MECH 420
Sensors and Actuators

Presentation Part 6

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Part 6: Analog Sensors and Transducers, Part a (Motion Sensors)

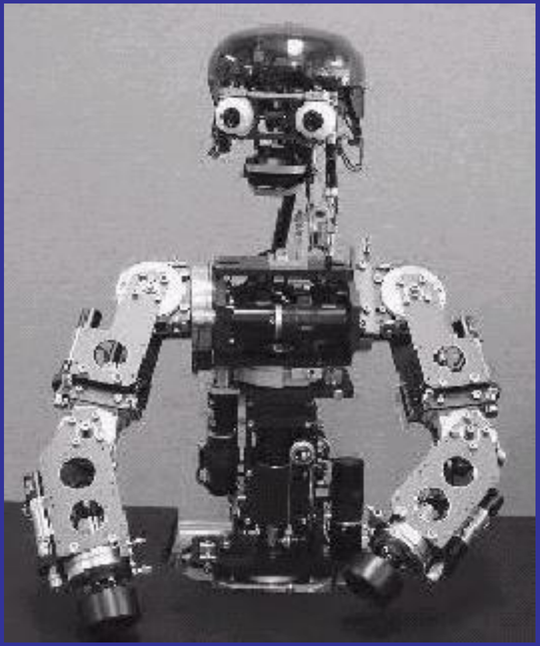
- Resistive
- Variable-inductance
- Eddy-current
- Capacitive
- Piezoelectric

Plan

***Note*: Some concepts have been discussed already. Only illustrative examples are elaborated. You should self-learn others through that knowledge.**

- **Sensor/transducer Applications**
- **Terminology**
- **Sensor Classification and Selection**
- **Motion Sensors (Potentiometer, Variable-inductance Transducers, LVDT, Proximity Sensor, Resolver, Tachometer, Eddy-current Transducers, etc.)**
- **Variable-capacitance Transducers**
- **Piezoelectric Sensors**

Sensors and Transducers



Sensor and Transducer

Measurand

(Typically analog)

Sensor | Transducer

Acquirable/ Transmittable variable

(Typically Electrical)

Example: Piezoelectric Accelerometer

Acceleration

Acceleration is sensed as an Inertia force | Inertia Force → Strain → Electric Charge

Electric Charge/voltage

***Note*: Usually, the term "sensor" or "transducer" is used to denote the entire "sensor/transducer unit." Signal conditioning may be integrated as well.**

A transducer may be "reversible." It may be able to function as both a sensor an actuator. Example?

Sensors and Transducers

Measurand: **Variable that is being measured**

Measurement: **Output/reading of the measuring device**

Two Stages in a Measuring Device:

1. Measurand is “felt” or *sensed*

2. Measured signal is *transduced* (or converted) into the form of sensor output.

***Note* 1:** **Typically sensor “senses” the measurand and automatically converts (transduces) into the sensor output (measurement)**

***Note* 2:** **Terms sensor and transducer are used interchangeably to denote a sensor-transducer unit.**

Sensors

- **Sensor:** Measures (senses) unknown signals and parameters of a plant and its environment
  (Sensors are needed to monitor and "learn" about the system)
- **Useful in:** Process monitoring; testing and qualification; product quality assessment; fault prediction, detection and diagnosis; warning generation; surveillance; controlling a system
- **Sensor System:** May mean, 1. Multiple sensors, sensor/data fusion (one sensor may not be adequate for the particular application) **or,** 2. Sensor and its accessories (signal processing, data acquisition, display, etc.)

Do we measure inputs or only the outputs?

Sensors and Actuators in Engineering Applications

Add more applications to this table

Process	Typical Sensors	Typical Actuators
Aircraft	Displacement, speed, acceleration, elevation, heading, force pressure, temperature, fluid flow, voltage, current, global positioning system (GPS)	DC motors, stepper motors, relays, valve actuators, pumps, heat sources, jet engines
Automobile	Displacement, speed, force, pressure, temperature, fluid flow, fluid level, vision, voltage, current, GPS, radar, sonar	DC motors, stepper motors, valve actuators, linear actuators, pumps, heat sources
Home Heating System	Temperature, pressure, fluid flow	Motors, pumps, heat sources
Milling Machine	Displacement, speed, force, acoustics, temperature, voltage, current	DC motors, ac motors
Robot	Optical image, displacement, speed, force, torque, tactile, laser, ultrasound, voltage, current	DC motors, stepper motors, ac motors, hydraulic actuators, pneumatic actuators
Wood Drying Kiln	Temperature, relative humidity, moisture content, air flow	AC motors, dc motors, pumps, heat sources

Automobile Sensors

Powertrain (Engine & Transmission) →

- Air flow
- Air-fuel ratio
- Camshaft motion
- Coolant fluid level
- Crankshaft motion
- Detonation
- Exhaust Oxygen
- Manifold pressure
- Oil level
- Oil temperature
- Throttle position
- Transmission output speed
- Transmission temperature

Driving Aid →

- Accelerator position
- Antilock braking (ABS)
- Cameras
- Radar/Ultrasonic/ Infrared (parking, object detection)
- Steering rate
- Tactile (haptic-touch)
- Vehicle speed

Safety and Comfort →

- Brake fluid
- Compartment temperature/humidity
- Door position
- Electronics monitoring and diagnosis
- Outside conditions
- Ride comfort (acceleration for active suspension control)
- Tire pressure
- Washer fluid level

Sensing Uses in Control Systems

- Measuring the system outputs for feedback control
- Measuring some types of system inputs (unknown inputs, disturbances, etc.) for feed-forward control
- Measuring output signals for system monitoring, parameter adaptation, self-tuning, and supervisory control
- Measuring input and output signal pairs for experimental modeling of the plant (i.e., for system identification)

Sensor Classes (Types) and Selection

Sensor Classification

(a) Based on Physics/Technology:

Active: Power for sensing does not come from sensed object (comes from external source)

Analog: Output is analog

Digital: Output is digital, pulses, counts, etc.

Electric; Integrated-circuit (IC); Mechanical; Optical

Passive: Power for sensing comes from sensed object

Piezoelectric: Pressure on sensor element generates a charge or voltage

Piezoresistive: Pressure/stress/strain on sensor element changes its electrical resistance

Photoelastic: Stress/strain on the sensor element changes its optical properties

What is the sensor stage and what is the transducer stage in 1. piezo device; 2. photo device?

Sensor Classification (Cont'd)

(a) Based on Physics/Technology (Cont'd)

Broader Classification:

Examples of the three categories?

1. **Resistive**
2. **Capacitive (may include piezoelectric)**
3. **Inductive (may include magnetic)**

***Note*: These categories may represent the majority (e.g., 70% of the sensor market)**

Sensor Classification (Cont'd)

(b) Based on Measurand/Application

Bio-medical: Motion, force, blood composition, blood pressure, temperature, flow rate, urine composition, excretion composition, ECG, EEG, EOG, EMG, respiratory flow rate and sound, pulse, X-ray image, ultrasonic image, oximetry (oxygen in blood)

Chemical: Organic compounds, inorganic compounds, concentration, heat transfer rate, temperature, pressure, flow rate, humidity, pH value, dissolved oxygen, oxidation-reduction potential (water quality)

Electrical/Electronic: Voltage, current, charge, passive circuit parameters, electric field, magnetic field, magnetic flux, electrical conductivity, permittivity, permeability, reluctance

Sensor Classification (Cont'd)

(b) Based on Measurand (Cont'd)

Mechanical: **Force (effort including torque), motion (including position and deflection), optical image, other images (X-ray, acoustic, etc.), stress, strain, material properties (density, Young's modulus, shear modulus, hardness, Poisson's ratio**

Thermo-fluid: **Flow rate, heat transfer rate, infrared waves, pressure, temperature, humidity, liquid level, density, viscosity, Reynolds number, thermal conductivity, heat transfer coefficient, Biot number, image.**

Sensor Selection Steps

(a) Study the application, its purpose, and what quantities (variables and parameters) need to be measured

(b) Determine what sensors are available; what quantities cannot be measured (due to inaccessibility, lack of sensors, etc.)

(c) Match available sensors with the required specifications

If Not Available or Cannot Measure:

1. Estimate using other quantities that can be measured
2. Develop a new sensor for the purpose, with parameters that meet the requirements/specifications.

The overall procedure: "Match" a sensor (its ratings) with the application (requirements/specifications)

Sensor Selection (Cont'd)

Complete the table for a selected application:

Item	Information (Complete)
What parameters or variables have to be measured in your application	
Nature of the information (parameters and variables) needed for the particular application (analog, digital, modulated, demodulated, power level, bandwidth, accuracy, etc.)	
Specifications for the needed measurements (measurement signal type, measurement level, range, bandwidth, accuracy, signal-to-noise ratio, etc.)	
List of available sensors that are needed for the application and their data sheets (ratings)	
Info on signal provided by each sensor (type—analog, digital, modulated, etc.; power level ; frequency range, etc.)	
Type of signal conditioning or conversion needed for the sensors (filtering, amplification, modulation, demodulation, ADC, DAC, voltage-frequency conversion, frequency-voltage conversion, etc.)	
Any other comments	

Sensor Terminology

Sensor/Transducer Terminology

Pure Transducers: **Depend on nondissipative coupling in the transduction stage (no wastage of signal power)**

Passive Transducers (Self-generating Transducers): **Depend on their power transfer characteristics for operation (Use power from the sensed object/measurand; Do not need an external power source).**

Note**: Pure transducers are passive devices. They derive their energy from the measurand => tend to distort (or load) the measured signal**

Active Sensors/Transducers: **Require external power for operation (Do not derive power from measurand; do not depend on power conversion characteristics for their operation)**

Note**: Power refers to that in the immediate transducer stage of the measurand (not the power used in transmission, subsequent signal conditioning/conversion, etc.)**

Active and Passive Transducers

Passive Transducers: Self generating transducers; depend on power transfer characteristics of the sensor (nondissipative coupling) for operation

- **Derive power from the measurand; May not require a separate power source for operation**
- **Tend to distort (or load) the measurand** Why?
- **Simple in design, Robust, Reliable, Less costly** Why?

E.g.: Electromagnetic, thermoelectric, piezoelectric, and photovoltaic

Active Transducers: Do not depend on power conversion characteristics of sensor; does not derive power from measurand; Requires a separate power source for operation

- **E.g., Potentiometer**

Is a thermocouple active or passive?

Perfect Measurement Device

It Possesses Following Characteristics: Discussed before.

1. Output of the measuring device instantly reaches the measured value (**Fast Response**).
2. Transducer output is sufficiently large (**High Gain, Low Output Impedance, High Sensitivity**).
3. Device output remains at the measured value (without drifting or being affected by environmental effects and other undesirable disturbances and noise) unless the measurand (what is measured) itself changes (**No drift, Stable, Robust**).
4. The output signal level of the transducer varies in proportion to the signal level of the measurand (**Static Linearity**).
5. Connection of a measuring device does not distort the measurand itself (**Loading effects are absent and Impedances are matched**).
6. Power consumption is small (**High Input Impedance**).

Commercial Sensors

Motion Sensors: Potentiometer, differential transformer (LVDT), magnetostrictive (temposonic) displacement sensor, magnetic induction proximity sensor, tachometer, resolver, synchro, gyro, piezoelectric accelerometer, laser ranger, ultrasound ranger

Force/Torque Sensors: Semiconductor strain gauge, motor current sensor

Fluid Flow Sensors: Coriolis velocity meter, pitot (pee-toh) tube, rotameter, orifice flow meter

Pressure Sensors: Manometer, Bourdon tube, diaphragm type

Temperature Sensors: Thermocouple, thermistor, resistance temperature detector (RTD)

Current Sensors: Measure magnetic field (e.g., Hall effect) or voltage across a resistor, due to current

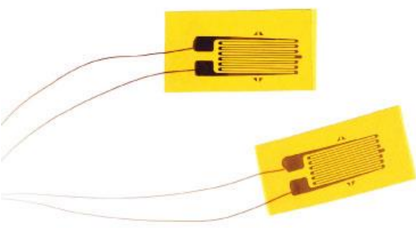
Sensor Examples

What do these measure?

Potentiometers (linear, rotary)

Piezoelectric Accelerometers

Resolvers



Strain Gauges

LVDTs

Thermocouples

Tachometers

Important Sensor Information

1. Measured quantity (measurand)
2. Sensor output (measurement)
3. Physical principle (including, whether pure, passive, active)
4. Signal conditioning, modification, conversion requirements/ technologies
5. Applications (and needed specifications/ratings for an application)

Collect this info for about 10 sensors—say those mentioned in the ppt notes

Analog Motion Transducers

Motion Transducers

Motion:

- **Displacement (position, distance, proximity, size, gage, etc.)**
- **Velocity**
- **Acceleration**
- **Jerk**

***Note*: Each variable = time derivative of preceding one**

***Note*: Direct relationship may not exist between a measuring device and a measured variable**

Example: Strain gauge adapted to measure displacements, using *front-end auxiliary sensor element* (e.g., cantilever or spring)

***Note*: Same measuring device may be used to measure different variables through appropriate data interpretation techniques (e.g., integration, differentiation)**

In principle, a force sensor can be used to sense: acceleration, velocity, or displacement, depending on front-end auxiliary element:

Or, the converse, to get force by sensing motion.

1. **Inertia element: Converts acceleration into force**
2. **Damping element: Converts velocity into force**
3. **Spring element: Converts displacement into force**

Note the purpose of the "front end auxiliary device" in each case.

Challenges/Limitations of Sensor Signal Conversion

Displacement, Velocity, Acceleration, Jerk: Related through integration or differentiation

In theory, measure only one variable and use analog/digital processing to get another motion variable

Feasibility Limitation of the Approach:

1. **Nature of measured signal (steady, highly transient, periodic, narrow/broad-band), etc.**
2. **Required frequency content of processed signal (frequency range of interest)**
3. **Signal-to-noise ratio (SNR) of the measurement**
4. **Available processing capabilities (e.g., analog or digital processing, limitations of digital processor and interface: speed of processing, sampling rate, buffer size, etc.)**
5. **Controller requirements and nature of plant (e.g., control bandwidth, operating bandwidth, time constants, delays, complexity, hardware limitations)**
6. **Required task accuracy (processing requirements, hardware costs depend on this)**

Example: Differentiation is unacceptable for noisy and high-frequency narrow-band signals. Costly signal-conditioning hardware may be needed for pre-preprocessing.

Rule of Thumb:

Problems with "numerical" differentiation and integration"?

Low-frequency applications (~ 1 Hz): Use displacement measurement

Intermediate-frequency applications (< 1 kHz): Use velocity measurement

High-frequency motions with high noise levels: Use acceleration measurement

Rule of thumb is not strict!

Engineering Applications of Motion Sensing

- **Manufacturing:** Rotating speed of work piece and feed rate of tool are measured to control machining operations
- **Robotics:** Displacements and speeds (angular, translatory) at joints (revolute and prismatic) of robot to control the end-effector trajectory
- **Transportation:** Acceleration and jerk measurements are used for active suspension control of vehicles (also see, control of self-driven vehicles)
- **Power Generation Plants:** Angular speed to monitor and control rotating machinery (turbines, pumps, compressors, motors, and generators)
- **Machine Health Monitoring (MHM):** Proximity sensors and accelerometers are commonly used in machine protection systems for:
  - condition monitoring; fault prediction, detection, diagnostic; and on-line (often real-time) control of large and complex machinery
- **Process Industry:** Displacement measurements are used for:
  - valve control in process applications, plate thickness in steel rolling mills (product quality control)

Motion Transducer Types

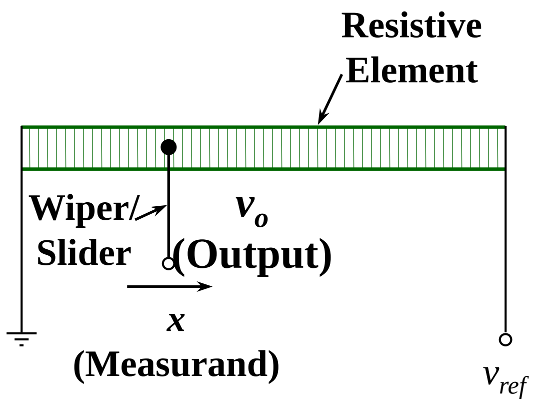
- **Potentiometers (resistively coupled devices)**
- **Variable Inductance Transducers (electromagnetically coupled devices)**
- **Eddy Current Transducers**
- **Variable Capacitance Transducers**
- **Piezoelectric Transducers**

Resistive Sensor: Potentiometer (Pot)

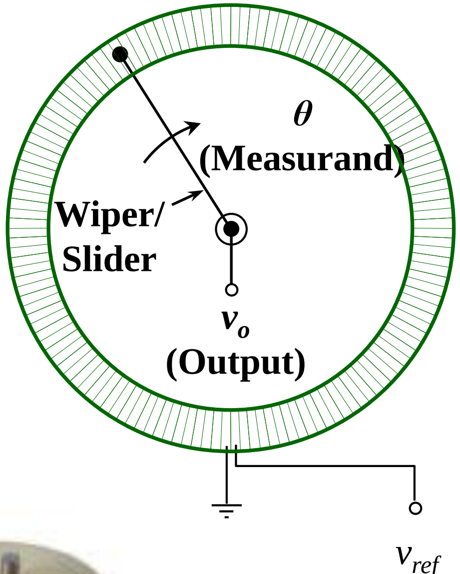
Potentiometers

Uniform coil of wire or a film of high resistive material – carbon, platinum, conductive plastic, etc.

