

# **Course Plan Overview – January 2015**

## Impedance:

- Traditional electrical sense - as generalized resistance: Simple & Complex!!
- In the mechanical sense, or in a general sense with regard to other domains (e.g., fluid, thermal) as well depending on the type of signals involved.
  - A voltmeter can modify the currents (and voltages) in a circuit, and this concerns electrical resistance of a dc circuit or more generally, electrical impedance, when ac circuits are considered.
  - A heavy accelerometer will introduce an additional dynamic (mechanical) load, which will modify the actual acceleration at the monitoring location. This concerns mechanical impedance.
  - A thermocouple junction can modify the temperature that is measured as a result of the heat transfer into the junction. This concerns thermal impedance.

Similarly we can define impedance for fluid systems, magnetic systems (reluctance), and so on. In general, impedance is defined as:

$$\text{Impedance} = \frac{\text{Across Variable}}{\text{Through Variable}}$$

The **across variable** is measured across the two ends (ports) of a component, and the **through variable** transmits through the component unaltered.

- Examples of **across** variables are voltage, velocity, temperature, and pressure.
- Examples of **through** variables are current, force, heat transfer rate, and fluid flow rate.
- Even though electrical impedance is defined as voltage/current, which is consistent with the definition.

Mechanical **impedance**, historically, has been defined as force/velocity, which is the inverse of the definition above. It is the **mobility** that is defined as velocity/force, and it should be interpreted as impedance in the general sense (i.e., generalized impedance), in our analysis.

## Cascade Connection of Devices:

The output impedance:  $Z_0 = \frac{\text{open-circuit (i.e.,no-load) voltage at the output port}}{\text{the short-circuit current at the output port}}$

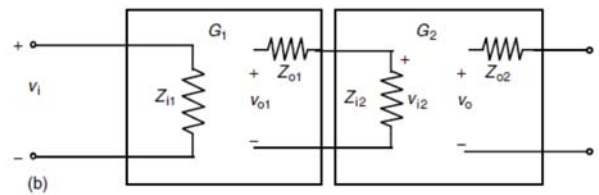
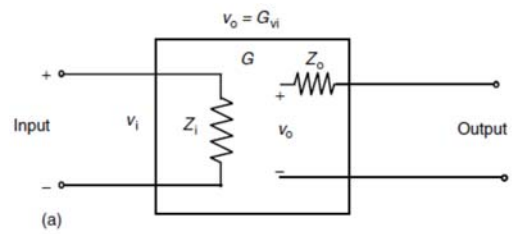
- O/C voltage at output is the output voltage present when there is no current flowing at the output port. This is the case if the output port is not connected to a load (impedance). *As soon as a load is connected at the output of the device, a current flows through it, and the output voltage drops to a value less than that of the open-circuit voltage.*
- To measure the open-circuit voltage, the rated input voltage is applied at the input port and maintained constant, and the output voltage is measured using a voltmeter that has a high (input) impedance.
- To measure the short-circuit current, a very low-impedance ammeter is connected at the output port.

The output impedance:  $Z_i = \frac{\text{Rated input Voltage}}{\text{corresponding current through the input terminals}}$

While Output terminals are maintained in O/C.

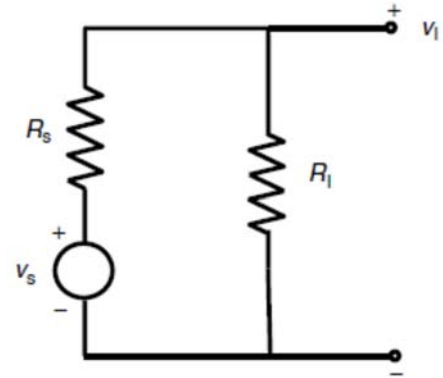
$Z_0$  and  $Z_i$  can be represented as shown in the diagram.

- Note that  $v_0$  is the open-circuit output voltage.
- When a load is connected at the output port, the voltage across the load will be different from  $v_0$  because this is caused by the presence of a current through  $Z_0$



## Loading Effect and Impedance Matching:

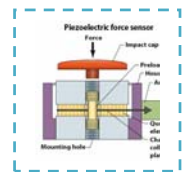
- When two electrical components are interconnected, current (and energy) flows between the two components and changes the original (unconnected) conditions. *This is known as the (electrical) loading effect, and it has to be minimized.*
- At the same time, adequate power and current would be needed for signal communication, conditioning, display, and so on.
- Both **situations can be accommodated** through proper *matching of impedances* when the two components are connected. Usually, an impedance-matching amplifier (i.e., an impedance transformer) would be needed between the two components.



From the analysis given in the preceding section:

- The **signal-conditioning circuitry should have a considerably large input impedance in comparison with the output impedance of the sensor-transducer unit** to reduce loading errors.

**Example:** Problem is quite serious in measuring devices such as **piezoelectric sensors**, which have **very high output impedances**. A **piezoelectric** sensor is a device that uses the **piezoelectric** effect, to measure changes in pressure, acceleration, temperature, strain, or force by converting them to an electrical charge.

