuit

$$v_0 = \frac{Z_1 Z_4 - Z_2 Z_3}{Z_1(Z_3 + Z_4)} v_{ref}$$

$$Balance: \frac{Z_2}{Z_1} = \frac{Z_4}{Z_3}$$

$$Z_2 \rightarrow Z_2 + \delta Z$$

$$\delta v_0 = -\frac{\delta Z}{Z_1(1 + Z_4/Z_3)} v_{ref}$$

Variable Capacitance Transducers - 2

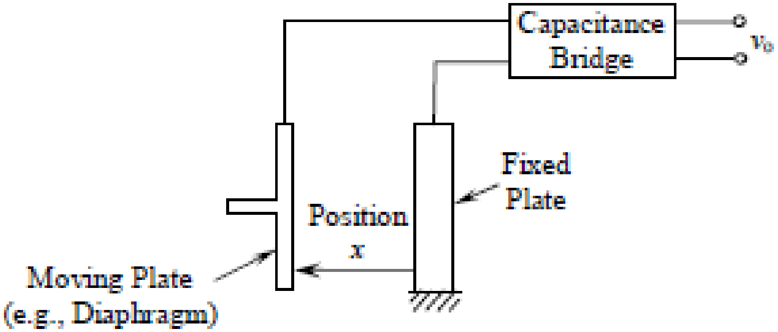
- Capacitive Displacement Sensor

$$C = \frac{\varepsilon A}{x} = \frac{K}{x} \Rightarrow nonlinear$$

$$Use\ inverting\ op\ amp:$$

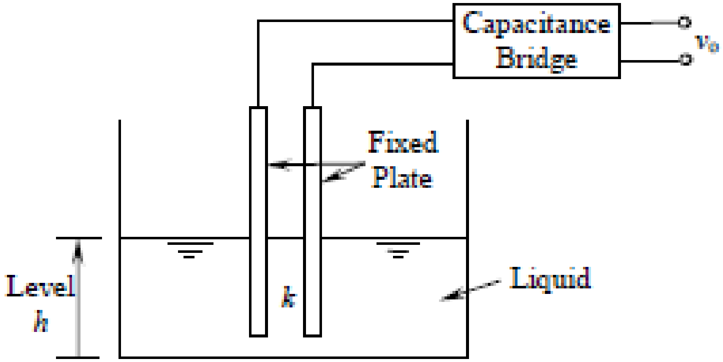
$$C_{ref}\ input\ end; C\ \ feedback\ \ path$$

$$v_0 = -\frac{x}{KC_{ref}} v_{ref}$$

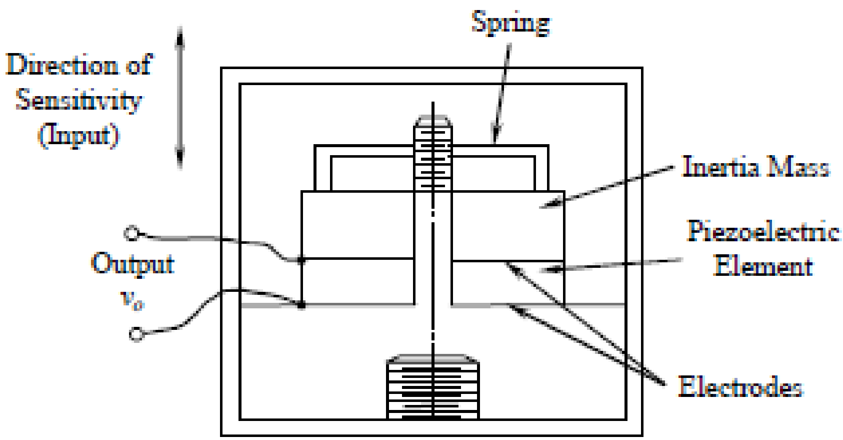


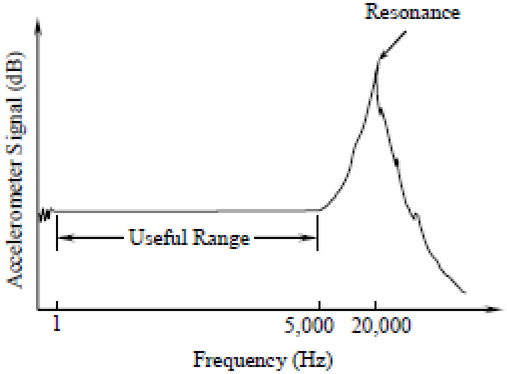
- Capacitive Liquid Level Sensor
  - Change in permittivity as the fluid level changes