Translatory (Linear) for Rectilinear Motions

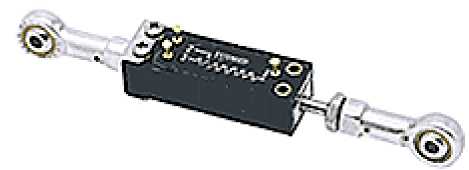


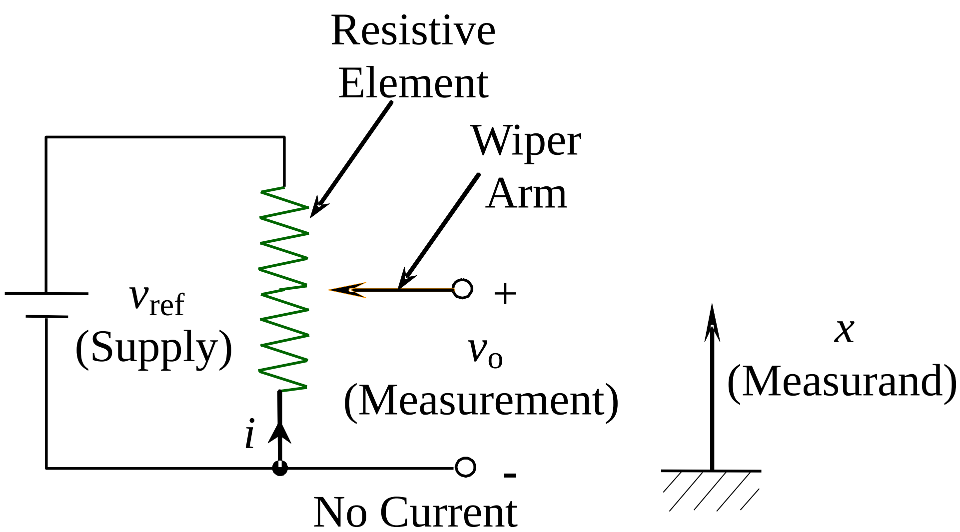
Rotatory (Rotary) for Angular Motions

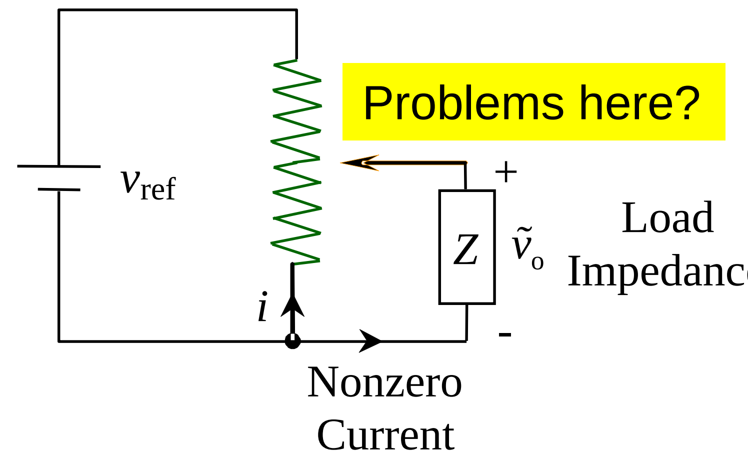


Linear Potentiometer

Resistance is proportional to the length of the wire or film







Slider displacement x is proportional to the output voltage

$$v_o = kx$$

***Note*: This relationship is valid only if the o/p terminals are open circuit (no current)**

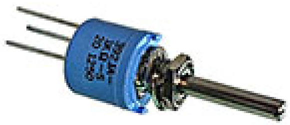
Potentiometer Characteristics

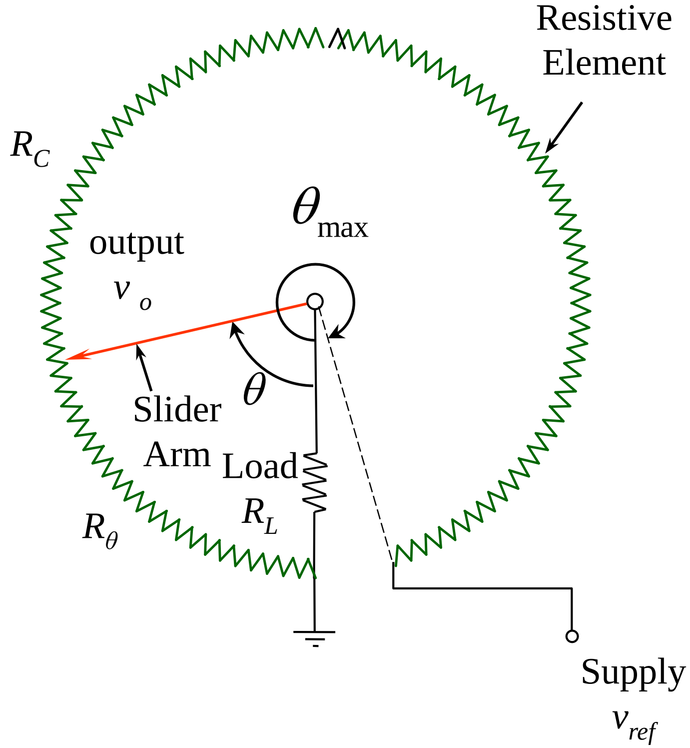
- Output voltage drops when a load with finite impedance is connected
- Loading effect ➔ linear relationship is not valid
- Loading also affects supply (reference) voltage
- To minimize loading effects use:
  - Regulated/stabilized power supply with low output impedance
  - Signal conditioning circuitry with high input impedance
- High element resistance ➔ reduced power dissipation; less thermal effects (Shortcoming: Requires higher output impedance ➔ increased loading nonlinearity error

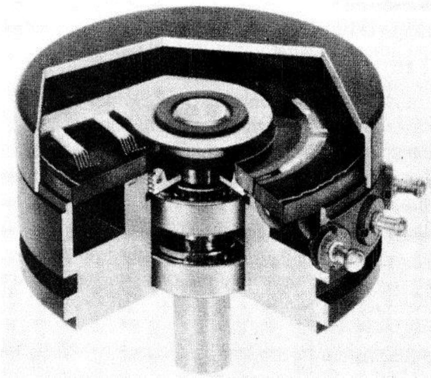
Why?

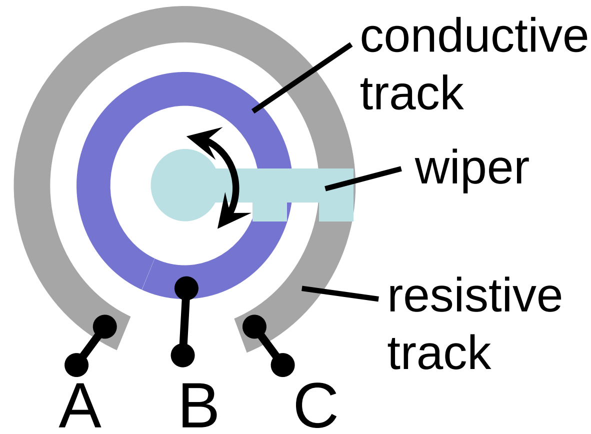
- Pot resistances can vary from low resistance 10Ω to high resistance 1 MΩ Conductive plastic can provide high resistances (100 Ω/mm) and less friction (low mechanical loading), reduced wear, reduced weight, and increased resolution

Rotary Potentiometer









Conductive Plastic Potentiometer

Current balance at slider contact point:

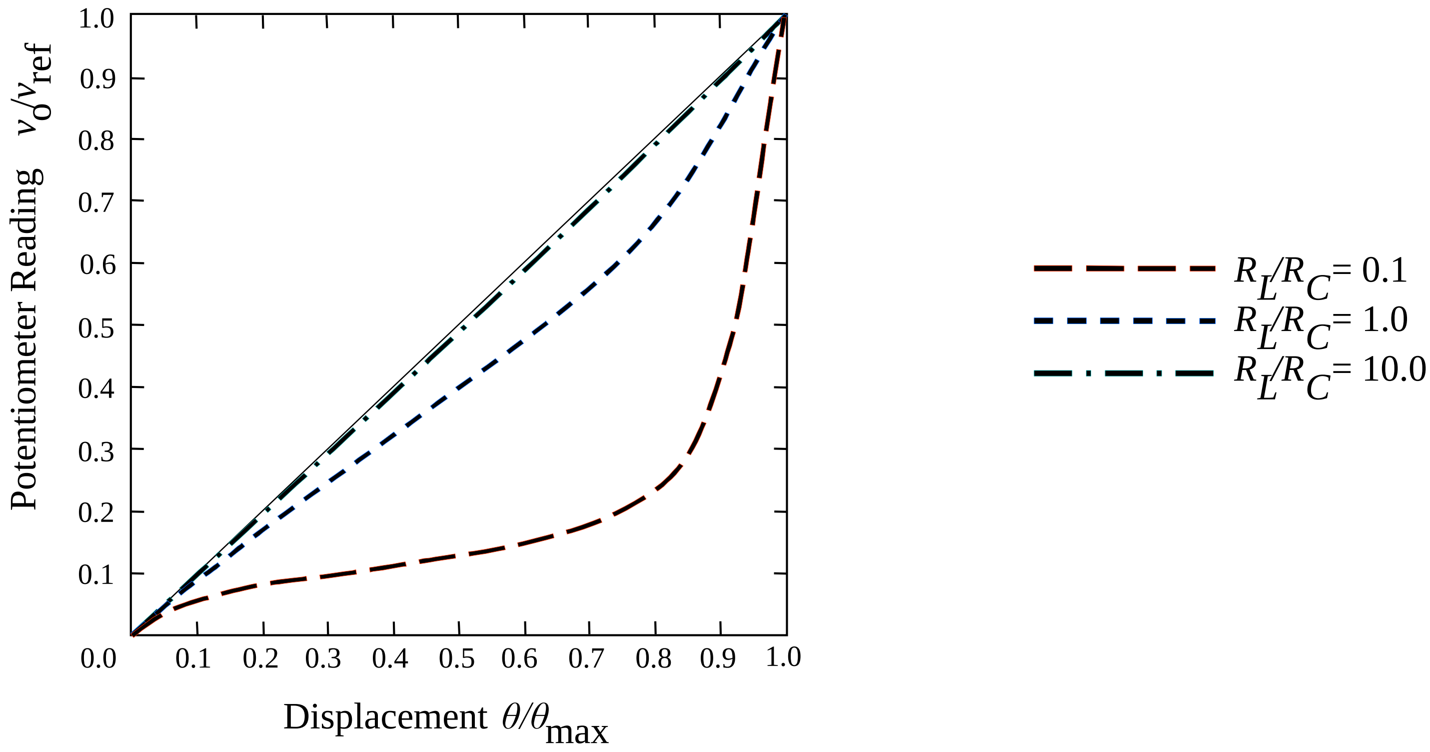
$$\frac{v_{ref} - v_o}{R_c - R_\theta} = \frac{v_o}{R_\theta} + \frac{v_o}{R_L}$$

For uniform coil: $R_\theta = \dfrac{\theta}{\theta_{max}} R_c$

$$\frac{v_{ref} - v_o}{1 - \theta/\theta_{max}} = \frac{v_o}{\theta/\theta_{max}} + \frac{v_o}{R_L/R_c}$$

$$\frac{v_o}{v_{ref}} = \left[\frac{(\theta/\theta_{max})(R_L/R_C)}{\left(R_L/R_C + (\theta/\theta_{max}) - (\theta/\theta_{max})^2\right)} \right]$$

Pot Characteristics (Loading Nonlinearity)



- **For low values of R_L/R_C , loading error is high (🡐use only a small segment of the curve of θ/θ_{max} , or use "nonlinear" calibration curve)**

- **Good accuracy is possible for R_L/R_C > 10 ➔ Increase R_L/R_C (increase load impedance, reduce coil impedance)**

Loading Nonlinearity

Loading nonlinearity error:

$$e = \frac{\left(v_o / v_{ref} - \theta / \theta_{\max}\right)}{\theta / \theta_{\max}} 100\%$$

Loading nonlinearity error in a potentiometer at $\theta/\theta_{\max} = 0.5$	
Load Resistance Ratio R_L / R_C	**Loading Nonlinearity Error (*e*)**
0.1	-71.4%
1.0	-20%
10.0	-2.4%

***Note*: If load resistance is small, a voltage follower may be used**

Performance of Potentiometer

Limitations:

1. The force needed to move the slider (against friction and arm inertia) is provided by the displacement source => mechanical loading => distorts measured signal
2. High-frequency (or highly transient) measurements are not feasible because of such factors as slider bounce, friction and inertia resistance, electrical “arcing” and induced voltages in the wiper arm and primary coil
3. Variations in the supply voltage cause error
4. Electrical loading error can be significant if the load resistance is low
5. Resolution is limited by the number of turns in the coil and by the coil uniformity. This will limit small-displacement measurements (not with conductive plastics)
6. Wear, heating up (with associated oxidation) and electrical “arcing” in the coil or film, and slider contact cause accelerated degradation.

Advantages:

1. They are robust, simple, and relatively inexpensive.
2. Provide high-voltage (low-impedance) output signals, requiring no amplification in most applications. Impedance can be varied simply by changing the coil resistance and supply voltage.