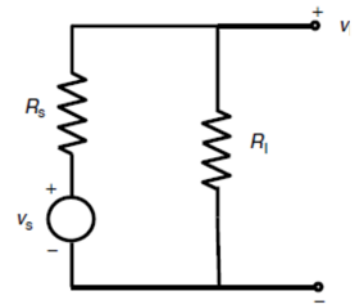


- *In such cases, the input impedance of the signal-conditioning unit might be inadequate to reduce loading effects;*
- *Also, the output signal level of these high impedance sensors is quite low for signal transmission, processing, actuation, and control.*
- *The solution for this problem is to introduce several stages of amplifier circuitry between the output of the first hardware unit (e.g., sensor) and the input of the second hardware unit (e.g., data acquisition unit).*
- *The first stage of such an interfacing device is typically an impedance-matching amplifier that has high input impedance, low output impedance, and almost unity gain.*
- *The last stage is typically a stable high-gain amplifier stage to step up the signal level. Impedance-matching amplifiers are, in fact, op-amps with feedback.*

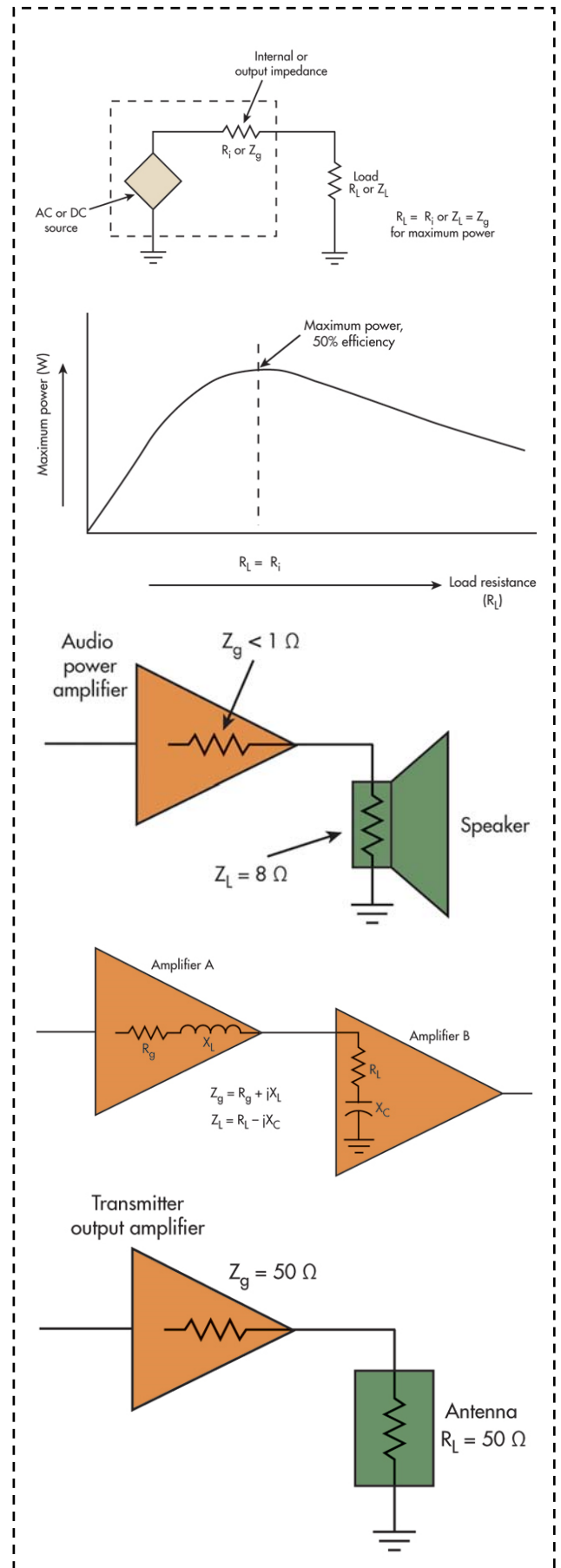
When connecting a device to a signal source, **loading problems can be reduced by making sure that the device has a high input impedance.**

Unfortunately, this will also reduce the level (amplitude, power) of the signal received by the device. In fact, a high impedance device may reflect back some harmonics of the source signal. A termination resistance might be connected in parallel with the device to reduce this problem.