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



Piezoelectric Accelerometer - 1





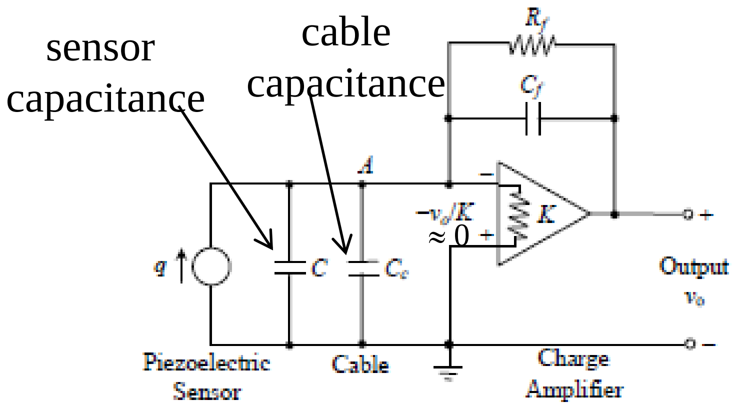
- Principles

/Typical sensitivities: 10pC|g or 5mV/g

  - When some materials (e.g., barium titanate, Lead Zirconate Titanate, Quartz, Rochelle salt) are subjected to stress or strain, they generate electrical charge and an associated potential difference
  - Used to measure pressure, strain, acceleration, velocity, torque, force
  - Reverse piezoelectric effect is used in actuators (e.g., valves, ink-jet printers, miniature stepper motors, hard-disk drives,…)
- In the compression –type accelerometer, the crystal and mass are restrained by very high stiffness spring $\Rightarrow$ $\omega_n = \sqrt{k/m}$ is high ($\approx$ 20kHz).

Piezoelectric Accelerometer - 2

- Piezoelectric devices need charge amplifier. Why?
  - High input impedance $\Rightarrow$ small output signals and large loading errors
  - The charge can quickly leak out through the load



$$C_f s v_0(s) + \frac{v_0(s)}{R_f} + s q(s) = 0$$

$$\Rightarrow \frac{v_0(s)}{q(s)} = -\frac{R_f s}{1 + R_f C_f s} \rightarrow -\frac{1}{C_f} \text{ as } s \rightarrow \infty$$

suppose we calibrate it so that $v_0'(s) = -C_f v_0(s)$

$$G(s) = \frac{v_0'(s)}{q(s)} = \frac{\overbrace{R_f C_f}^{\tau} s}{1 + R_f C_f s} = \frac{\tau s}{1 + \tau s};$$

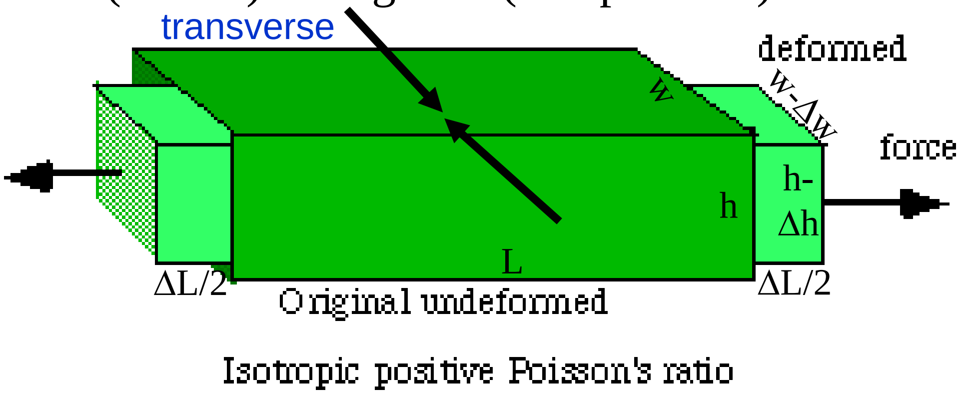
$$|G(j\omega)| = \frac{\tau\omega}{\sqrt{\tau^2\omega^2 + 1}}$$

Suppose want a gain of 0.99 at the smallest measurable frequency, $\omega_{\min}$. Then, $\tau\omega_{\min} \approx 7$.