Sensitivity

Potentiometer sensitivity = change in output signal (Δv_0) associated with a small change in measurand ($\Delta\theta$):

$$S = \frac{\Delta v_0}{\Delta \theta}$$

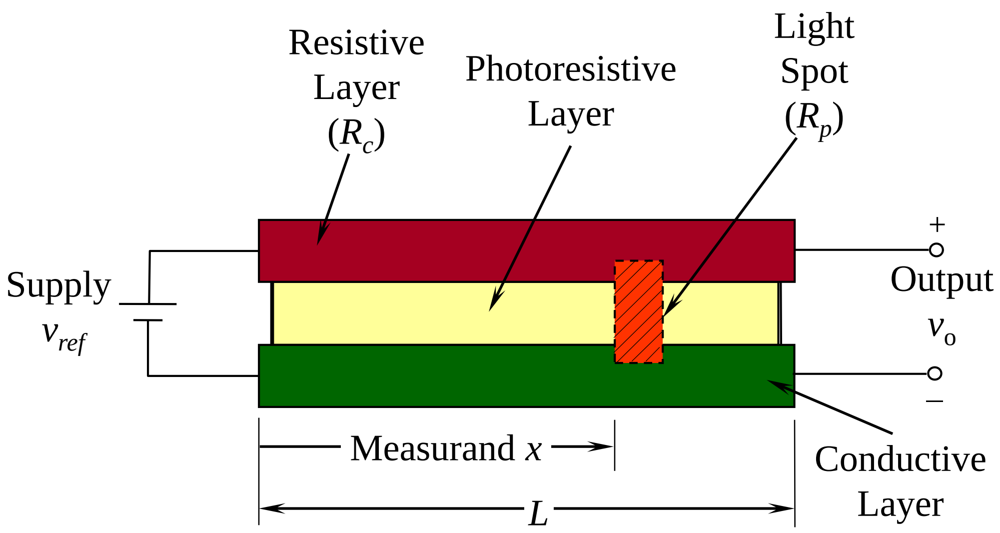
In the limit:

$$S = \frac{\partial v_0}{\partial \theta}$$

Exercise: Determine an expression for sensitivity of a rotary pot

Also, properly nondimensionalize it

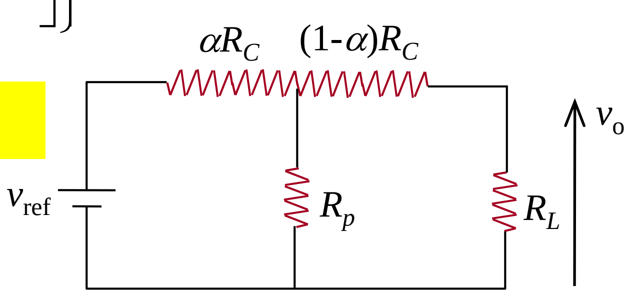
Optical Potentiometer



$$\frac{v_o}{v_{ref}}\left\{\frac{R_c}{R_L}+1+\frac{x}{L}\frac{R_c}{R_p}\left[\left(1-\frac{x}{L}\right)\frac{R_c}{R_L}+1\right]\right\}=1$$ Prove

Note: $\alpha = x/L$

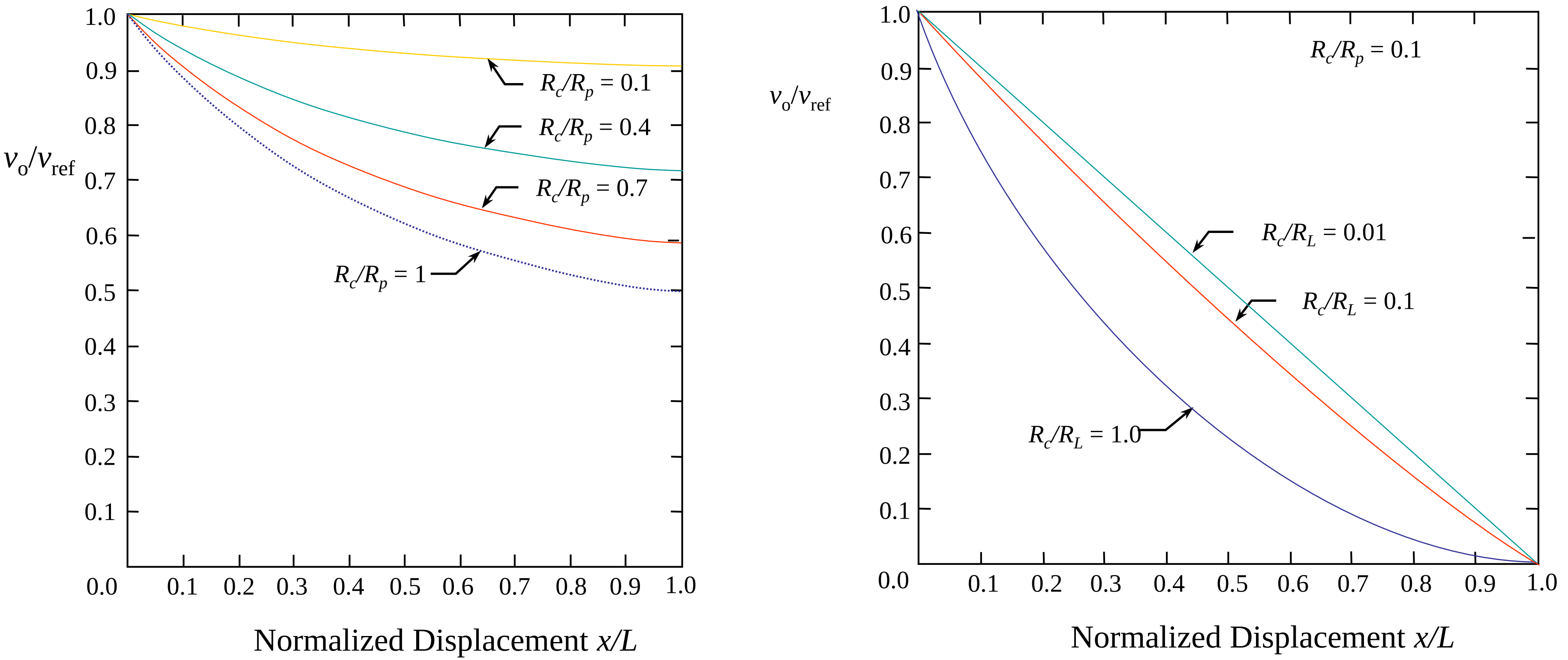
Equation when $R_L \rightarrow \infty$?



Optical Potentiometer Characteristics

For open-circuit; infinite load resistance

Obtain an expression for direct sensitivity. Nondimensionalize it. Make some observations.



Note**: Optical potentiometer becomes more linear for high photo-resistance and high load resistance; but never quite linear even for very high load resistance (prove)**

How would you linearize it?

Resolution

For coil type pots (*N* turns):

Resolution $$r = \frac{1}{N} \times 100\%$$

- **Resolutions better than 0.1% (1000 turns) are available with coil potentiometers**
- **Very high resolutions (infinitesimal) are possible with conductive plastic resistive film potentiometers**

Variable-inductance Transducers

Variable-Inductance Transducers

Employ the principle of electromagnetic induction.

Electromechanical devices coupled by a magnetic field.

Three Primary Types:

Carefully learn these terms/definitions.

1. **Mutual-induction transducers**
2. **Self-induction transducers**
3. **Permanent-magnet transducers.**

Variable-reluctance Transducers: Use non-magnetized ferromagnetic medium to alter reluctance (magnetic resistance) of flux path (magnetic circuit). They are also variable-inductance transducers

***Note*: Some mutual-induction transducers and most self-induction transducers are of this type.**

***Note*: Permanent-magnet transducers are not variable-reluctance transducers.**

Inductance, Reactance and Reluctance (Self-study)

Magnetic flux linkage $\phi = Li$ **; Units: weber (Wb); Depends on magnetic flux density, number of turns in coil, and coil area (not wire area)**

Involves some basic electrical engineering knowledge (electro-magnetic).

i **= current generating magnetic field; Units: amperes (A)**

L **= inductance; Units: Wb/A or henry (H)**

Induced voltage: Electromotive force (emf) $v = L\dfrac{\mathrm{d}i}{\mathrm{d}t}$

Reactance = reactive impedance of inductance = $X = Lj\omega$ **Units: Ohm (Ω)**

Permeability $\mu = B/H$ **= [Magnetic flux density *B*; Units: tesla or T; weber per square meter or Wb/m^2]/[Magnetic field strength *H*; Units: ampere.turns per meter or At/m] = *L/l* = Inductance per unit length; Units: tesla.meter per ampere (T.m/A) or henry per meter (H/m)**

➔ measure of easiness magnetic field passage

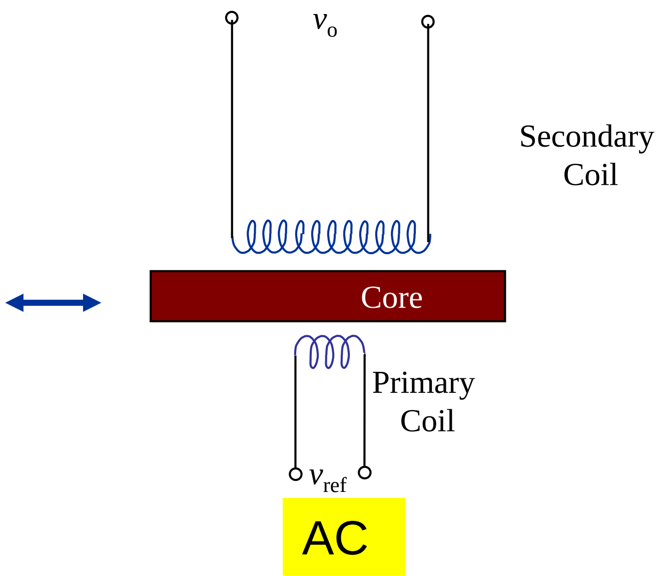
Relative permeability = permeability wrt free space $\mu_r = \mu / \mu_o$ **;** $\mu_o = 4\pi \times 10^{-7} = 1.257 \times 10^{-6}$ H/m

Reluctance = magnetic resistance of a magnetic circuit segment $\Re = \dfrac{l}{\mu A}$

l **= length, *A* = area of X-section of magnetic circuit; Units: "turns per henry" (t/H) or "ampere.turns per weber" (At/Wb); inversely proportional to inductance ➔ measured using an inductance bridge**

Inverse of reluctance = Permeance.

Mutual Induction Transducers E.g., Differential Transformer

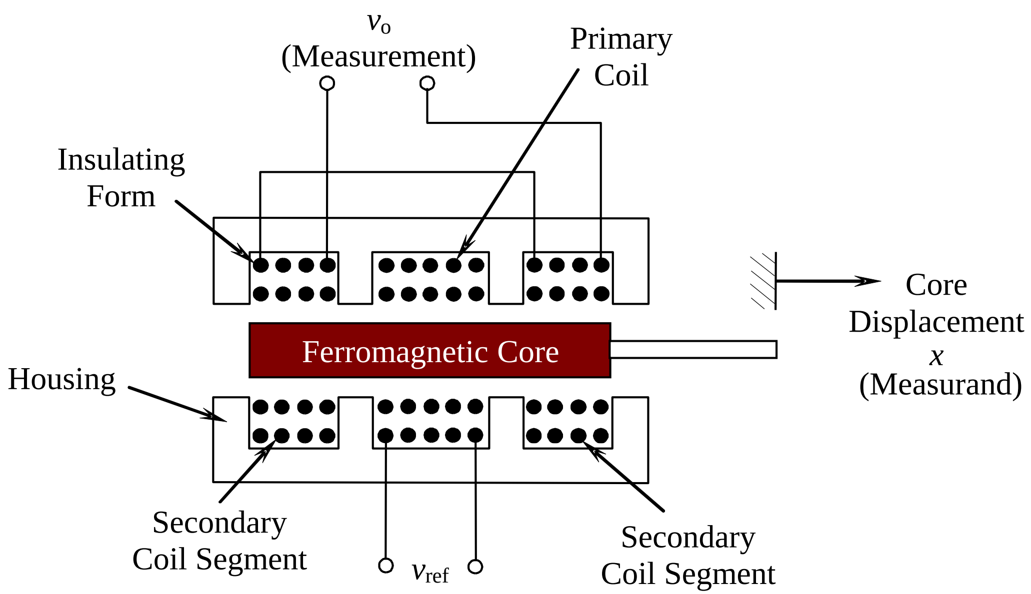


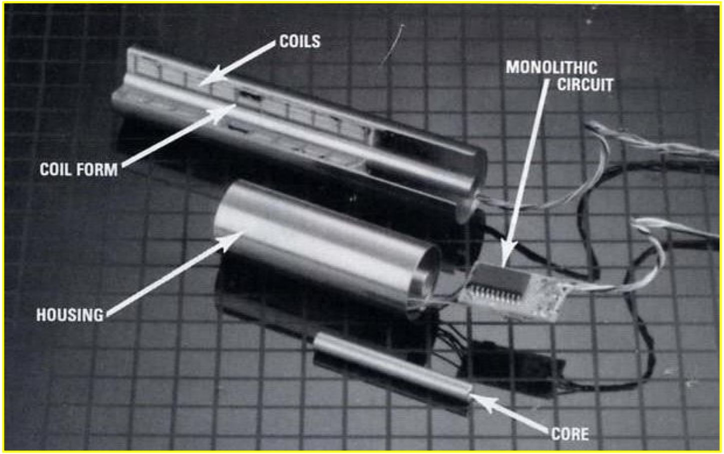
- **AC excitation in primary winding induces AC voltage in secondary winding**
- **Amplitude of induced voltage depends on flux linkage between two coils**

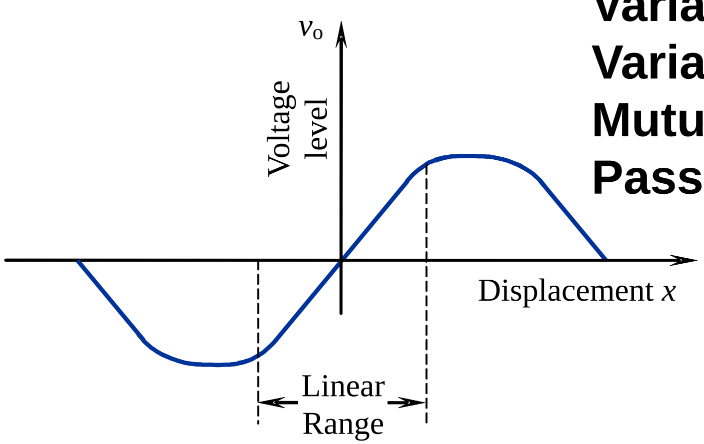
In mutual induction transducers change in flux is effected by:

- **Moving a ferromagnetic material in flux path (e.g., LVDT, RVDT, mutual induction proximity probe)**
- **Moving one coil with respect to the other (e.g., resolver, synchro-transformer, ac induction tachometer)**

Linear Variable Differential Transformer (Transducer), LVDT



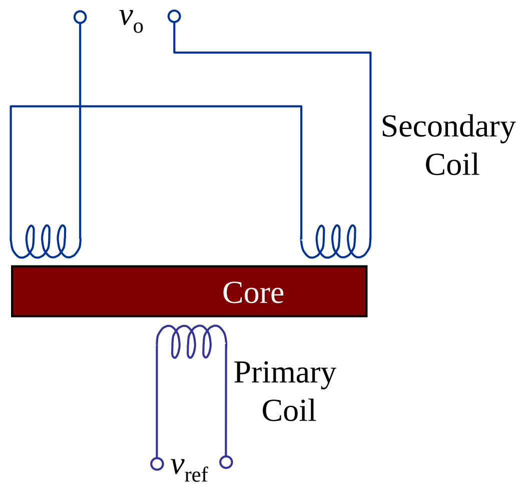




It is a:

Variable-inductance transducer
Variable-reluctance transducer
Mutual-induction transducer
Passive transducer

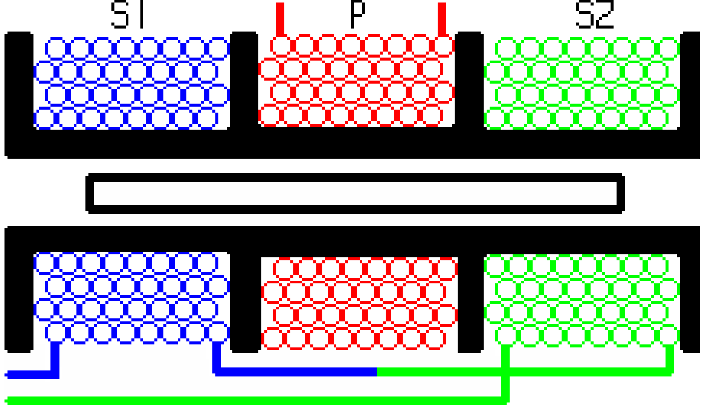
LVDT Operation

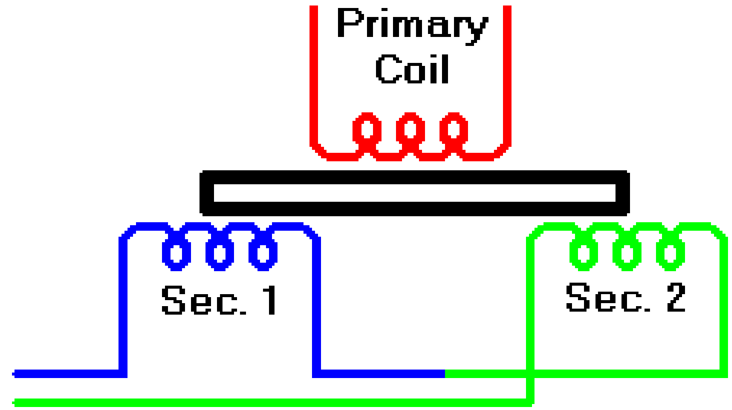


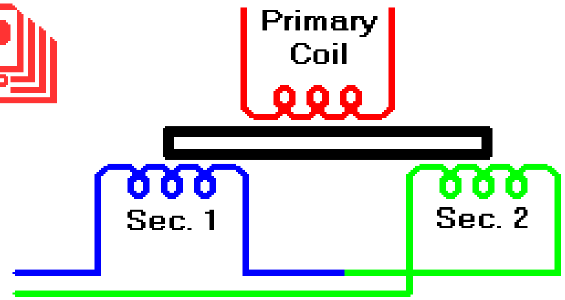
- **When core moves, reluctance of flux path changes the amount of flux linkage**
- **Two secondary windings are in series opposition ➔ When the core is at center, output = zero (null position)**
- **In linear operating range, output voltage $\propto$ core displacement**
- **Provides both magnitude and direction. Direction is obtained:**