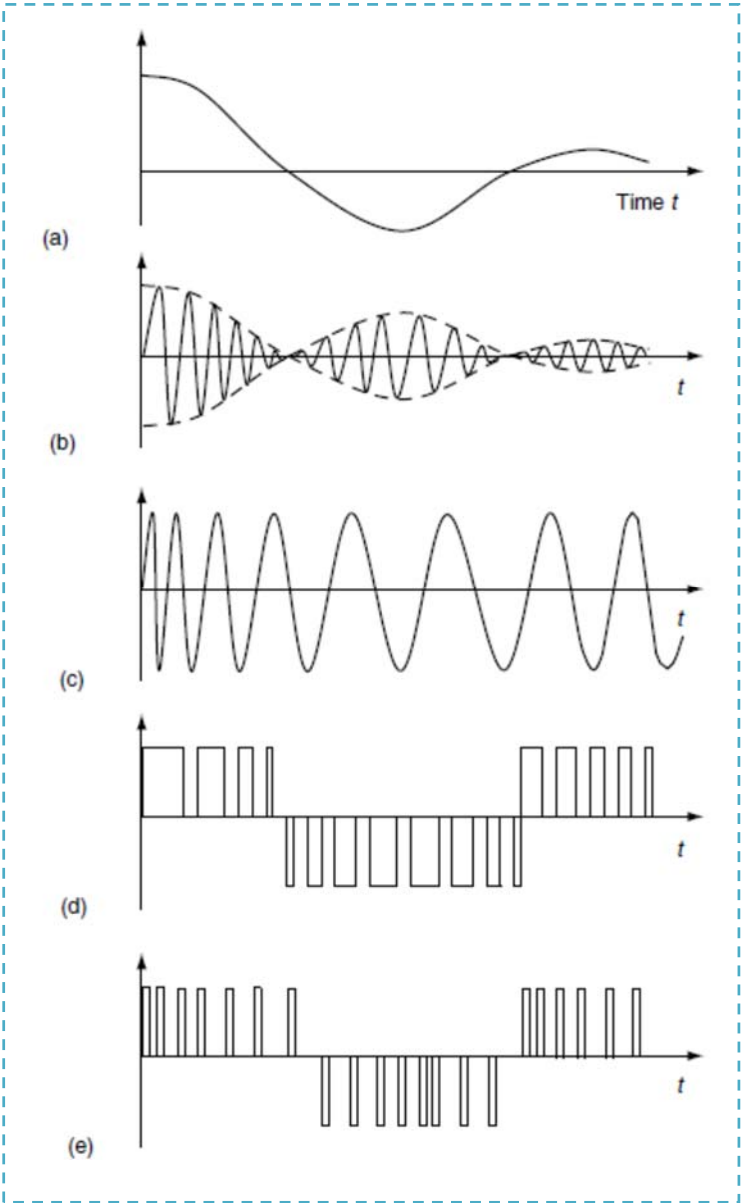
In many data acquisition systems, output impedance of the output amplifier is made equal to the transmission line impedance. **When maximum power amplification is desired, conjugate matching is recommended.** In this case, input and output impedances of the matching amplifier are made equal to the complex conjugates of the source and load impedances, respectively.