- Can measure velocity by integrating acceleration
- Device sizes can be as small as 1 cm

Strain Gages

- Strain is the amount of deformation of a body due to an applied force. Strain can be positive (tensile) or negative (compressive)



- Hooke's law: Stress (σ) is proportional to strain (ε_L)

$$\text{Stress}, \sigma = \frac{\text{Force}}{\text{Area}} = \frac{F}{wh} \text{ in } \frac{\text{Newtons}}{\text{m}^2} \textit{ or } \text{Pascal (Pa)} \quad \text{Logitudinal Strain}, \varepsilon_L = \frac{\text{change in length}}{\text{original length}} = \frac{\Delta l}{L}$$

$$\sigma = E\varepsilon;\ E = \text{ Elastic (Young's) Modulus}$$

- Poisson's Ratio, ν (constant across all directions for isotropic materials)
  - Strain in the transverse direction (*w or h*)

$$\nu = \frac{\text{Transverse Strain}}{\text{Longitudinal Strain}} = -\frac{\varepsilon_w}{\varepsilon_L} = -\frac{\varepsilon_h}{\varepsilon_L}$$

Most materials: ν = 0.3-0.5

Strain Gage Theory

- A wire of cross-sectional area A, resistivity ρ, and length L the resistance is given by

$$R=\frac{\rho L}{A};A=\pi r^2 \text{ for circular cross-sections; } A=wh \text{ for rectangular cross-sections}$$

$$\ln R=\ln\rho+\ln L-\ln A=\ln\rho+\ln L-2\ln r-\ln\pi \text{ for circular}$$

$$\ln R=\ln\rho+\ln L-\ln A=\ln\rho+\ln L-\ln w-\ln h \text{ for rectangular}$$

- When the wire is stretched, length L is increased and the cross-sectional area A is reduced ⇒ total wire resistance increases. In addition, since the lattice structure is altered by the strain, the resistivity of the material, ρ may also increase, and this, in general, causes the resistance to increase further. For *isotropic* materials

$$\frac{\Delta R}{R}=\frac{\Delta\rho}{\rho}+\frac{\Delta L}{L}-2\frac{\Delta r}{r} \text{ for circular}$$

$$\frac{\Delta R}{R}=\frac{\Delta\rho}{\rho}+\frac{\Delta L}{L}-\frac{\Delta w}{w}-\frac{\Delta h}{h} \text{ for rectangular}$$

⇒

$$\frac{\Delta R}{R}=\frac{\Delta\rho}{\rho}+(1+2\nu)\frac{\Delta L}{L}$$

$$=\frac{\Delta\rho}{\rho}+(1+2\nu)\varepsilon_L$$

Gage Factor :

$$S_s=\frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}}=(1+2\nu)+\frac{\frac{\Delta\rho}{\rho}}{\frac{\Delta L}{L}}$$

- For most materials, S_s ranges from 2.0 to 4.0

Examples: Constantan = 2.1, Nichrome = 2.1-2.63

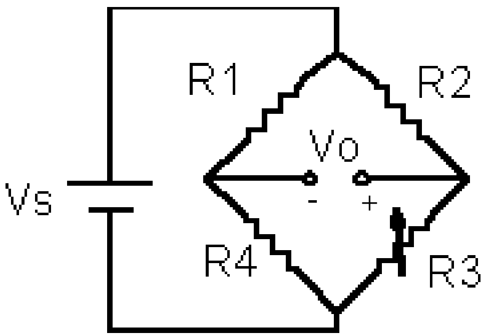
Strain Gage Fctors

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

Figure 9.5 Properties of strain-gage materials. (From Cobbold, R. S. C. 1974. Transducers for biomedical measurements: principles and applications, New York: Wiley.)

- Semiconductor materials such as Silicon and Germanium are used for strain gages because of their high gage factors.
- Diffused semiconductor gages (as opposed to bonded gages) on a single silicon wafer allow lower manufacturing costs. The deviation from linearity is approximately 1%

Wheatstone Bridge to Measure Strain



- Wheatstone bridge with strain gauge R_3

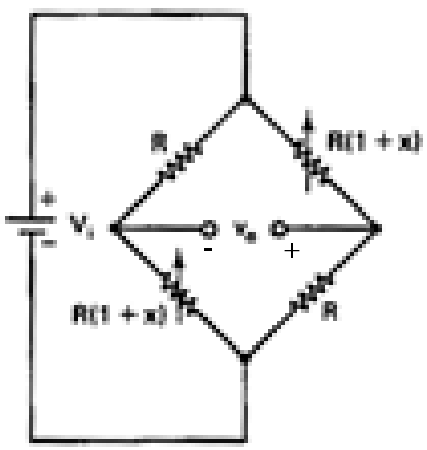
$$V_0 = \left(\frac{R_3}{R_2 + R_3} - \frac{R_4}{R_1 + R_4} \right) V_s = \frac{R_1 R_3 - R_2 R_4}{(R_1 + R_4)(R_2 + R_3)} V_s$$