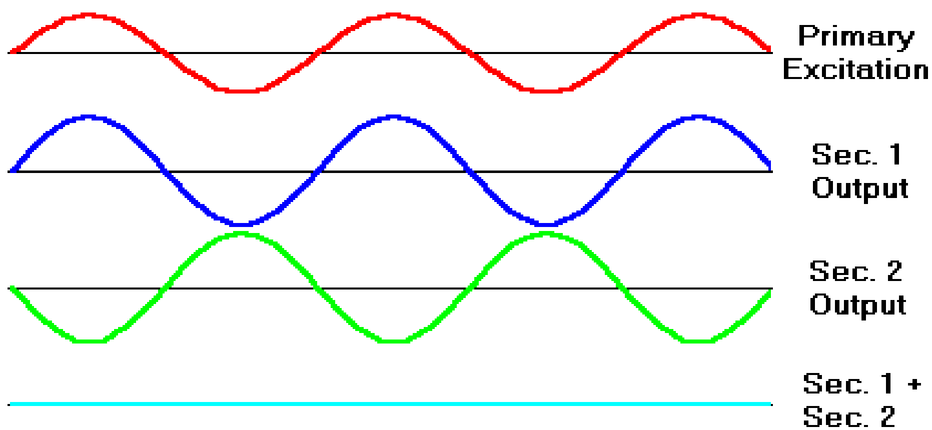
  (a) By demodulating the output signal,

  (b) or From phase angle of output signal
- **For accurate measurement of transient motions: Make the reference (carrier) signal frequency $\approx$ 10 times larger than the largest frequency of interest**

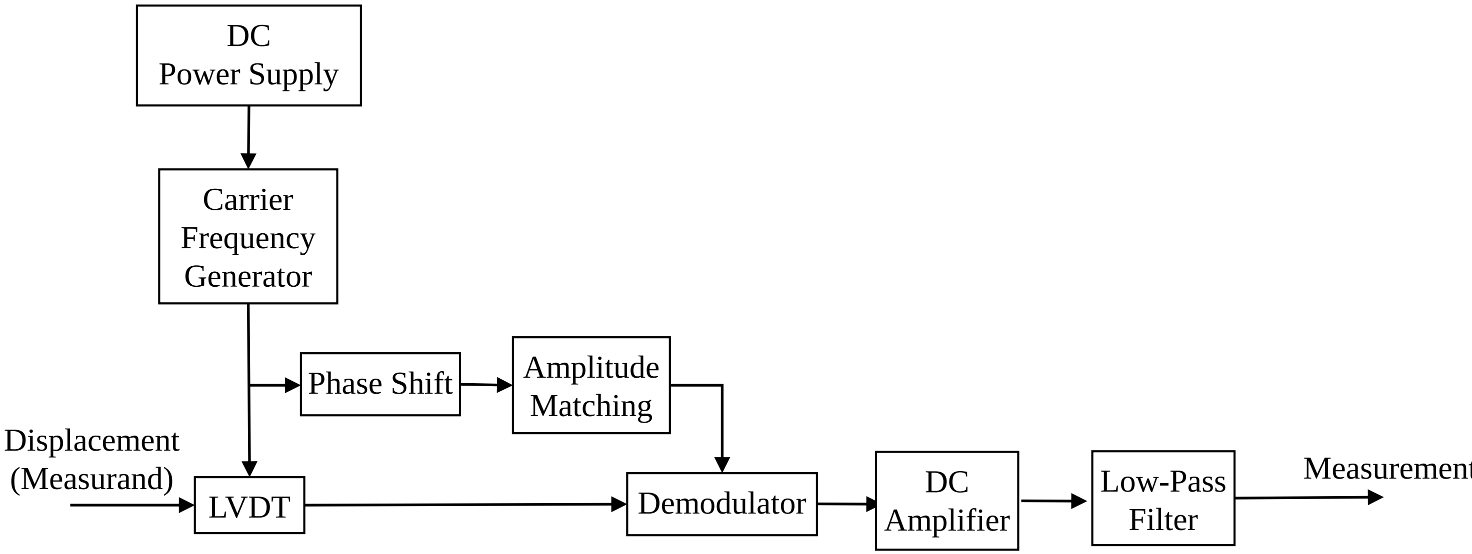

S1
P
S2


Primary Coil
Sec. 1
Sec. 2


Primary Coil
Sec. 1
Sec. 2

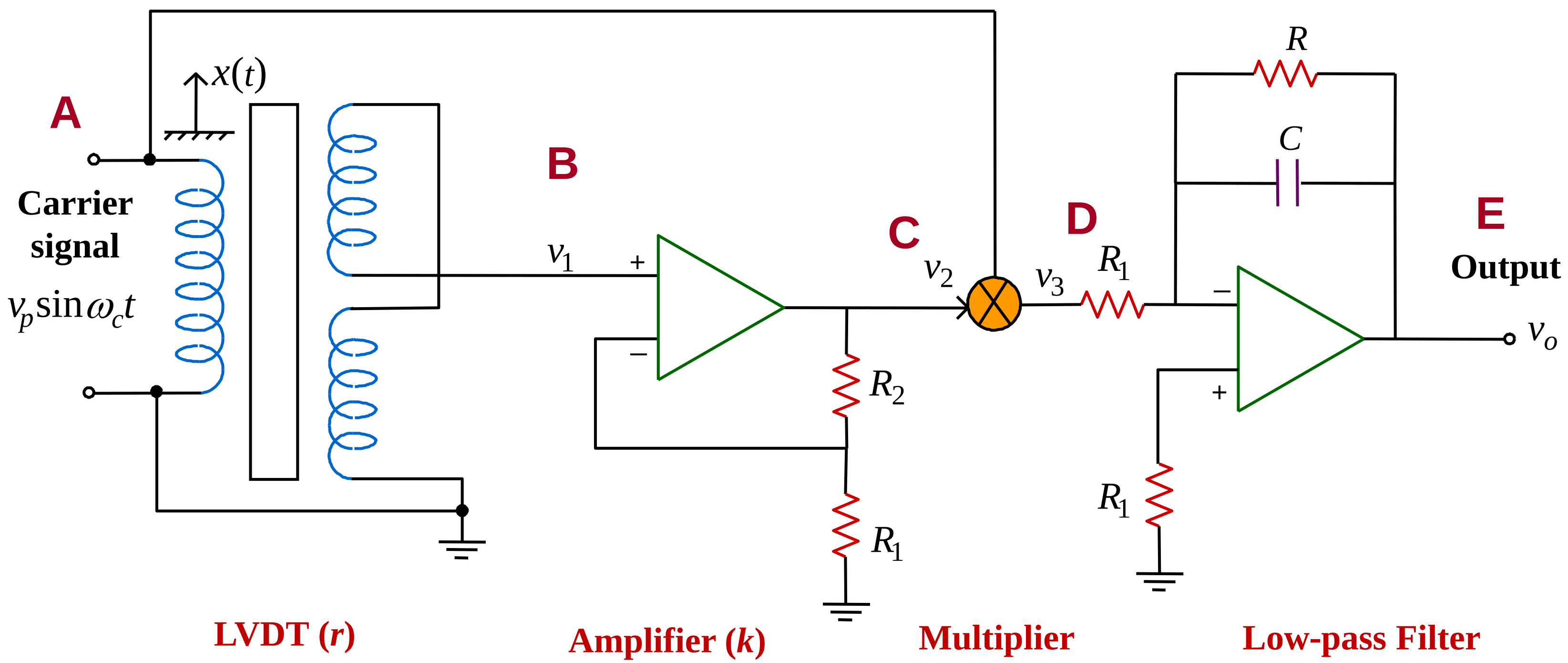

Primary Excitation
Sec. 1 Output
Sec. 2 Output
Sec. 1 + Sec. 2

Signal Conditioning/Demodulation



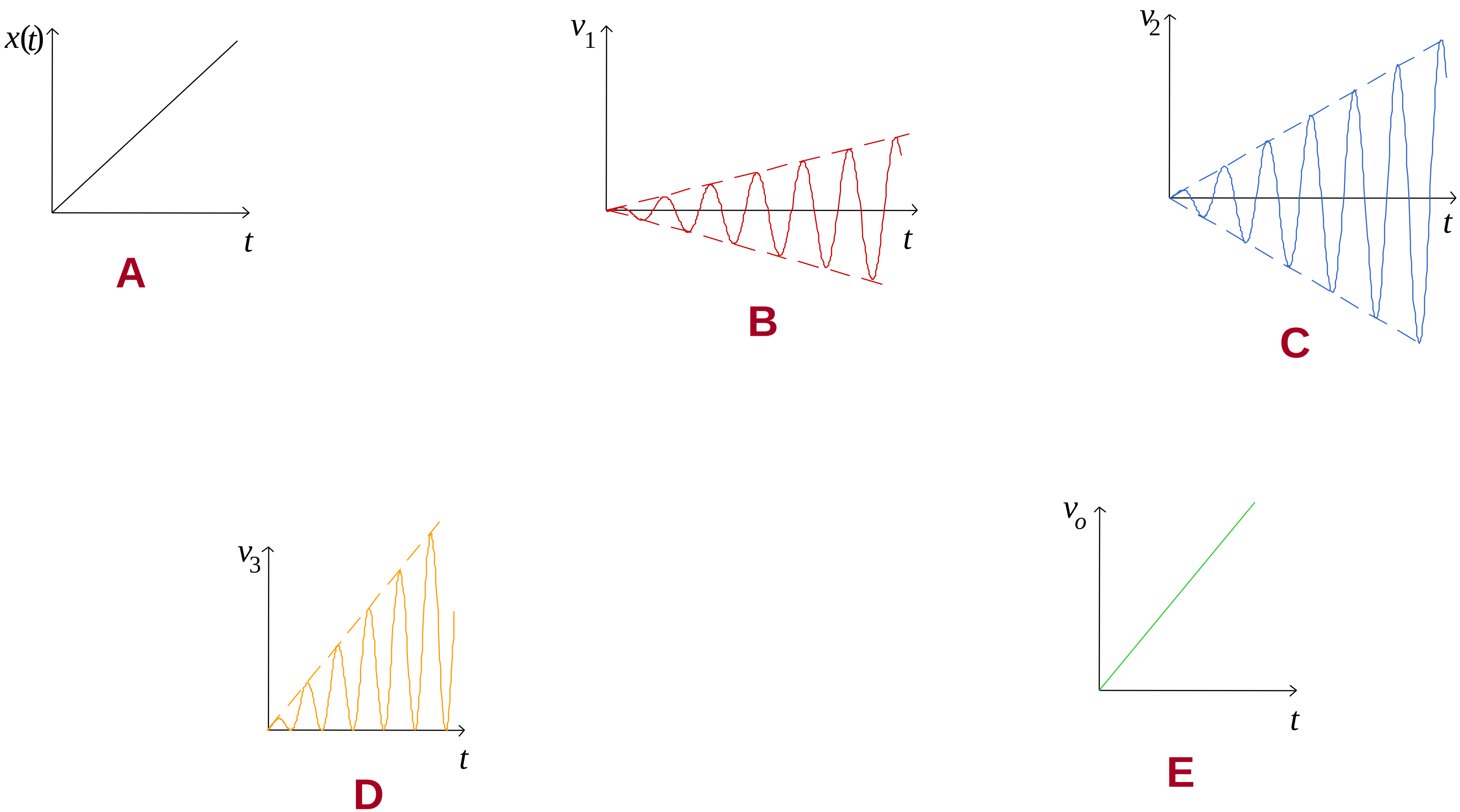
- **Carrier frequency component is rejected from output signal by: 1. Comparing it with a phase-shifted and amplitude adjusted version of the reference signal; or 2. by “demodulation” (see next slide)**
- **Differential transformers with built in signal conditioning are commonly available today**
- **DC differential transformers have built in oscillators to generate carrier signal**
- **Supply voltage $\sim$ 25V; Sensor output voltage $\sim$ 5V.**

LVDT Signal Conditioning/Demodulation



$$v_3 = \frac{{v_p}^2 rk}{2} x(t)\left[1 - \cos 2\,\omega_c t\right]$$

Signals at Various Stages of LVDT Demodulation



A: Measurand; B: “Amplitude modulated” output; C: Amplified signal; D: Product signal (*Note*: Positive, due to “square”); E: Low-pass filtered output.

Advantages of LVDT

Note: Passive device

1. **Noncontacting device: no frictional resistance. Near-ideal electromechanical energy conversion and light-weight core => very small resistive forces. Hysteresis (both magnetic hysteresis and mechanical backlash) is negligible**
2. **Low output impedance ~ 100 Ω. (Signal amplification is not usually needed beyond what is provided by the conditioning circuit)**
3. **Directional measurements (positive/negative) are obtained**
4. **Available in small sizes (e.g., 2 mm long with stroke of 1 mm)**
5. **Simple and robust construction (inexpensive and durable)**
6. **Fine resolution (theoretically, infinitesimal resolution; practically, much better than a coil potentiometer)**

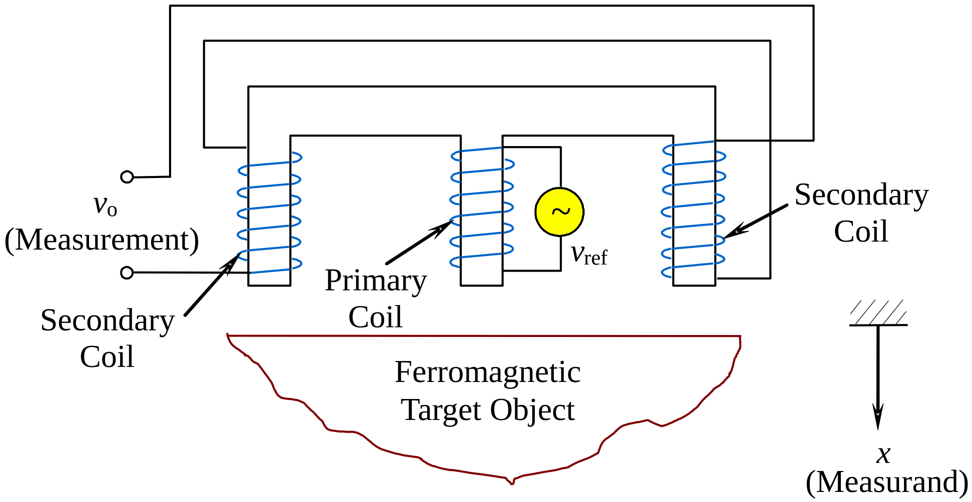
Rate Error

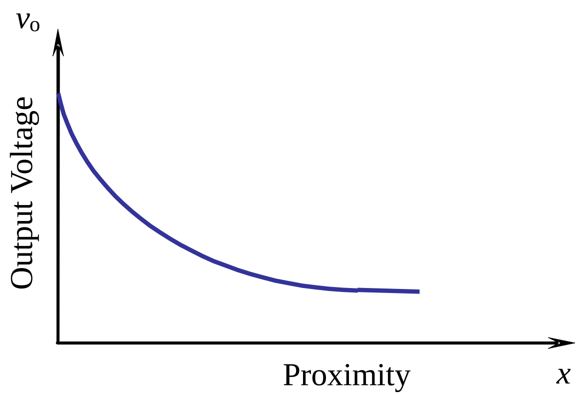
- **Induced voltage is generated through rate of change of magnetic flux**
- **Displacement measurements are distorted by velocity; Velocity measurements are distorted by acceleration**
- **For the same displacement, transducer reading will depend on the velocity at that displacement**
- **This error is proportional to:**

  (Cyclic velocity of core)/(Carrier frequency)
- **Rate error can be reduced by increasing carrier frequency (Good Ratio = 5). Note: This is required also for accurate transient measurements (see "demodulation")**

***Note*: For LVDT, cyclic frequency =** $\dfrac{\text{Maximum speed of operation}}{\text{Stroke of LVDT}} = \omega_o$

Mutual Induction Proximity Sensor





Usage of Mutual Induction Proximity Sensor

Generally used to measure:

- **Transverse displacements (but can sense axial motions too, but limited range)**
- **Small displacements (nonlinear)**
- **Presence or absence (i.e., two-state, e.g., limit switch)**

Mechanical loading is negligible (non contacting)

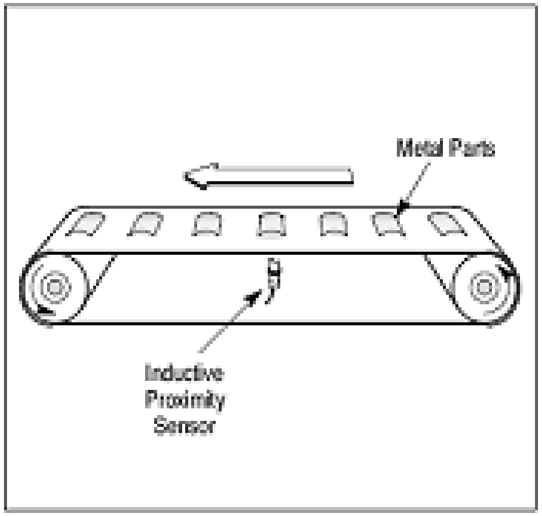
Applications:

- **Robotic welding: Measurement and control of gap between torch head and work surface**
- **Angular Speed Measurement: Counting number of rotations or tooth passing per unit time**
- **Object Detection: Bottling plant to check whether the lid is placed**
- **Proximity/Vibration Measurement: Machine health monitoring**

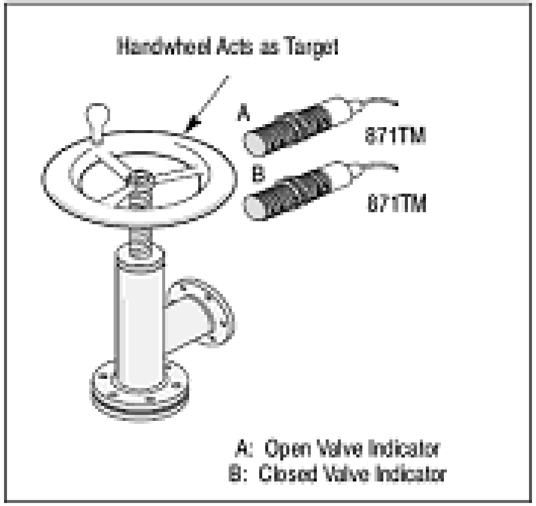
Any others?