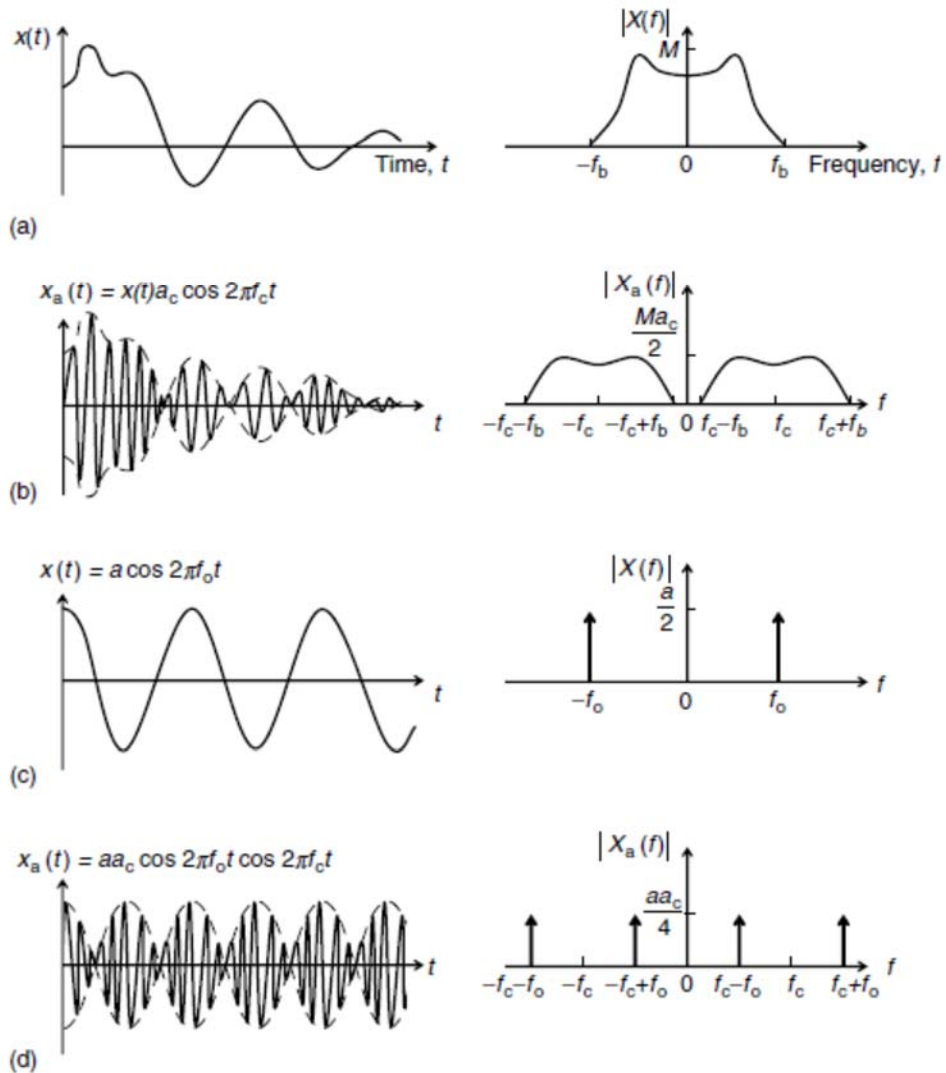


# Using Complex Impedance:



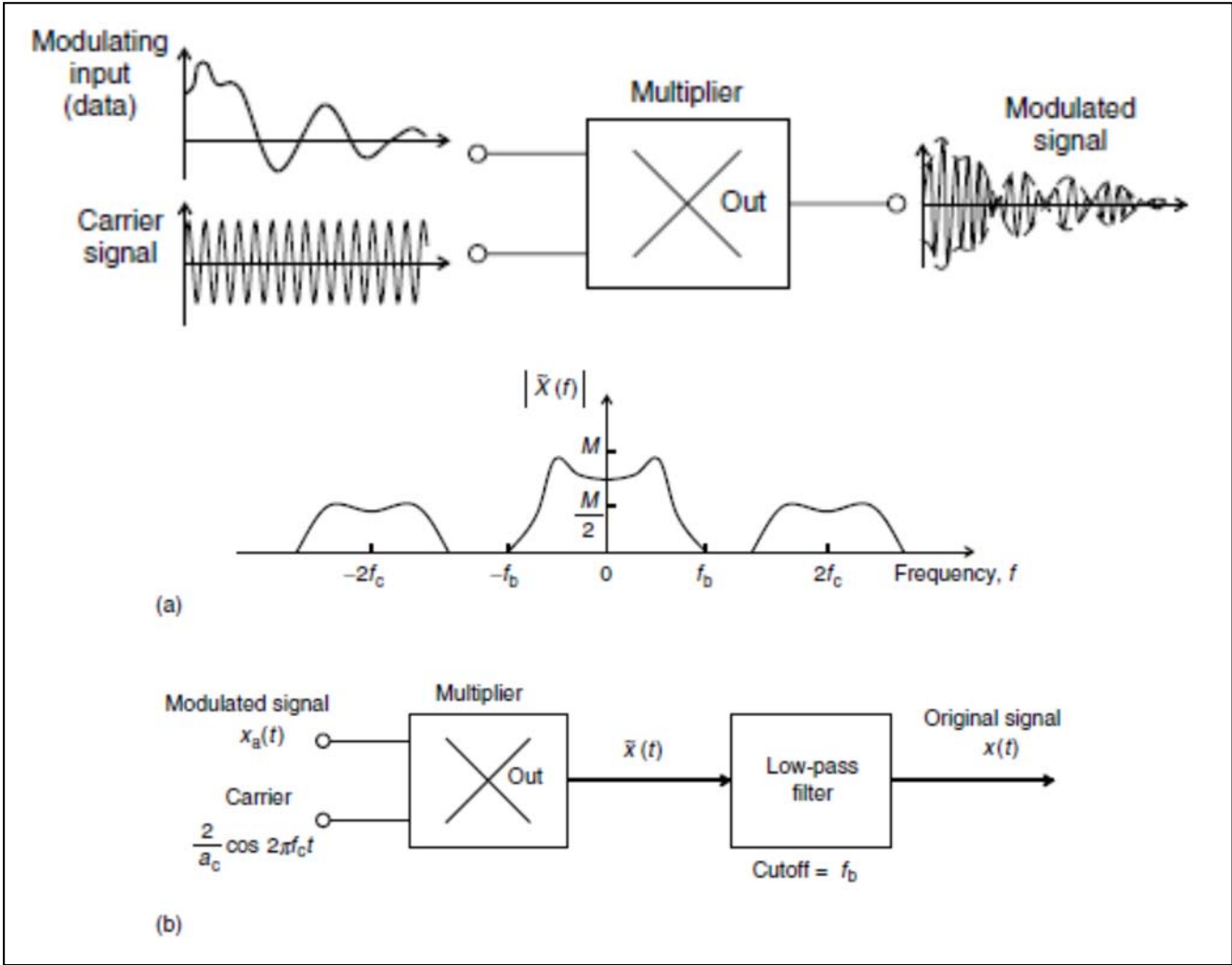
Modulation:





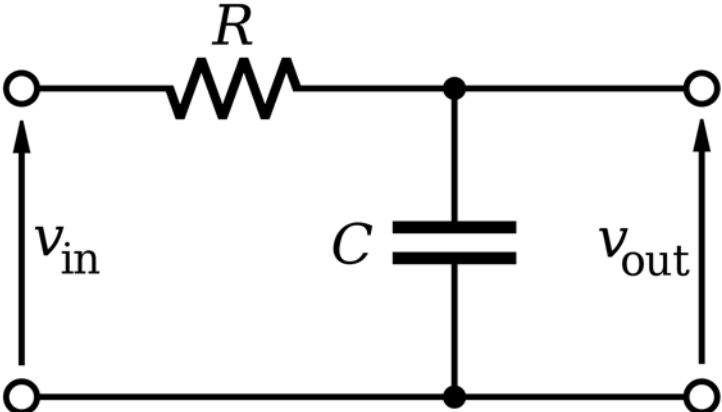
**FIGURE 2.22** Illustration of the modulation theorem. (a) A transient data signal and its Fourier spectrum magnitude. (b) Amplitude-modulated signal and its Fourier spectrum magnitude. (c) A sinusoidal data signal. (d) Amplitude modulation by a sinusoidal signal.