- When $R_1 R_3 = R_2 R_4$, V_0 is zero $\Rightarrow$ Balanced
- When resistance changes, $R_3 \rightarrow R_3 (1+x)$

$$V_0 \approx \frac{R_1 R_3 x}{(R_1 + R_4)(R_2 + R_3)} V_s \Rightarrow \varepsilon = \frac{x}{S_s} \approx \frac{(R_1 + R_4)(R_2 + R_3)}{R_1 R_3 S_s} \frac{V_0}{V_s}$$

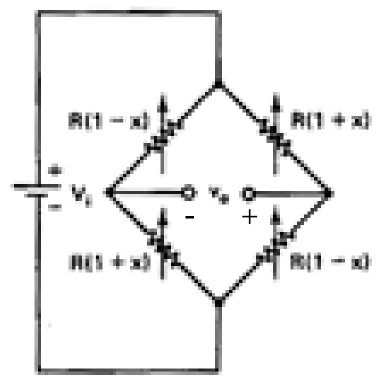
- When $R_i = R$, $\boxed{\varepsilon = \frac{x}{S_s} \approx \frac{4}{S_s} \frac{V_0}{V_s}}$

- Other Bridge Configurations



$$V_0 = \left(\frac{1}{2+x} - \frac{1+x}{2+x} \right) V_s$$
$$= -\frac{x}{2+x} V_s \approx -\frac{x}{2} V_s$$
$$\varepsilon = \frac{x}{S_s} \approx -\frac{2}{S_s} \frac{V_0}{V_s}$$

2-gage configuration

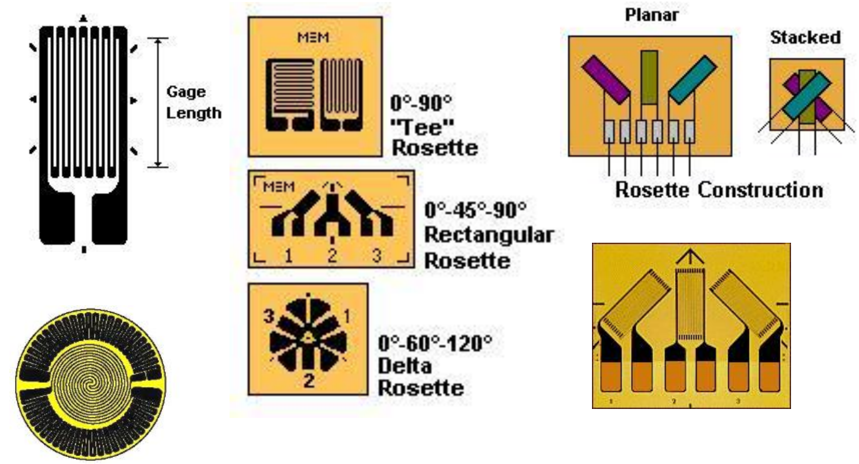


$$V_0 = \left(\frac{1-x}{2} - \frac{1+x}{2} \right) V_s$$
$$= -x V_s$$
$$\varepsilon = \frac{x}{S_s} = -\frac{1}{S_s} \frac{V_0}{V_s}$$

4-gage configuration

Strain Gage Specifications

Gauge selection



1. Grid length (250 = 0.250 inch)
2. Grid pattern and tab geometry (uniaxial, biaxial, three-element rosette, shear pattern)
3. Type of grid alloy and backing (strain gauge series EA, Constantan grid, polyimide backing)
4. Option features: protection, termination (L = pre-attached Leads, E= Encapsulated with exposed tabs.)
5. Strain gauge resistance (350=350 ohms)
6. Self-temperature compensation (STC # = 06 for steel substrate)

Note : The S-T-C number is the approximate thermal expansion coefficient in ppm/ deg F of the structural material on which the strain gage will display minimum thermal output.

http://www.vishay.com/brands/measurements_group/strain_gages/mm.htm

Torque Sensing Methods

- Measure strain in a sensing member (a circular shaft) between drive element and driven load, using a strain gage bridge:

$$\varepsilon = \frac{r}{2GJ}T;\ r = \text{ radius of shaft; } J = \text{polar moment of area of cross section, } G\text{=shear modulus}$$