Proximity Sensor Applications

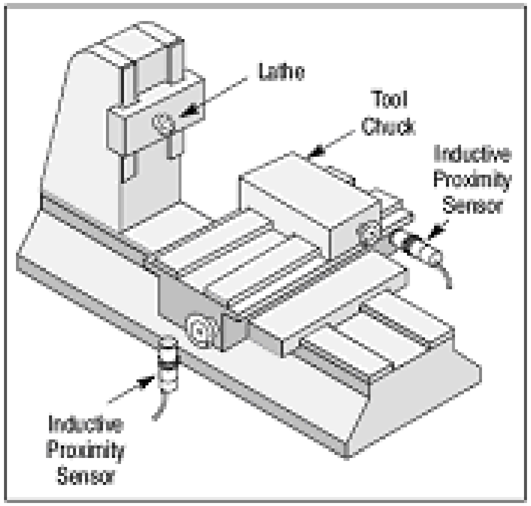
Conveyor Belts



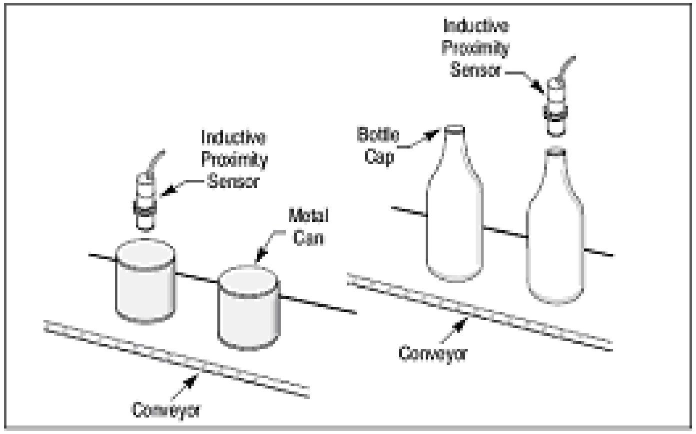
Petroleum Industry—Valve Position



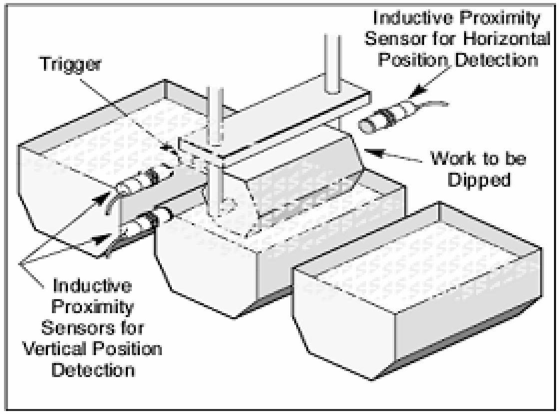
Machine Tools



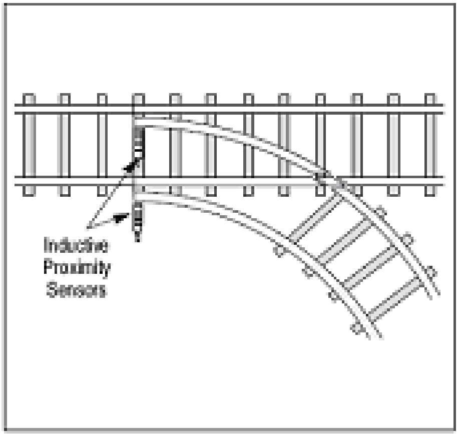
Food Industry



Plating Line



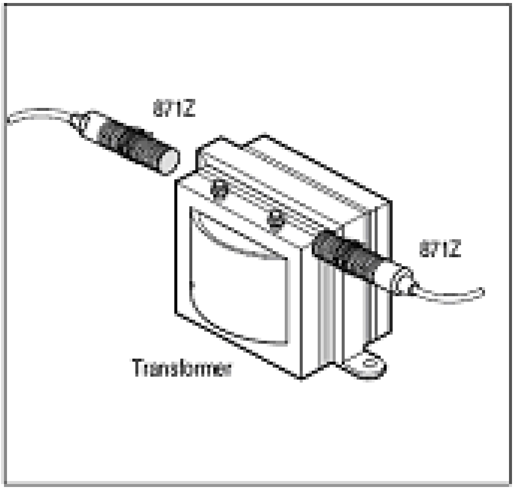
Railroad Yard Position Sensing



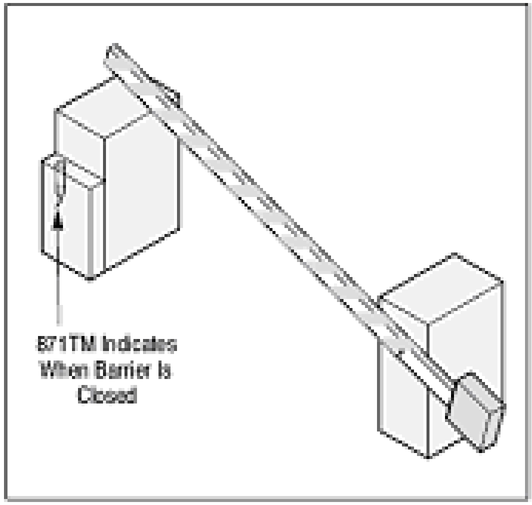
Proximity Sensor Applications (Cont'd)

What is a bush?

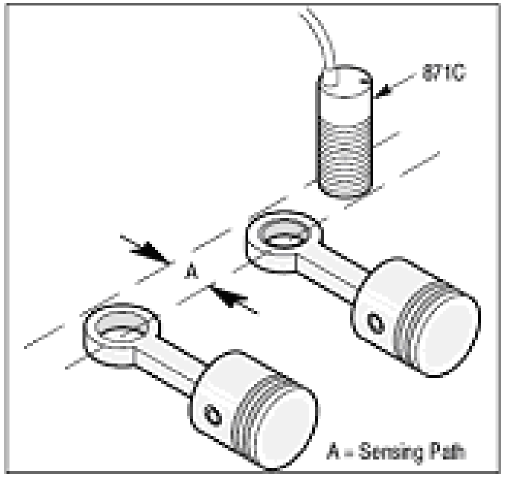
Nut Placement on Transformer



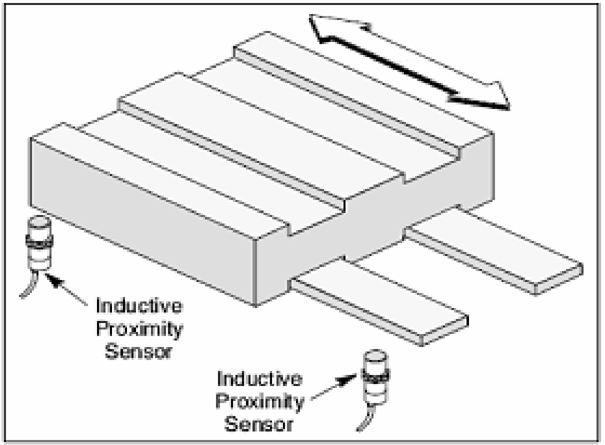
Closed Barrier Indicator



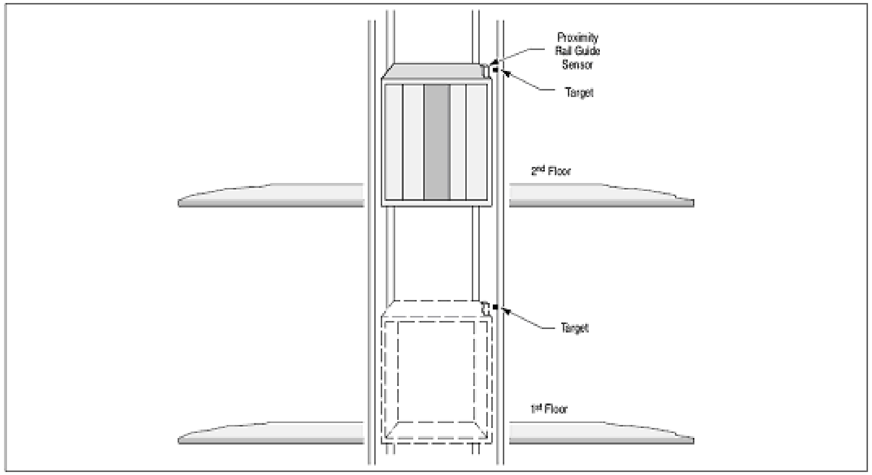
Detect Presence of Bushing in Piston



Grinding Machines



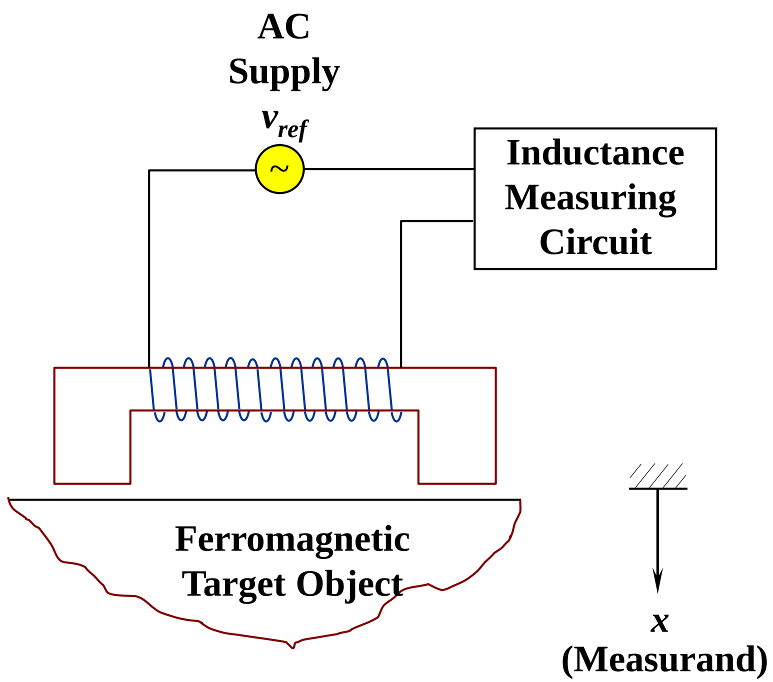
Elevator Positioning



Self-Induction Transducers

- Single coil (self-induction)
- Coil is activated by ac supply ➔ Magnetic flux links with the same coil
- Sensing Principle: Amount of flux linkage (self-inductance) is varied by moving ferromagnetic object (target object)

Out of mutual induction and self-induction transducers, which one do you prefer? Why?



Self-Induction Proximity Sensor

Questions: Give Yes or No Answers

(a) Potentiometer is an active sensor:

(b) LVDT is an active sensor:

(c) Potentiometer (regular) introduces negligible mechanical loading:

(d) LVDT is a non-contact sensor:

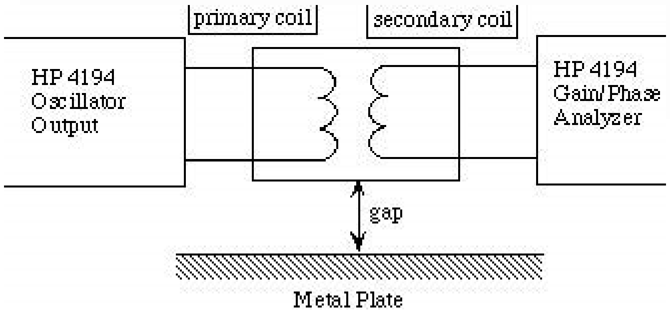
(e) LVDT introduces no mechanical loading:

(f) Optical potentiometer is more linear than a regular potentiometer:

(g) Optical potentiometer is a non-contact sensor:

Question

Signal processing (analog) steps for Extracting the measurement from the Output signal of a mutual induction Proximity sensor:



1.

2.

3.

4.

Permanent-magnet Transducers

Permanent Magnet (PM) Transducers (E.g., DC Tachometer)

Permanent Magnet (PM) Transducer: Uses a permanent magnet to generate magnetic field, which is needed for sensing

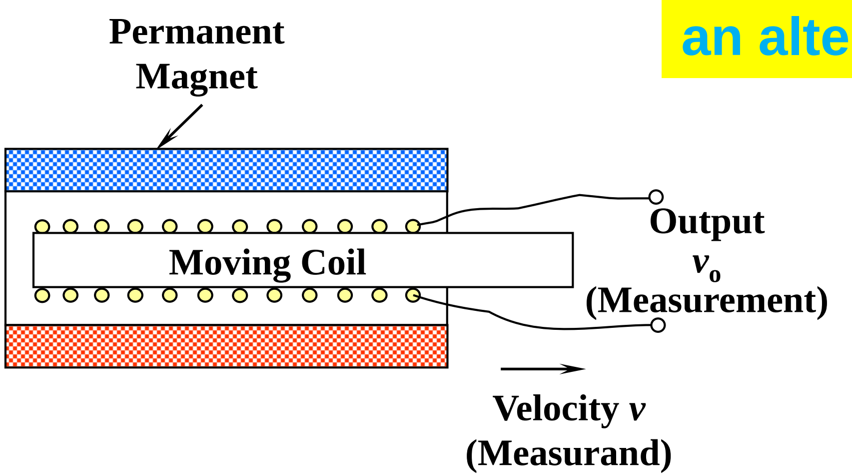
DC Tachometer:

- **Relative speed between magnetic field and electrical conductor → induced voltage**
- **Induced voltage $\propto$ speed of conductor crossing the magnetic field**
- **Depending on the configuration, (a) Rectilinear speeds, (b) Angular speeds can be measured**

Disadvantage? Suggest an alternative design.

Rectilinear DC Tachometer:

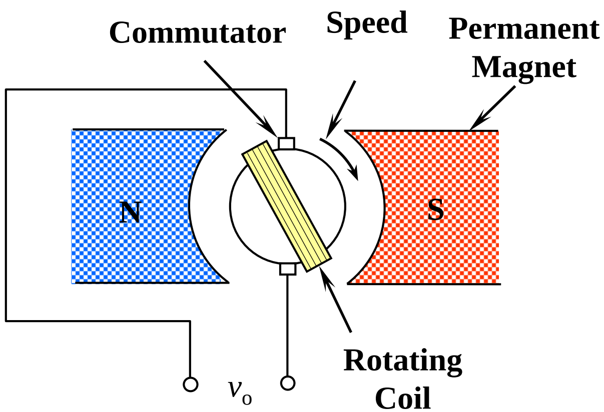
$$v_0 \propto v$$

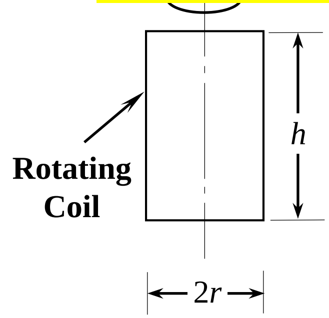


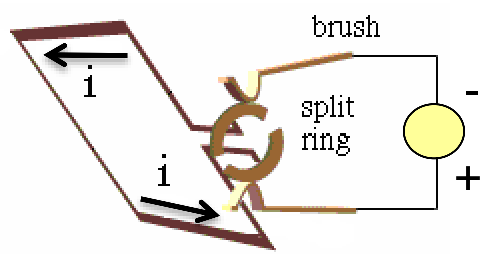
DC Tachometer (Rotary, for Angular Velocity)

A Permanent-magnet velocity sensor; Uses electromagnetic induction; Rectilinear or angular speeds can be measured.