# Modulation and De-Modulation:



Consider the modulated signal above:

Low Pass Filter with a cut-off:



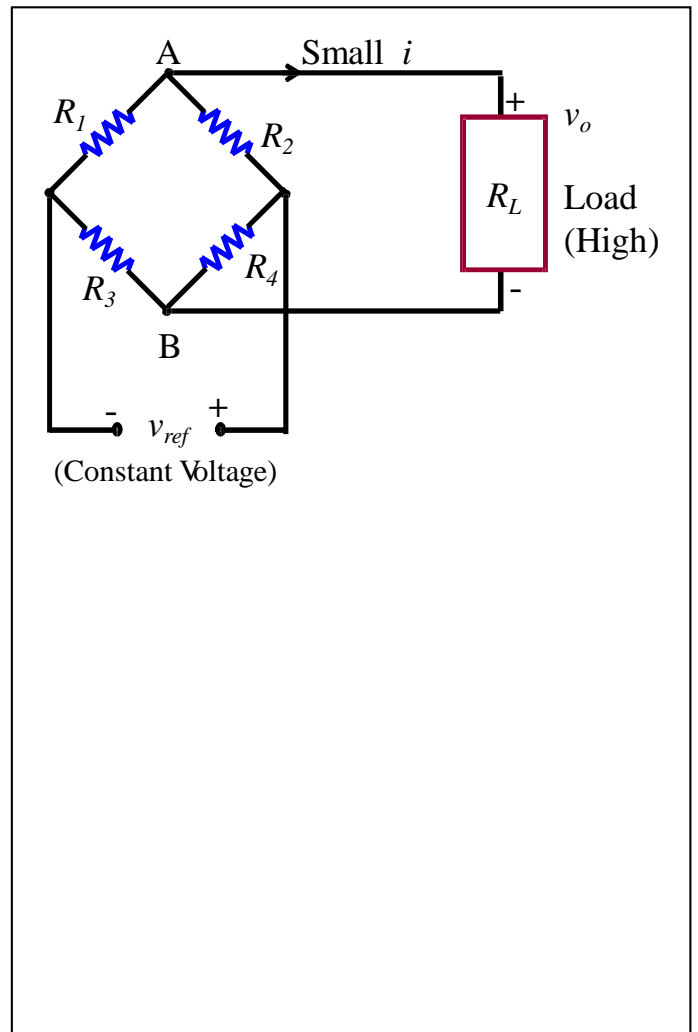
**What if you applied a sine wave to this filter?**

**What if you applied a Step Function to this filter?**

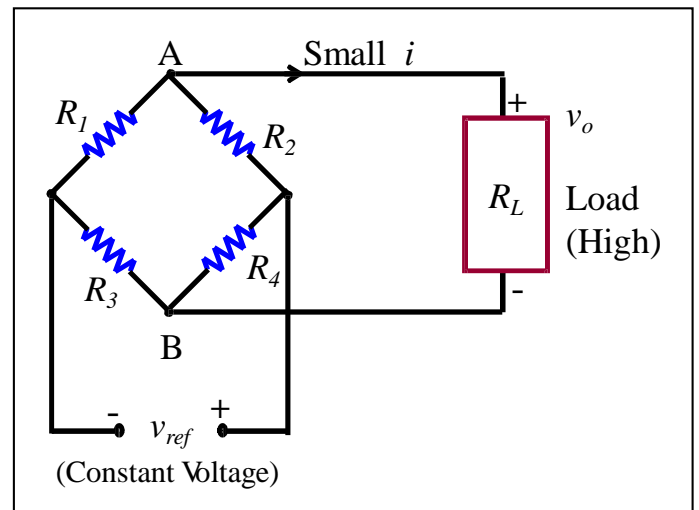
## Bridge Circuits:

Bridge circuits are used to make a form of measurement:

- Change in resistance
- Change in inductance
- Change in capacitance
- Oscillating frequency