- Measure angular displacement in a sensing member (as in Method 1)--either directly, using a displacement sensor, or indirectly, by measuring a variable, such as magnetic inductance or capacitance, that varies with displacement:

$$T = \frac{GJ}{L}\theta;\ L = \text{ length of shaft}$$

- Measure reaction in support structure or housing (by measuring a force) and the associated lever arm length: $T_R = F_R L;\ F_R = \text{ reaction Force; } L = \text{Lever Arm Length}$
- In electric motors, measure the field or armature current that produces motor torque; in hydraulic or pneumatic actuators, measure actuator pressure:

$$T = K_T i_A; T = \frac{Q\Delta p}{\omega};\ Q = \text{ Flow rate; } \Delta p = \text{Pressure Difference}$$

- Measure torque directly, using piezoelectric sensors, for example: $T = J\dot{\omega}$
- Employ a servo method-- balance the unknown torque with a feedback torque generated by an active device (say, a servomotor) whose torque characteristics are precisely known
- Measure angular acceleration caused by torque in a known inertia element: $T = J\dot{\omega}$

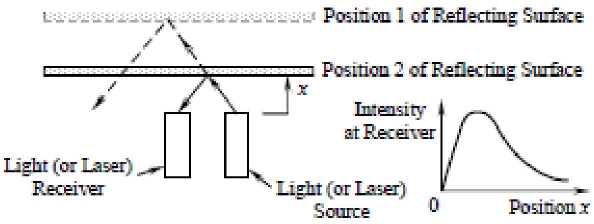
Rating Parameters of Sensors and Transducers

Transducer	Measurand	Measurand Frequency Max/Min	Output Impedance	Typical Resolution	Accuracy	Sensitivity
Potentiometer	Displacement	5 Hz/DC	Low	0.1 mm	0.1%	200 mV/mm
LVDT	Displacement	2,500 Hz/ DC	Moderate	0.001 mm or less	0.3%	50 mV/mm
Resolver	Angular displacement	500 Hz/ DC (limited by excitation freq)	Low	2 min.	0.2%	10 mV/deg
Tachometer	Velocity	700 Hz/ DC	Moderate (50 Ω)	0.2 mm/s	0.5%	5 mV/mm/s 75 mV/rad/s
Eddy current proximity sensor	Displacement	100 kHz/ DC	Moderate	0.001 mm 0.05% full scale	0.5%	5 V/mm
Piezoelectric accelerometer	Acceleration (and velocity, etc.)	25 kHz/ 1Hz	High	1 mm/s^2	1%	0.5 $mV/m/s^2$
Semiconductor strain gage	Strain (displacement, acceleration, etc.)	1 kHz/ DC (limited by fatigue)	200 Ω	1 - 10 με (1με=10^{-6} unity strain)	1%	1 V/ε, 2,000 με max
Loadcell	Force (10 - 1000 *N*)	500 Hz/ DC	Moderate	0.01 N	0.05%	1 mV/N
Laser	Displacement/ Shape	1 kHz/ DC	100 Ω	1.0 μm	0.5%	1 V/mm
Optical encoder	Motion	100 kHz/ DC	500 Ω	10 bit	±½ bit	10^4/rev.

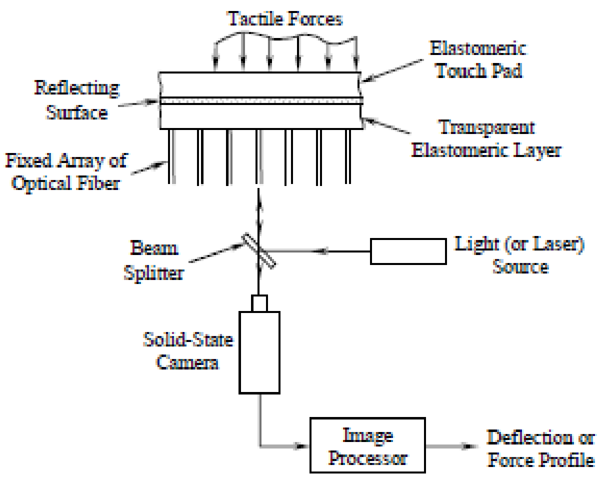
$$T = J\dot{\omega}$$

Tactile Sensors

- Force distribution is measured using a closely spaced array of force sensors. Useful in grasping and object identification
- Gripping Considerations
  - Spatial resolution of about 2mm
  - Force resolution (sensitivity) of 2gm
  - Force capacity (maximum touch force) of 1kg
  - Response time of 5ms or less
  - Low hysteresis (low energy dissipation)
  - Durability under harsh working conditions
  - Robustness and insensitivity to change in environmental conditions (temperature, dust, humidity, vibration, and so on)
  - Capability to detect and even predict slip