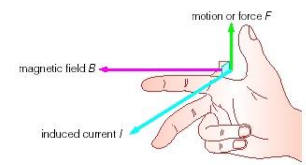
Read about AC tachometer. Two types: 1. PM; 2. Induction







Angle of rotation of coil: $\theta = \omega t$; Induced net voltage: $v_0 = |2nhrB\omega \sin \omega t|$



- **The rotor is directly connected to the rotating object.**
- **The output signal that is induced at the rotating coil is picked up using a commutator device (consists of slip ring and low resistance carbon brushes)**
- **Commutator is stationary but makes contact with the split slip rings**
- **Generated voltage is (Faraday's Law)**

Sensitivity (output) ranges: 0.5 to 3 V, 1 to 10 V, 11 to 25 V, or 25 to 50 V per 1000 rmp
Armature resistance: 100 Ω for low-voltage tachos; 2000 Ω for high-voltage tachos
Size: 2 cm in length; Good linearity (0.1% is typical).

Disadvantage? An alternative design?

Modeling of DC Tachometer

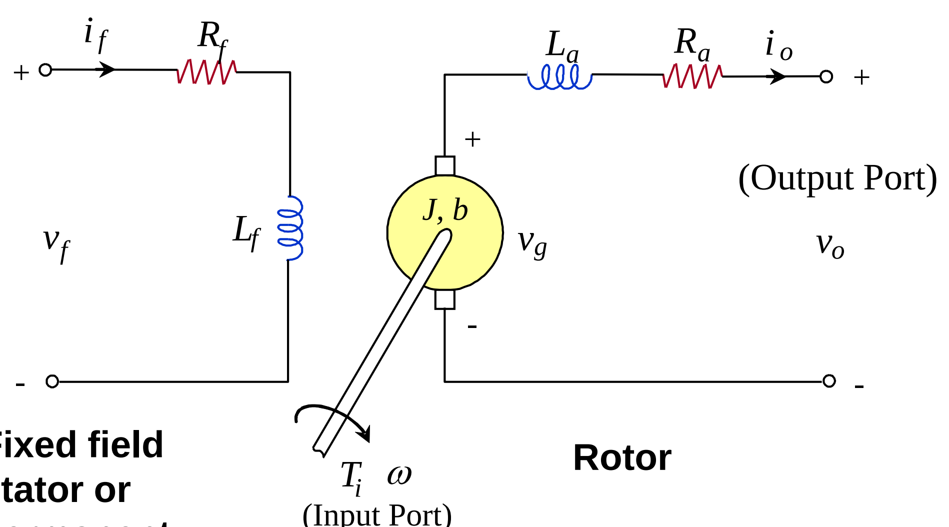
A two-port device (like a generator; reverse of a dc motor)

Input-port Variables: **Angular speed ω, torque T_i**

Output-port Variables: **Armature voltage v_o, armature circuit current i_o**

Field windings are powered by dc voltage v_f or use a permanent magnet (constant)

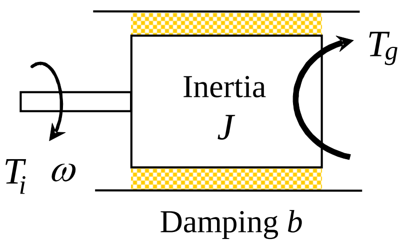
Equivalent Circuit



Fixed field stator or permanent magnet

Rotor

Free-body Diagram (Mechanical)



DC Tachometer Model

Induced voltage: $$v_g = K' i_f \omega_i \Rightarrow v_g = K\omega_i$$

Armature Torque: $$T_g = K' i_f i_o \Rightarrow T_g = K i_o$$

K **= gain or sensitivity of tachometer**

Note**: Assume dissipation-free energy transfer**

Armature Circuit: $$v_o = v_g - R_a i_o - L_a \frac{di_o}{dt} \Rightarrow V_o = K\omega_i - (R_a + sL_a) I_o$$

Mechanical Dynamics (Newton's 2nd law):

$$T_i = J\frac{d\omega_i}{dt} + b\omega_i + T_g \Rightarrow KI_o = T_i - (b + sJ)\omega_i$$

After Some Algebra:

$$\begin{bmatrix} V_o \\ I_o \end{bmatrix} = \begin{bmatrix} K + (R_a + sL_a)(b + sJ)/K & -(R_a + sL_a)/K \\ -(b + sJ)/K & 1/K \end{bmatrix} \begin{pmatrix} \omega_i \\ T_i \end{pmatrix}$$

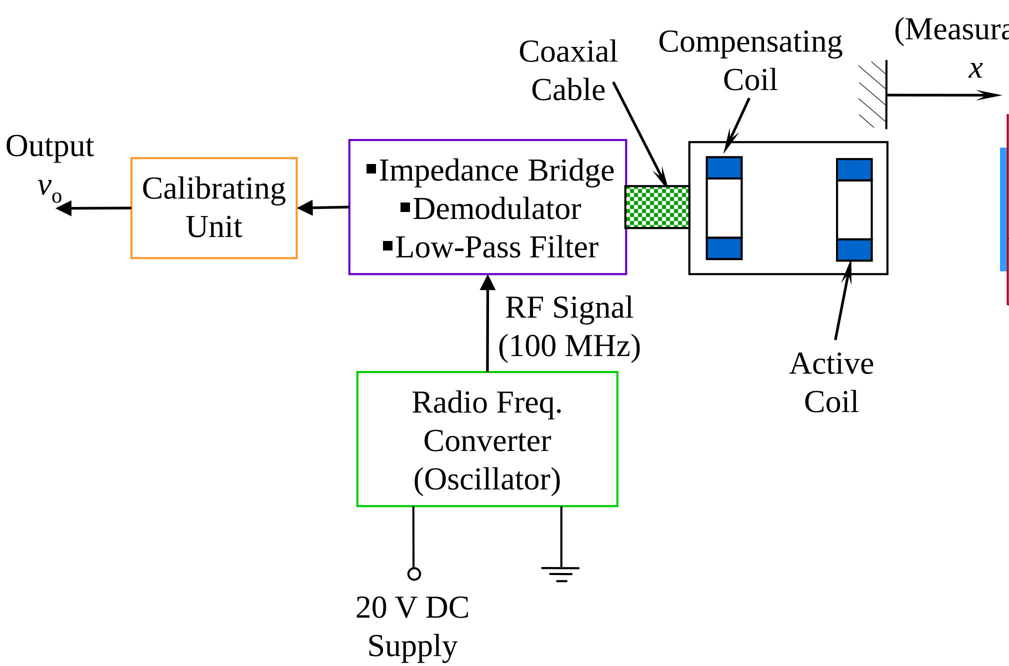
Electrical Time constant: $\tau_e = \dfrac{L_a}{R_a}$ **; Mechanical time constant:** $\tau_m = \dfrac{J}{b}$

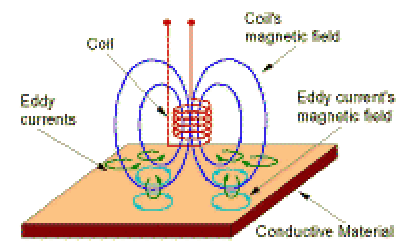
How would you make measurements more accurate?

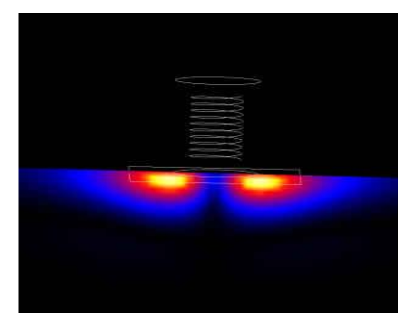
Eddy Current Transducers

Eddy Current Transducers

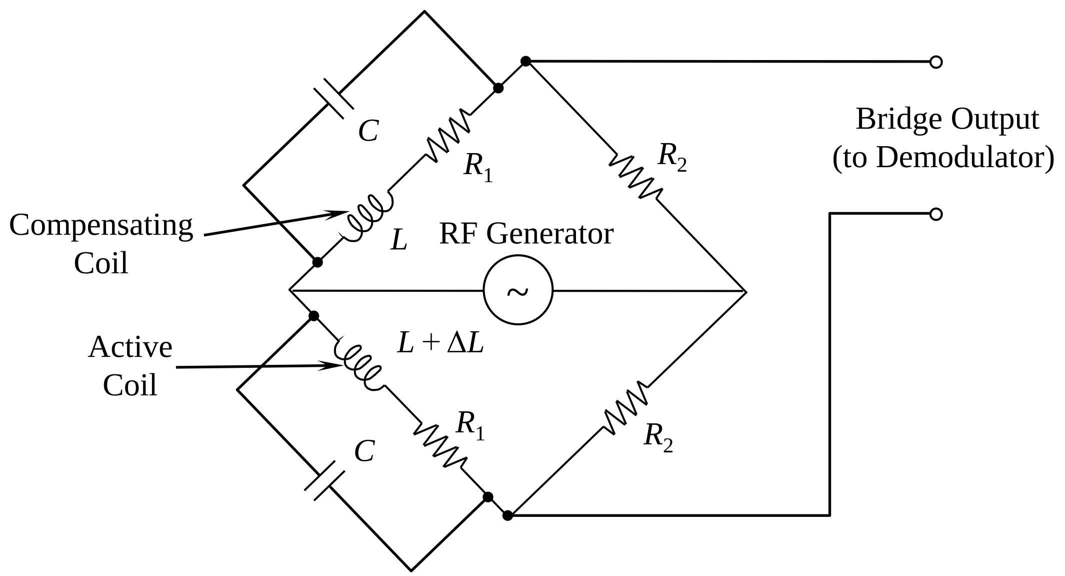
- Eddy-current transducer has **two coils**: active coil and compensating coil; A high-frequency (radio-frequency) voltage is applied to the **bridge circuit two of whose arms are the two coils**
- Conducting materials when subjected to a fluctuating magnetic field produce eddy currents
- When a target object is moved closer to the sensor, the inductance of the active coil changes **(due to eddy currents)**
- The output of the bridge is an amplitude modulated signal, from which the **displacement** signal of the probe head can be demodulated







Impedance Bridge for Eddy-current Transducer

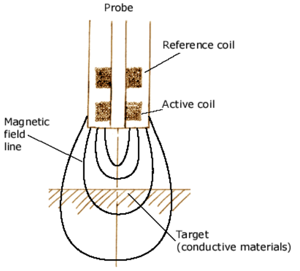


- The inductance bridge is **balanced** when there is no object
- The **change in inductance** creates an imbalance in the circuit and results in the bridge output signal
- The modulated signal needs to be demodulated to determine the displacement **(transient)**; or sense **"change in inductance"**
- For large displacements output is not linearly related to the displacement; needs **nonlinear calibration**

Eddy Current Transducers

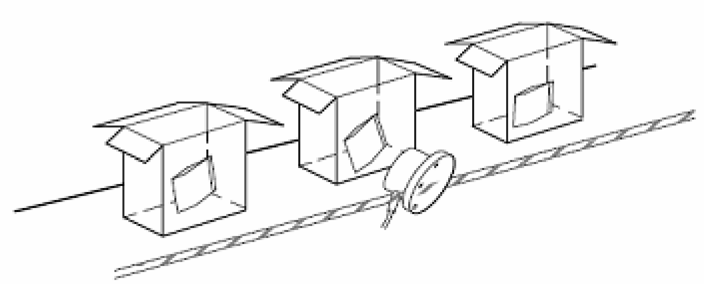
Characteristics, Advantages:

- Target objects only a small and thin layer of conducting material (e.g., glued aluminum foil)
- Typical diameter of the probe is about 2 mm (larger ones can be 75 mm)
- Target object has to be slightly > frontal area of probe
- Output impedance ~ 1 kΩ (medium output impedance)
- Sensitivity ~ 5 V/mm
- Measurement Range: 0.25 mm – 30 mm
- Suitable for high transient measurements (up to ~ 100 kHz)



Why?

- Applications include
  - Displacement/proximity sensing
  - Machine health monitoring, Fault detection
  - Metal detection
  - Braking
  - Parts counting



Inductive proximity sensor used to detect a foil seasoning bag inside of a cardboard container.

Variable-capacitance Transducers

Variable-capacitance Transducers

Capacitance of a two (parallel) plate capacitor: $C = \dfrac{kA}{x}$

x – gap width
A – overlapping Area
k – dielectric constant (permittivity)

$k = \varepsilon_0 \varepsilon_r$; ε_0 – **permittivity of vacuum** ; ε_r – **relative permittivity**

- **A change in any one of these parameters may be used for sensing**

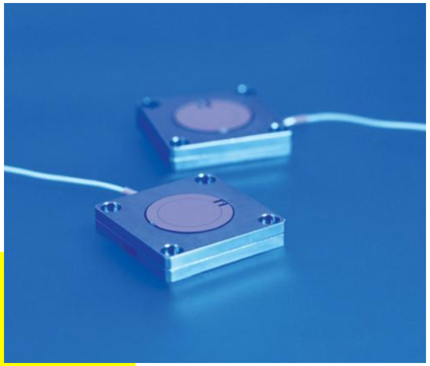
  Examples: Transverse displacement (x), rotation (A), fluid level (k)
- **A capacitance bridge is used to measure change in capacitance**
- **Other methods include measuring a change in:**
  - **Charge – charge amplifier**
  - **Voltage – high impedance device in parallel**
  - **Current – low impedance device in series**
  - **Inductance capacitance oscillator circuit**

What is its resonant frequency?

Capacitive Displacement Sensor

- **One plate is attached to moving (target) object and other is kept stationary**
- **Capacitance:** $C = \dfrac{K}{x}$ **; Sensitivity:** $S = \dfrac{\partial C}{\partial x} = -\dfrac{K}{x^2}$

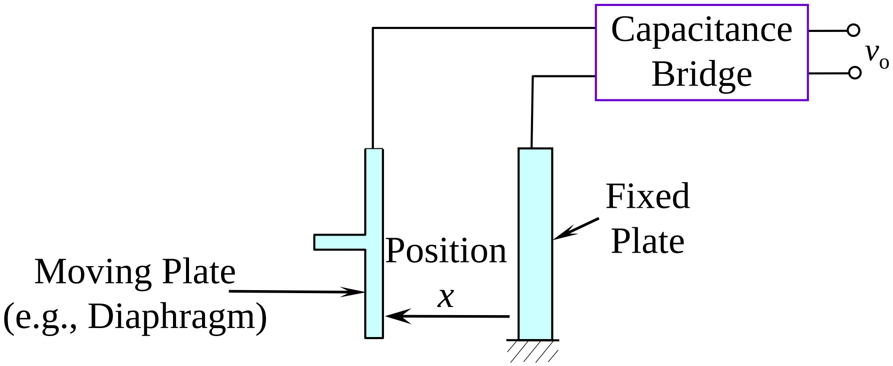
***Note*: This relationship is nonlinear; can be linearized using an op amp circuit (or nonlinear calibration)**

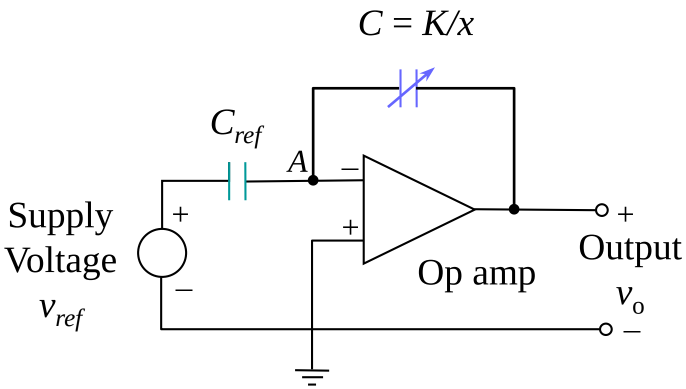


Charge balance at node A: $v_{ref}\,C_{ref} + v_o C = 0$

➔ $$v_o = -\frac{v_{ref} C_{ref}}{K} x$$

Apart from linearization, any other advantages of this active circuit?