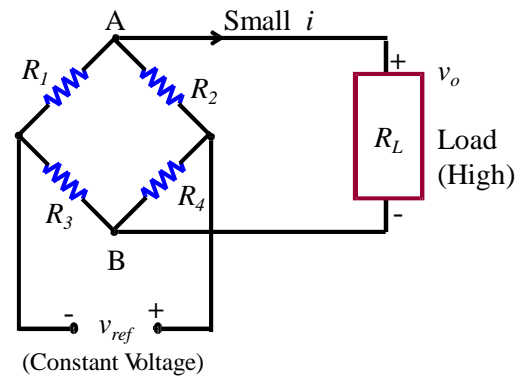


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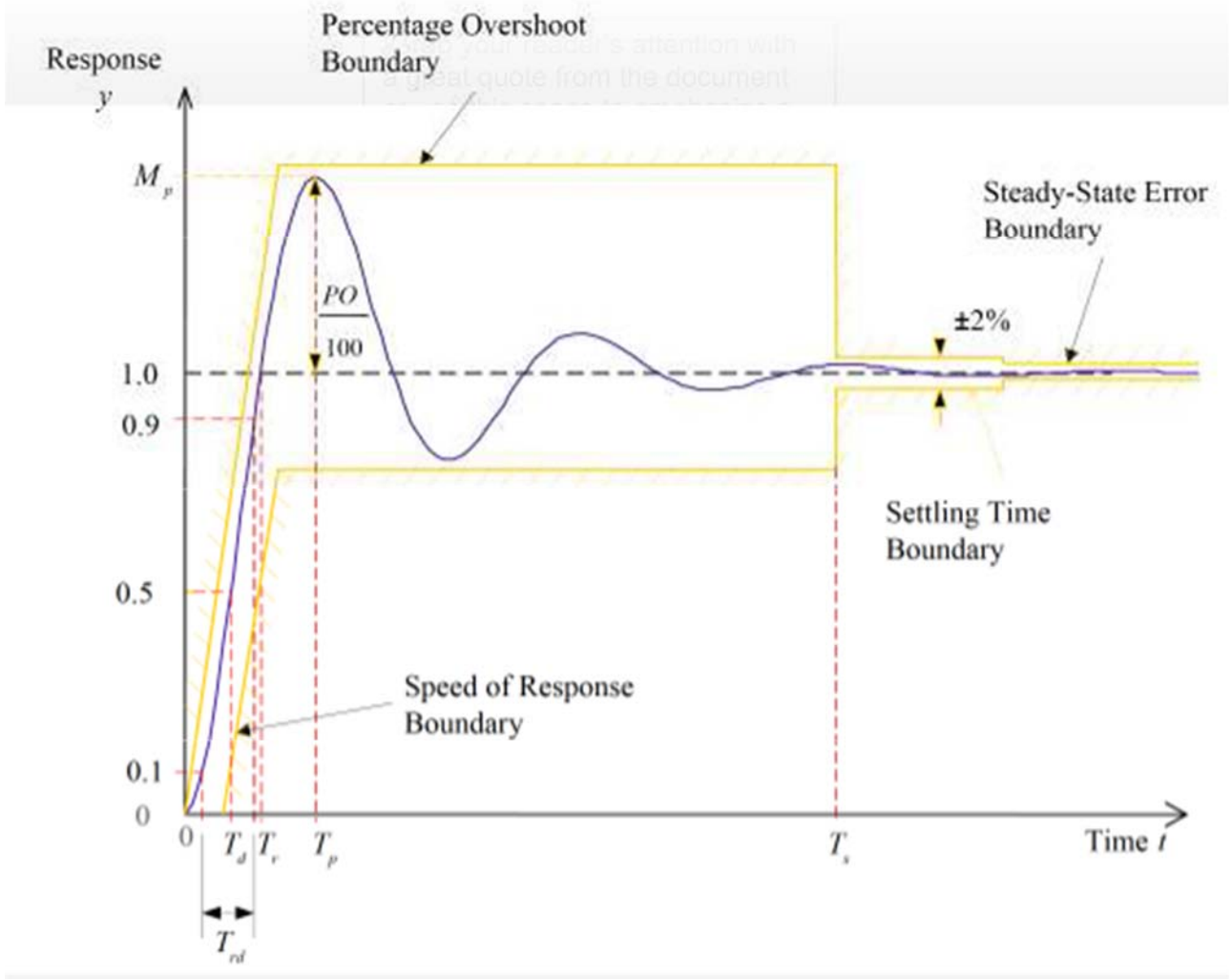


### Example:

Suppose that in Figure on the right, at first  $R_1 = R_2 = R_3 = R_4$ . Now increase  $R_1$  by  $\delta R$ , decrease  $R_2$  by  $\delta R$ . This will represent two active elements that act in reverse, as in the case of two strain gage elements mounted on the top and the bottom surfaces of a beam in bending. Show that the bridge output is linear in  $\delta R$  in this case.

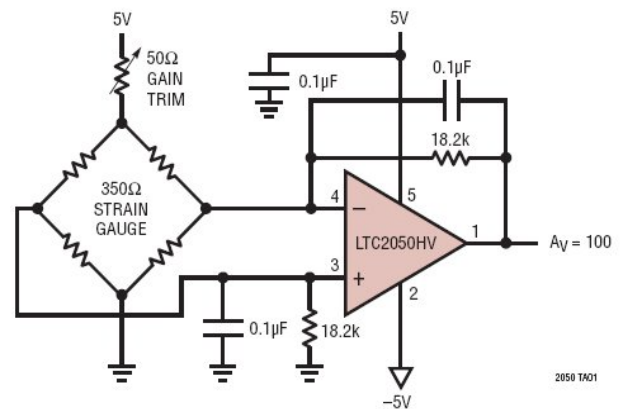
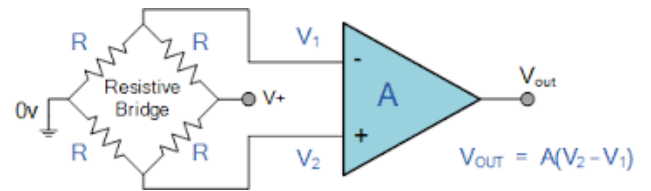