Optical proximity sensor



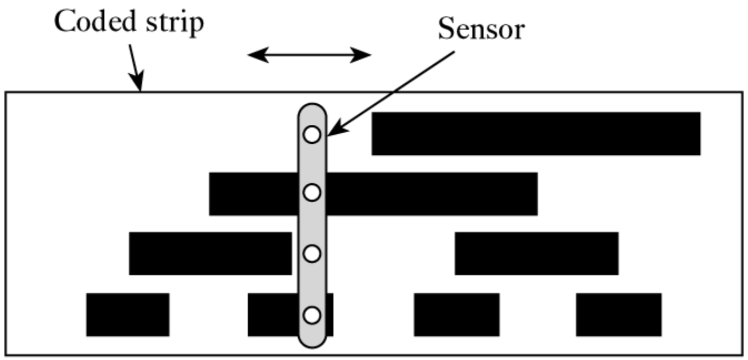
A fiber-optic tactile sensor

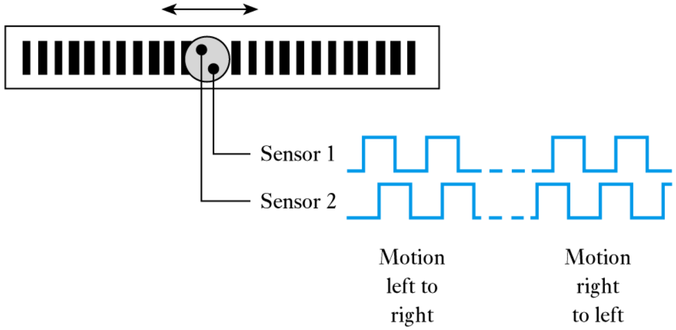
Digital Transducers

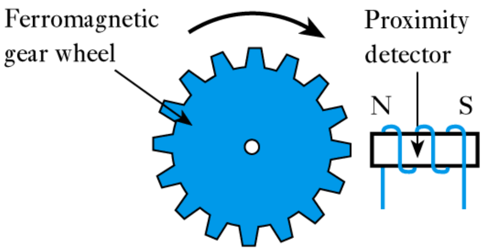
- A measurement device that produces a digital output (a pulse or a frequency)
- Advantages:
  - Less susceptible to noise, disturbances, or parameter variation in sensors
  - Complex signal processing with very high accuracy and speed by digital means (Hardware implementation is faster than software implementation)
  - High reliability by minimizing analog hardware components
  - Large amount of data may be stored using compact, high-density methods
  - Large amounts of data may be stored using compact, high-density methods
  - Data can be stored/maintained for very long periods of time without any drift or being affected by adverse environmental conditions
  - Fast data transmission over long distances without significant dynamic delays (unlike analog systems)
  - Digital signals use low voltages (e.g., 0-12V DC) and low power
  - Digital devices typically have low overall cost

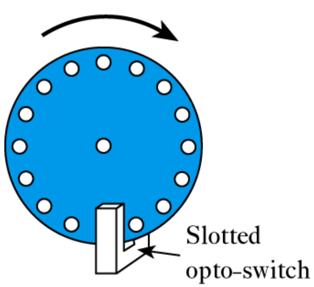
Optical Encoders

- Absolute position encoders: a pattern of light and dark strips is printed on to a strip and is detected by a sensor that moves along the strip
  - Pattern takes the form of a series of lines
  - Pattern is arranged so that the combination is unique at each point
  - Sensor is an array of photodiodes (light →ΔI)
- Incremental position encoder: uses a single line that alternates black/white
  - Two slightly offset sensors produce outputs
  - Detects motion in either direction, pulses are counted to determine absolute position (which must be initially reset)
  - Other counting techniques









Encoder Resolution

- Displacement Measurement
  - Count = n pulses; Maximum count possible = M pulses; Range: $\pm \theta_{max}$
  - Measurement: $\theta = \frac{n}{M}\theta_{\max}$
  - Digital resolution: $\Delta\theta_d = \frac{360}{2^r}$; r = number of bits
  - Physical resolution: $\Delta\theta_p = \frac{360}{4N}$; N = Number of windows in code disk; Factor 4 comes from quadrature signals $\Rightarrow$ two pulse signals, one out of phase with the other by 90^0 and the ability to detect both rising and falling edges of a pulse
- Velocity Measurement
  - Pulse counting method (for high speeds)

$$\omega = \frac{2\pi / N}{T/n} = \frac{2\pi n}{NT} \text{ (count during a time period } T \text{ is } n\text{); velocity resolution: } \Delta\omega_c = \frac{2\pi}{NT} \, rad/\sec$$