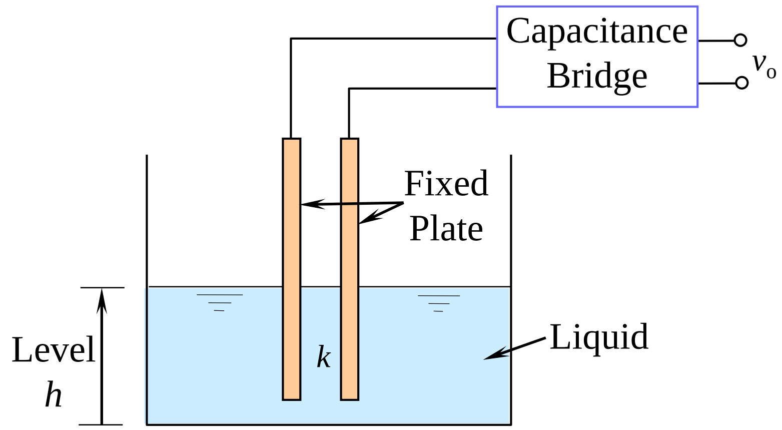


Level Measurement

(by changing dielectric constant)

- **Liquid level shown in figure is part of the dielectric medium between the plates. As the liquid level changes, *k* changes → measures the liquid level**

Alternative Sensor (Displacement Sensor): Attach moving object (sensed object) to a solid dielectric element placed between the plates ➔ *k* measures the displacement

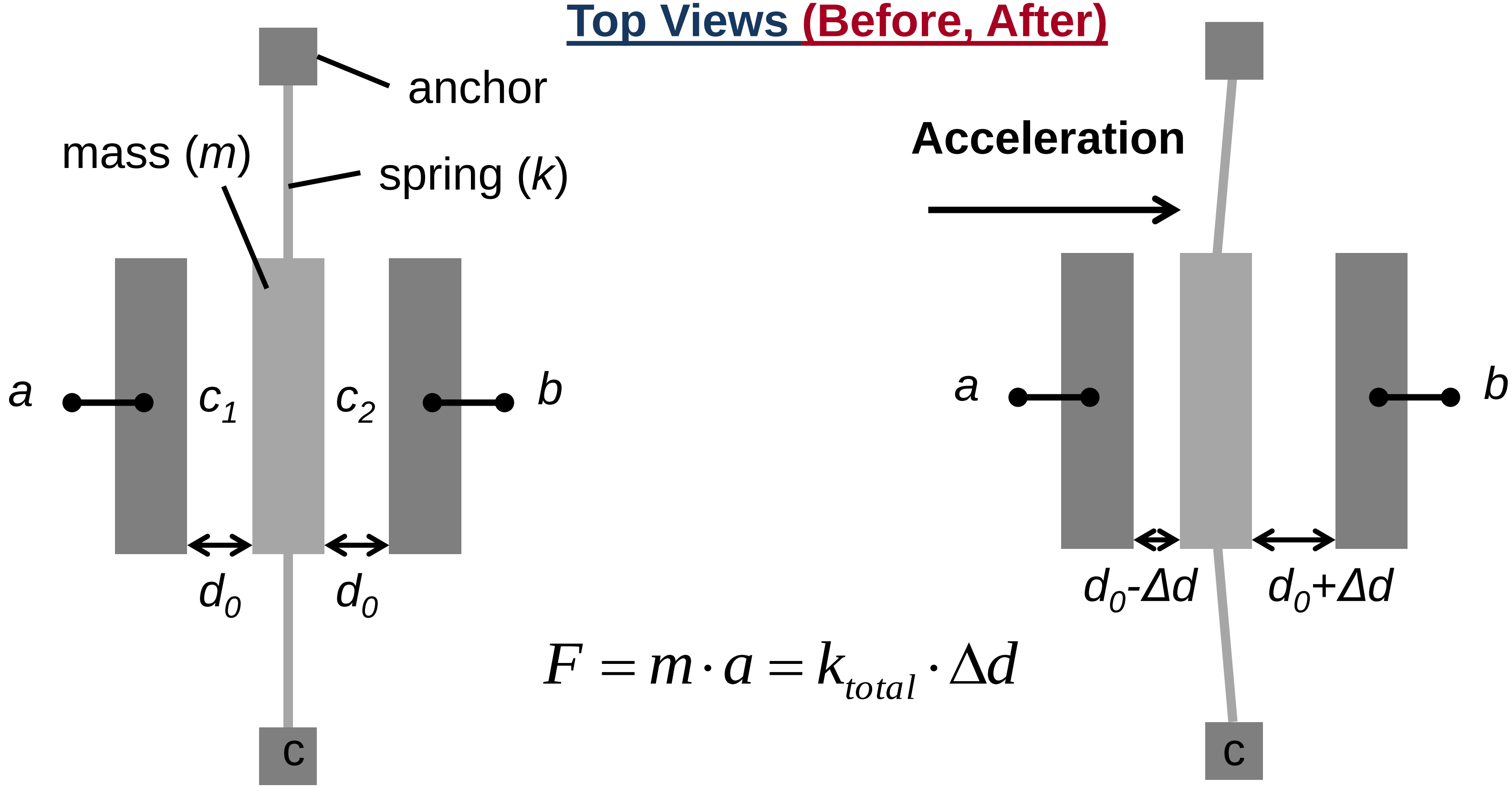


Differential Capacitor Accelerometer

- **3 sets of electrodes:**
  - **Two sets are fixed to the substrate**
  - **One set is free to move**
    (suspended through springs or flexible beam elements)
- **Capacitance changes due plate displacement (inertia force from acceleration**

Inertia force from mass produces a reaction on the spring (in opposite direction)

Top Views (Before, After)



$$F = m \cdot a = k_{total} \cdot \Delta d$$

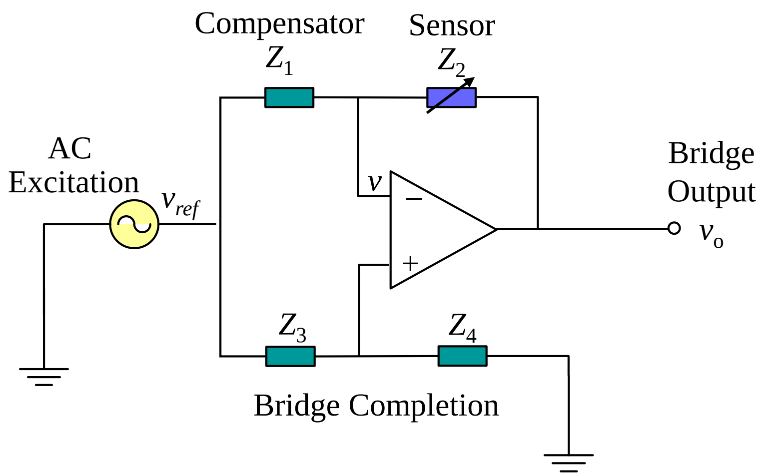
Capacitance Accelerometer Commercial Data

Other applications?

- **Automotive industry: ABS, suspension (0-2 G), air bags (up to 50 G)**
- **Development: mid 1990s → mid 2000s → mid 2010s**
  - **Price: 100 \$ | 10 \$ | \$1**
  - **Number of axes: 1 | 2 | 3**
  - **Increased sensitivity**

Manufacturer	Analog devices	Analog devices	Motorola	NXP (Freescale)	Bosch	Bosch
Part no.	ADXL50JH	ADXL203	XMMAS4	FXLN83xxQ	SMB060	BMA222E
Number of axes	1	2	1	3	2	3
Full-scale range [G]	+/- 50	+/- 1.7	+/- 40	+/- 2-16 (model/selectable)	+/- 35	+/- 2-16 (selectable)
3 dB bandwidth [Hz]	1,300	up to 2,500 (selectable)	400	up to 2,700 (xy) 600 (z)	400	8 – 1,000 (programmable)
Nonlinearity [%FS]	0.2	0.2	0.5	0.5	0.5	0.5
Axis alignment [°]	N/A	0.1	N/A	?	1	+/- 0.5

Capacitance Bridge Circuit



$$\frac{v_{ref} - v}{Z_1} + \frac{v_o - v}{Z_2} = 0$$

$$\frac{v_{ref} - v}{Z_3} + \frac{0 - v}{Z_4} = 0$$

$$v_o = \frac{\left(Z_4 / Z_3 - Z_2 / Z_1\right)}{1 + Z_4 / Z_3} v_{ref}$$

Prove.

For a balanced circuit:

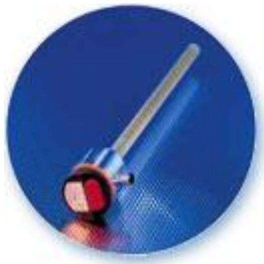
$$\frac{Z_2}{Z_1} = \frac{Z_4}{Z_3}$$

Bridge output due to sensor change:

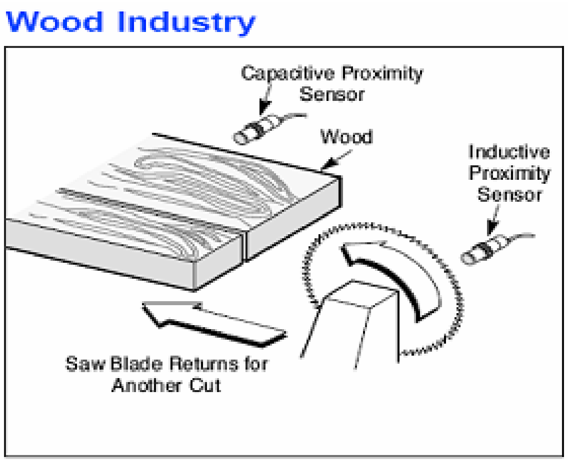
$$\delta v_o = -\frac{v_{ref}}{Z_1\left(1 + Z_4 / Z_3\right)} \delta Z$$

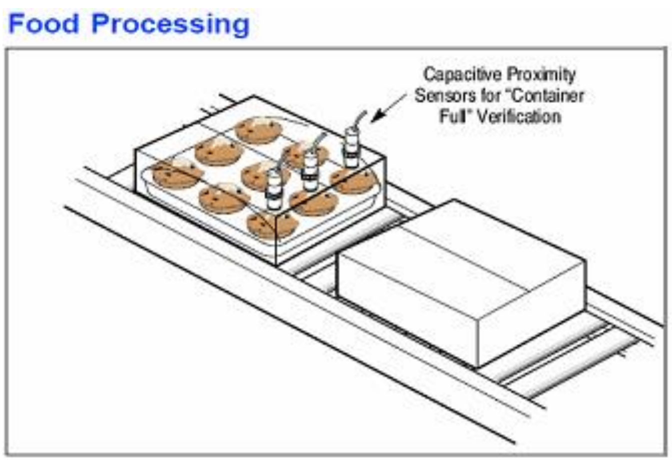
Why?

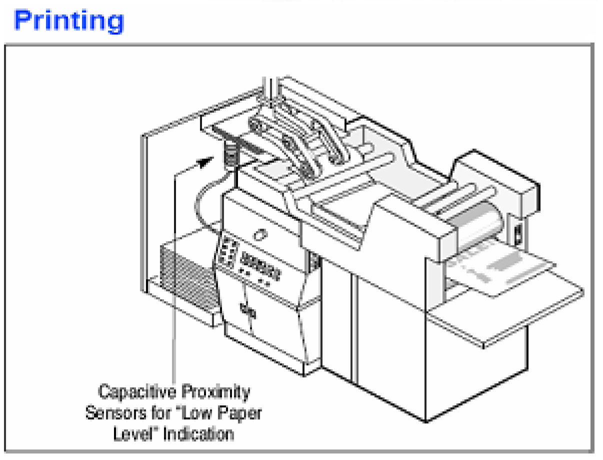
Capacitive Sensor Advantages, Disadvantages, Applications



- Mechanical loading effects (except inertia) are negligible (non-contact)
- Variations in dielectric properties due to humidity, temperature, pressure, and impurities will cause errors
- Capacitance bridge can compensate for these effects
- Sensitivity – 1pF per mm
- At low frequencies high output impedance (disadvantage)







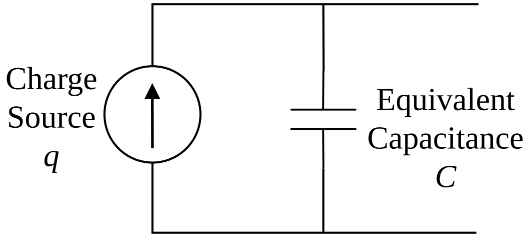
Piezoelectric Transducers

Piezoelectric Sensors

- Substances such as $BaTiO_3$ (barium titanate),SiO_2 (quartz in crystalline), and lead zirconate titanate (PZT) generate an electric charge when subjected to stress (strain)
- **Applications:**
  - Pressure and strain measuring devices
  - Touch screens
  - Accelerometers
  - Torque/Force sensors

Are these active or passive sensors?

- **Reverse Effect:** Piezoelectric materials deform when a voltage is applied. Applications:
  - Piezoelectric valves
  - Microactuators and MEMS



$$Z = \frac{1}{j\omega C}$$

- **Output impedance of a piezoelectric sensor is high**

  (decrases with frequency;

  ~MΩ at 100 Hz)

Where is the internal resistance of the element?

Charge and Voltage Sensitivities

- **Charge sensitivity: Change of charge due to unit force** $$S_q = \frac{\partial q}{\partial F}$$

For a surface area *A* and pressure/stress *p*: $$S_q = \frac{1}{A}\frac{\partial q}{\partial p}$$

For crystal capacitor: $\delta q = C\delta v$ → $$S_q = \frac{C}{A}\frac{\partial v}{\partial p}$$

- **Voltage sensitivity:** $$S_v = \frac{1}{d}\frac{\partial v}{\partial p}$$

Change in voltage due to unit increment in pressure per unit thickness of crystal (*d* = thickness)

***Note*:** $$C = \frac{kA}{d}$$

➔ $$S_q = kS_v$$

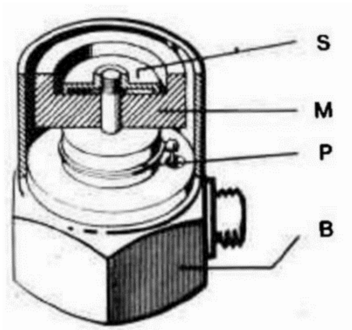
***k* = dielectric constant of crystal capacitor**

Piezoelectric Material Sensitivities

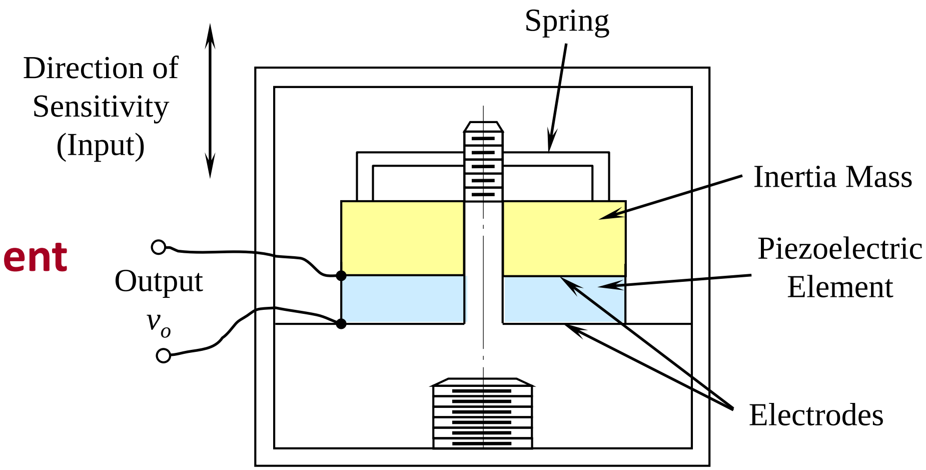
Material	Charge Sensitivity S_q (pC/N)	Voltage Sensitivity S_v (mV.m/N)
Lead Zirconate Titanate (PZT)	110	10
Barium Titanate	140	6
Quartz	2.5	50
Rochelle Salt	275	90

The two sensitivities are directly related through *k* (see previous formula)

Piezoelectric Accelerometer



P: piezoelectric element
M: mass
R: ring
B: base

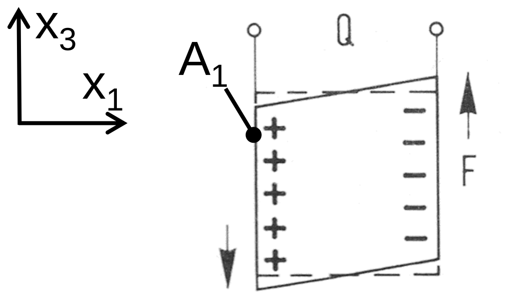


- **Inertia force caused by the acceleration produces a voltage**
- **Light weight, high frequency response (1 MHz)**
- **High output impedance – small voltages ~1 mV**
- **High spring stiffness – natural frequency or resonant frequency is high (20 kHz)**
- **Useful frequency range – 5kHz**

It can be argued that the piezoelectric element here is not the sensor but the transducer. Why?