### Solution:



## Bridge Amplifiers:

- The output signal from a resistance bridge is usually very small in comparison to the reference signal, and it has to be amplified to increase its voltage level to a useful value (e.g., for use in system monitoring, data logging, or control).
- This is typically an instrumentation amplifier, which is essentially a sophisticated differential amplifier.
- The bridge amplifier is modeled as a simple gain  $K_a$ , which multiplies the bridge output.



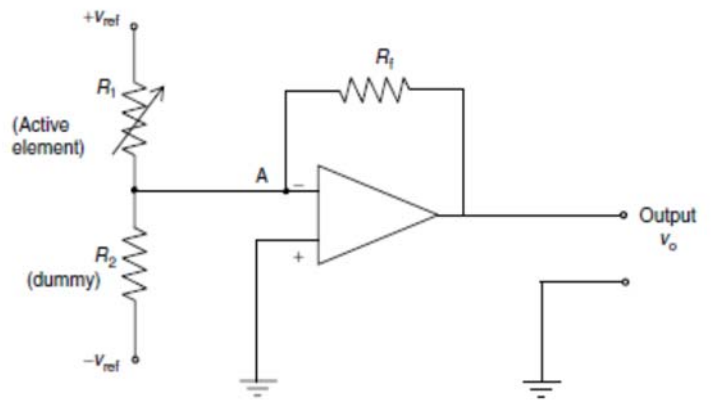
## Half-Bridge Circuits:

- A half bridge has only two arms.
- Output is tapped from the mid-point of these two arms.
- The ends of the two arms are excited by two voltages, one of which is positive and the other negative.
- Initially, the two arms have equal resistances so that nominally the bridge output is zero.
- One of the arms has the active element. Its change in resistance results in a nonzero output voltage.
- It is noted that the half-bridge circuit is somewhat similar to a potentiometer circuit (a voltage divider).

The two bridge arms have resistances  $R_1$  and  $R_2$ , and the output amplifier uses a feedback resistance  $R_f$ .

To get the output equation, we use the two basic facts for an unsaturated op-amp;

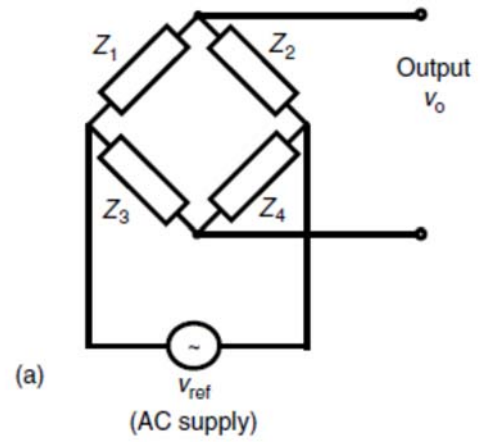
1. The voltages at the two input leads are equal (due to high gain), and
2. The current in either lead is zero (due to high input impedance).



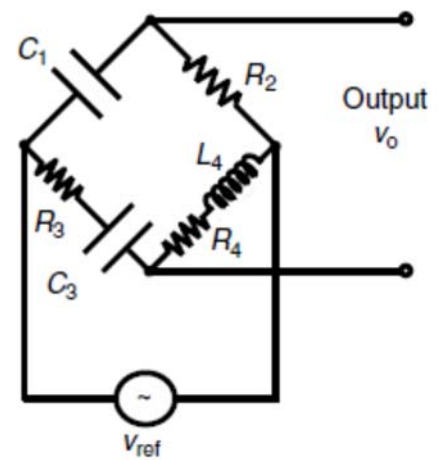
Hence, voltage at node A is zero and the current balance equation at node A is given by:

## Impedance Bridges:

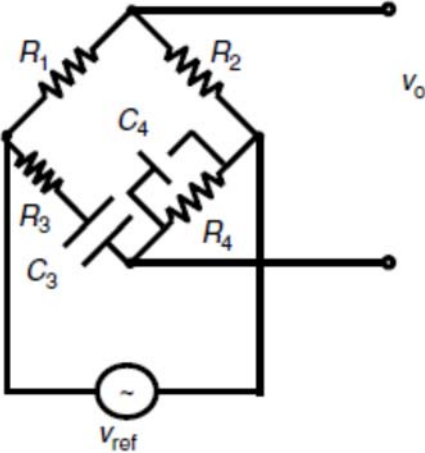
- AC Bridge
- Contains four impedances:  $Z_1, Z_2, Z_3$  and  $Z_4$



## Owen Bridge:



# Wien Bridge Oscillator:



## Response parameters for time-domain specification of performance:

### Delay Time:

This is usually defined as the time taken to reach 50% of the steady-state value for the first time. This parameter is also a measure of speed of response.