  - Pulse timing method (for low speeds)

$$\omega = \frac{2\pi / N}{m/f} = \frac{2\pi f}{Nm} \text{ (} m \text{ clock counts with clock frequency } f \text{ } Hz\text{)}$$

$$\text{Velocity resolution: } \Delta\omega_t = \frac{2\pi f}{Nm^2} = \frac{N\omega^2}{2\pi f}$$

Hall Effect Sensors

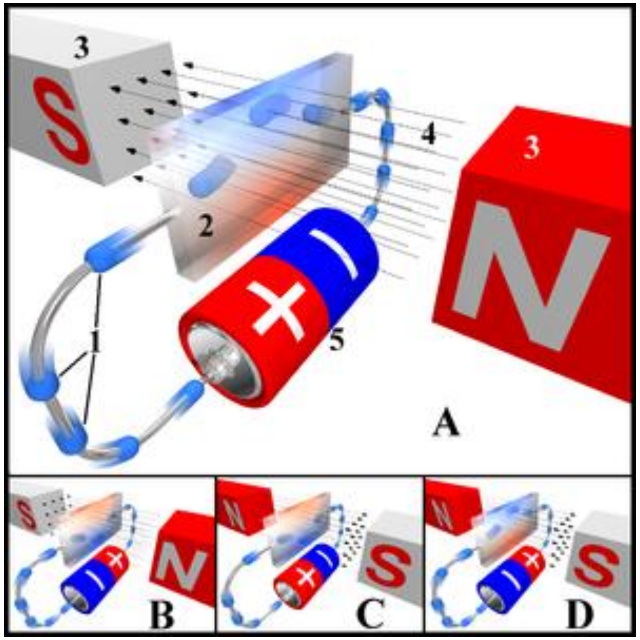
- When an electron moves along a direction perpendicular to an applied magnetic field, it experiences a force, called Lorentz force, acting normal to both directions
- The electrons move in response to this force and the force effected by the internal electric field.
- Electrons subject to the Lorentz force result in an excess surface electrical charge and this results in the Hall voltage, a potential drop across the two sides of the sample

$$|VH| = \frac{IB}{q.ns}$$

I = Current; B = Magnetic field;

$q = 1.602 \times 10^{-19}$ Coulombs; ns = Sheet density

- Uses
  - Thickness of nonferrous materials (1% acc.)
  - Measure the magnetic field
  - Current sensor
  - Position/rotation sensing (tacho, power sensing, ignition firing timing,…)



(source: http://en.wikipedia.org/wiki/File:Hall_effect.png)

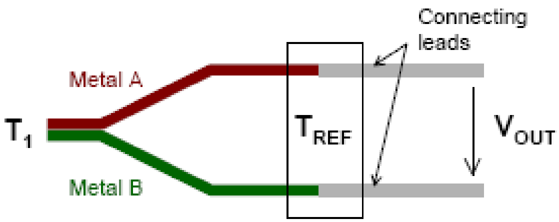
1. Electrons
2. Hall element, or Hall sensor
3. Magnets
4. Magnetic field
5. Power source

Temperature Sensors - 1

- Temperature sensors are in building, chemical plants, engines, appliances, computers, and many other devices requiring temperature monitoring
- We can measure temperature indirectly by measuring pressure, volume, electrical resistance, strain and color

	THERMOCOUPLES	RTD	IC
ACCURACY	Limits of error wider than RTD or IC Sensor	Better accuracy than thermocouple	Best accuracy
RUGGEDNESS	Excellent	Sensitive to strain and shock	Sensitive to shock
TEMPERATURE	-400 to 4200° F	-200 to 1475° F	-70 to 300° F
DRIFT	Higher than RTD	Lower than TC	
LINEARITY	Very non-linear	Slightly non-linear	Very linear
RESPONSE	Fast dependent on size	Slow due to thermal mass	Faster than RTD
COST	Rather inexpensive except for noble metals TCs, which are very expensive	More expensive	Low cost