Shear-type Piezoelectric Accelerometer

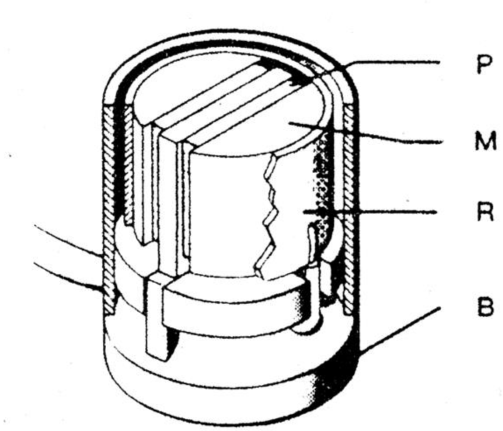
Shear-effect



$$\tau_5 = F_3 / A_1$$

$$D_1 = d_{15}\tau_5$$

By Brüel & Kjær



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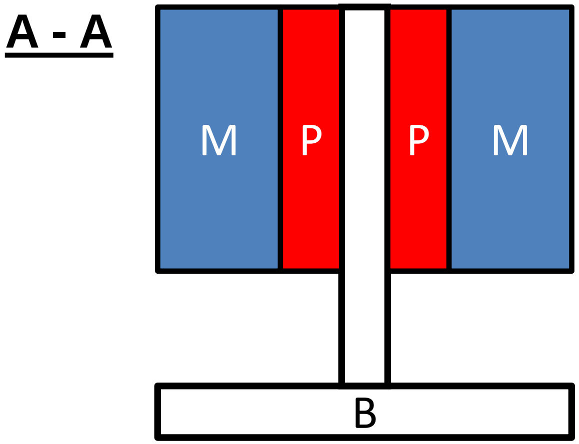
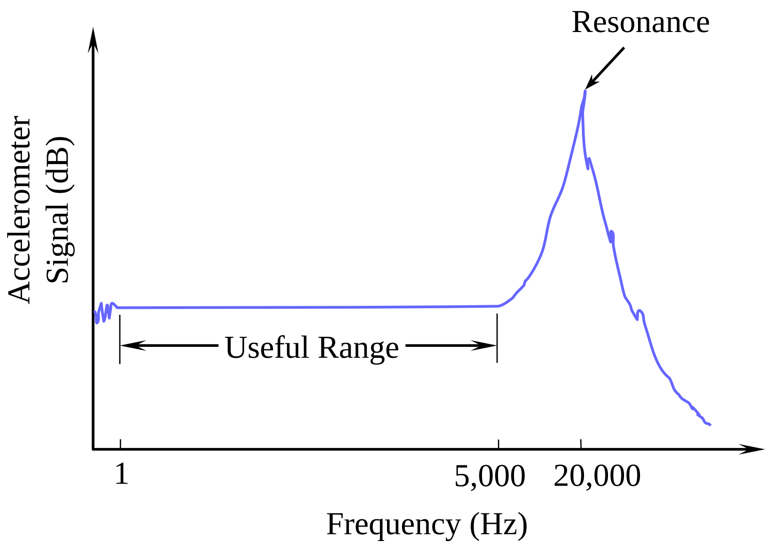


Advantage over the axial (previous) arrangement?

Typical frequency range: 0.1 Hz – 50 kHz

Frequency Response



Note: DC measurements are not possible. Why? Also see sensor time constant relation.

Frequency response curve of a piezoelectric accelerometer

- **Typical accelerometer sensitivities – 10 pC/g (pico Coulomb per gravity) or 5mV/g**
- **Sensitivity depends on the piezoelectric properties and the way the inertia force is applied**
- **Large mass (conflict) ➔**

  large force, large output signal (good)

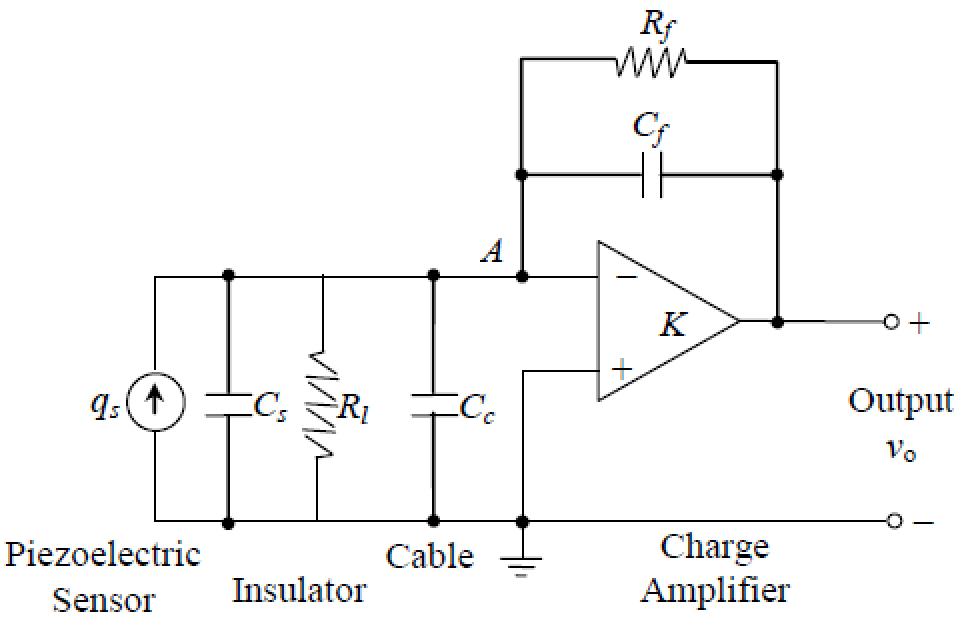
  Increased mechanical loading of measurand (bad)

  Lower resonant frequency (bad)

Charge Amplifier

Advantages:

1. **Compensates for extraneous impedances**
2. **Decides time constant**
3. **Avoids charge leakage**



***Note*: Capacitance feedback**

Current balance at node A:

$$\dot{q} + C_f \dot{v}_o + \frac{v_o}{R_f} = 0$$

Note the potential difference between the op-amp leads)

***Note*: Extraneous impedances are compensated for!**

$$\rightarrow \quad \frac{v_o(s)}{q(s)} = -\frac{R_f s}{[R_f C_f s + 1]} \quad \rightarrow \quad \frac{v_o(j\omega)}{q(j\omega)} = -\frac{R_f j\omega}{[R_f C_f j\omega + 1]}$$

Normalize: $G(j\omega) = \dfrac{j\tau_s \omega}{[j\tau_s \omega + 1]}$

Time Constant: $\tau_s = R_f C_f$ **(precisely decided by user)**

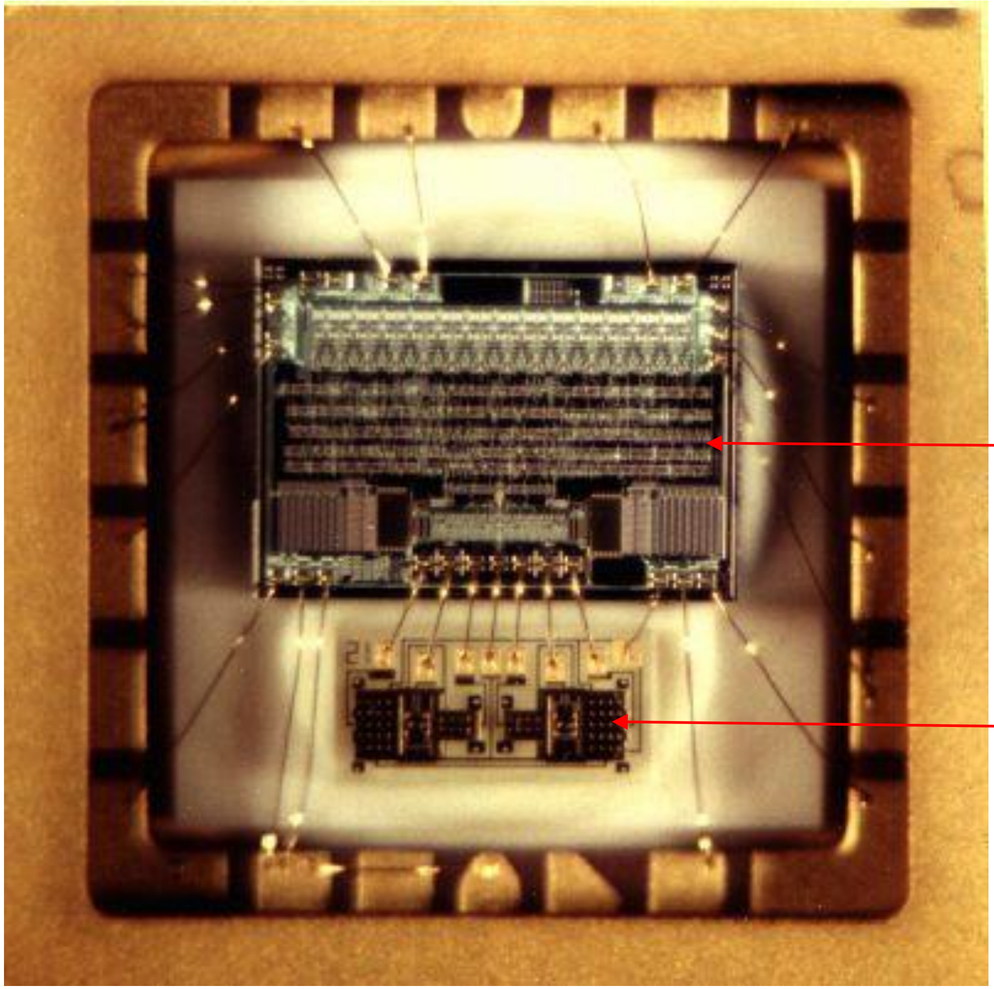
Data Sheet: Piezo-electric Force sensor

DYNAMIC PERFORMANCE			
Measurement Range:			
Compression (for +5V output)	lb [kN]	10 [0,04448]	
Tension (for -5V output)	lb [kN]	10 [0,04448]	
Useful Overrange:			
Compression (for +10V output)	lb [kN]	20 [0,08896]	
Tension (for -10V output)	lb [kN]	20 [0,08896]	
Maximum Static Force:			
Compression	lb [kN]	100 [0,4448]	
Tension	lb [kN]	100 [0,4448]	
Broadband Resolution (1 Hz to 10 kHz)	lb-rms [N-rms]	0.0001 [0,00045]	[3]
Low Frequency Response (-5%)	Hz	0.01	[1]
Upper Frequency Limit	Hz	36,000	[5]
Amplitude Linearity	%FS	≤1	[2]
ENVIRONMENTAL			
Temperature Range	°F [°C]	-65 to +250 [-54 to +121]	
Temperature Coefficient	%/°F [%/°C]	≤0.05 [≤0,09]	
ELECTRICAL			
Sensitivity	mV/lb [mV/kN]	500 [112 410]	[±15%]
Discharge Time Constant (at Room Temperature)	sec	≥50	
Power Requirements: Voltage	VDC	18 to 30	[4]
Constant Current	mA	2 to 20	
Output Impedance	ohms	≤100	
Output Bias Voltage	VDC	8 to 12	[7]
Spectral Noise: 1 Hz	lb/√Hz [N/√Hz]	1.26E-5 [5,62E-5]	[3]
10 Hz	lb/√Hz [N/√Hz]	4.24E-6 [1,89E-5]	[3]
100 Hz	lb/√Hz [N/√Hz]	1.49E-6 [6,65E-6]	[3]
1 kHz	lb/√Hz [N/√Hz]	5.22E-7 [2,33E-6]	[3]
Polarity	compression	Positive	
MECHANICAL			
Stiffness	lb/µin [kN/µm]	6 [1,05]	[3]
Dimensions	in [mm]	0.625 x 0.625 [15,88 x 15,88]	
Weight	oz [gm]	0.80 [22,7]	
Housing/Sealing	material/type	Stainless Steel/Hermetic	
Connector/Connector Orientation	type/location	10-32 Coaxial Jack/Side	
Mounting Thread	type	10-32 UNF-2B	
Recommended Mounting Torque	in-lb [N-cm]	16 to 20 [181 to 226]	

CE [6]

All specifications are at room temperature unless otherwise specified.

MEMS Accelerometer



Signal Conditioning

Mechanical Structure

Applications: **Airbag Deployment**

Questions

Suggest a suitable sensor for the following applications:

1. To measure the proximity of a block of wood:

2. To sense the presence of a ferromagnetic object:

3. To measure the position of the conducting surface of a wooden block:

4. To measure the acceleration of an object:

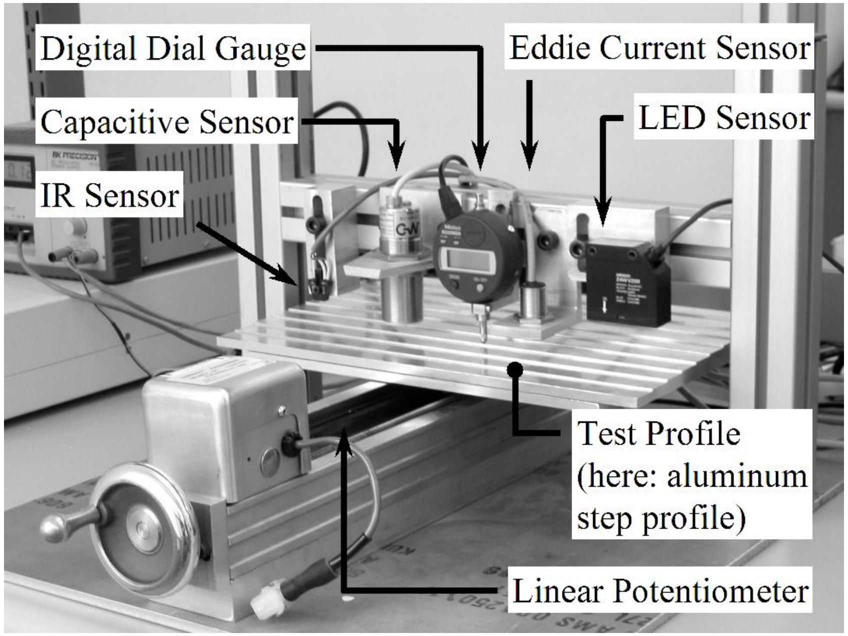
5. To measure the vibration of a non-metallic reed:

Lab 1: Data Acquisition and Proximity Sensors for Object Detection

Objectives

- To understand how to acquire sensor signals with a PC-based data acquisition (DAQ) system
- To become familiar with the principles of potentiometric displacement sensor, LED proximity sensor, eddy current inductive proximity sensor, capacitive proximity sensor, and infrared reflective object detector
- To learn to calibrate sensors and determine their static transfer characteristics
- To recognize the limitations and possible areas of application for these sensor types
- Some results from lab exercises will be used again in later labs

  Example: You will need calibration results from Lab 1 in Lab 4



Laboratory Report

- **Carefully follow the Lab Manual**
- **On the first page indicate**
  - **Your name and student ID#**
  - **Lab date**
  - **Names of the TAs**
- **The report can be typed or handwritten**
- **Document the experimental setup and conditions such as sampling rates for data acquisition**
- **Document mathematical operations you have performed on the data by providing the corresponding equations as well as the results. Any person reading your report should understand what you have done**
- **Follow the manual questions instructions; answer questions**
  - **Always report the correct units**
  - **Make sure all graphs (including axes) are properly labelled**
  - **Data analysis and report preparation are individual work**