- Thermocouples
  - Based on the Seebeck effect: joining dissimilar metals at different temperatures produces a voltage
  - Sensitivity: $10 mV/^0C$; Fast response time: 1ms
  - Nonlinear



Temperature Sensors - 2

- Resistance Temperature Detectors (RTDs)
  - Platinum (α =0.0039/) , Nickel (α =0.0068), Copper (α =0.0043) are typically used $R_T = R_0(1+\alpha T)$
  - positive temperature coefficients. Useful for measuring -130^{0}C – 800^{0}C
- Thermistors ("thermally sensitive resistor")
  - formed from semiconductor materials, not metals
    - often composite of a ceramic and a metallic oxide (Mn, Co, Cu or Fe)
  - typically have negative temperature coefficients
  - Nonlinear: $R_T = R_0 \exp\left[\beta\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]$

- Bimetallic Strip
  - A bimetallic strip is made of two ribbons of dissimilar metals bonded together
  - Thermostat (makes or breaks electrical connection with deflection)

$$L = L_0[1+\beta(T - T_0)] \Rightarrow T = T_0 + \frac{L-L_0}{\beta}$$

- pn-junction
  - inexpensive, linear and easy to use
  - limited temperature range (perhaps -50°C to 150°C)

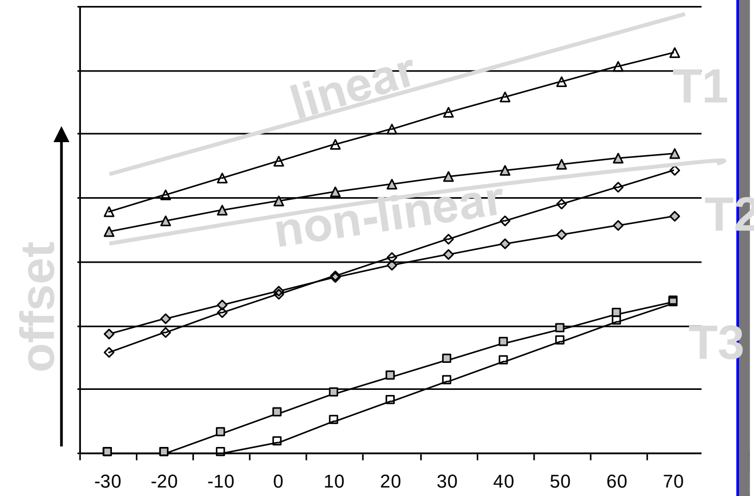
Connecting Sensors to μ-Controller and Network

- Micro-controllers
  - Analog: Many microcontrollers have a built-in A/D (8,12 or 16-bits) and have multi-channel A/D inputs
  - Digital: serial I/O port, synchronize (with clock), asynchronous (no clock), frequency encoded
    - Synchronous: must match byte format, stop/start bits, parity check, etc.
    - Asynchronous: must match baud rate and bit width, transmission protocol, etc.
    - frequency encoded: use timing port, measure pulse width or pulse frequency
- PC/Network
  - DAQ card with analog and digital I/O interfaced through LabView or custom code
  - Synchronous serial communication via serial peripheral interface (SPI)
  - Asynchronous serial communication
    - universal asynchronous receive and transmit (UART): 1 receive line + 1 transmit line. nodes must match baud rate & protocol
    - RS232 Serial Port on PCs uses UART format (but at +/- 12V). can buy a chip to convert from UART to RS232
    - I^2C = Inter Integrated Circuit bus: designed by Philips for TVs, used in several sensors
    - IEEE P1451: Sensor Comm. Standards for different applications

Sensor Calibration

- Sensors can exhibit non-ideal effects
  - **Offset**: nominal output ≠ nominal parameter value
  - **Nonlinearity**: output not linear with parameter changes
  - **Cross parameter sensitivity**: secondary output variation with, e.g., temperature

- Calibration = adjusting output to match parameter
  - analog signal-conditioning
  - look-up table
  - digital calibration
    - $T = a + bv + cv^2$,
      - T= temperature; v=sensor voltage;
      - a,b,c = calibration coefficients



- Compensation
  - remove secondary sensitivities
  - must have sensitivities characterized
  - can remove with polynomial evaluation
    - $P = a + bv + cT + dvT + e\,v^2$, where P=pressure, T=temperature

Summary

1. Analog and Digital Sensors
   - Position, Velocity and Acceleration
   - Temperature
   - Strain, Stress, Force and Torque
   - Pressure and Flow

2. Interfacing
   - Micro-controllers
   - PC/Network