### Peak Time

The time at the first peak of the device response is the peak time. This parameter also represents the speed of response of the device.

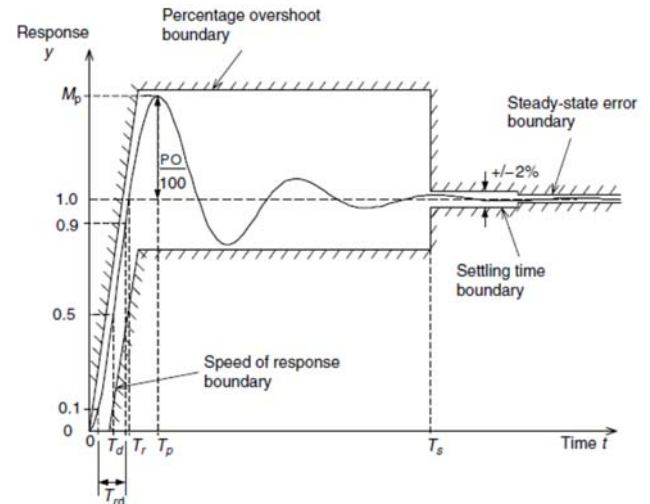
### Settling Time

This is the time taken for the device response to settle down within a certain percentage (typically  $\pm 2\%$ ) of the steady-state value. This parameter is related to the degree of damping present in the device as well as the degree of stability.

### Percentage Overshoot

This is defined as,  $PO = 100(M_p - 1)\%$ , using the normalized-to-unity step response curve, where  $M_p$  is the peak value. Percentage overshoot (PO) is a measure of damping or relative stability in the device.

### Simple Oscillator Model:



**TABLE 3.1**

Time-Domain Performance Parameters Using the Simple Oscillator Model

Performance Parameter	Expression
Rise Time	$T_r = \frac{\pi - \phi}{\omega_d}$ with $\cos \phi = \zeta$
Peak Time	$T_p = \frac{\pi}{\omega_d}$
Peak Value	$M_p = 1 - e^{-\pi \zeta / \sqrt{1-\zeta^2}}$
Percentage Overshoot (PO)	$PO = 100 e^{-\pi \zeta / \sqrt{1-\zeta^2}}$
Time Constant	$\tau = \frac{1}{\zeta \omega_n}$
Settling Time (2%)	$T_s = -\frac{\ln [0.02 \sqrt{1-\zeta^2}]}{\zeta \omega_n} \approx 4\tau = \frac{4}{\zeta \omega_n}$

An automobile weighs 1000 kg. The equivalent stiffness at each wheel, including the suspension system, is approximately  $60.0 \times 10^3$  N/m. If the suspension is designed for a percentage overshoot of 1%, estimate the damping constant that is needed at each wheel.

**Solution:**

### **Active Transducer:**

- External power is required to operate active sensors/transducers, and they do not depend on their own power conversion characteristics for operation.
- A good example for an active device is a resistive transducer, such as a potentiometer, which depends on its power dissipation through a resistor to generate the output signal.
- Note that an active transducer requires a separate power source (power supply) for operation,

### **Passive transducer:**

- Draws its power from a measured signal (measurand).
- Since passive transducers derive their energy almost entirely from the measurand, they generally tend to distort (or load) the measured signal to a greater extent than an active transducer would. Precautions can be taken to reduce such loading effects.
- On the other hand, passive transducers are generally simple in design, more reliable, and less costly.
- For example, a piezoelectric charge generation is a passive process. But, a charge amplifier, which uses an auxiliary power source, would be needed by a piezoelectric device in order to condition the generated charge.

### **Error Analysis:**

- $\text{Error} = (\text{instrument reading}) - (\text{true value})$
- **Measurement Accuracy:** Determines the closeness of the measured value to the true value
- **Instrument Accuracy:** Related to the worst accuracy obtainable within the dynamic range of the instrument in a specific operating environment

## More discussion on Active and Passive Sensors:

- **An active sensor** is a sensing device that requires an external source of power to operate; active sensors contrast with passive sensors, which simply detect and respond to some type of input from the physical environment.
- In the context of remote sensing, an active sensor is a device with a transmitter that sends out a signal, light wavelength or electrons to be bounced off a target, with data gathered by the sensor upon their reflection.
- Active sensors are also widely used in manufacturing and networking environments for example to monitor industrial machines or data center infrastructure so anomalies can be detected and components can be repaired or replaced before they break and shut everything down.
- **Examples of other active sensor-based technologies include:** scanning electron microscopes, radar, GPS, x-ray, sonar, infrared and seismic. However, as can be the case with some sensors, seismic and infrared light sensors exist in both active and passive forms.
- **A passive sensor** is a device that detects and responds to some type of input from the physical environment.
- Passive sensor technologies gather target data through the detection of vibrations, light, radiation, heat or other phenomena occurring in the subject's environment.
- They contrast with active sensors, which include transmitters that send out a signal, a light wavelength or electrons to be bounced off the target, with data gathered by the sensor upon their reflection.
- Sensors can also be used in harsh environments and places inaccessible to people.
- **Examples of passive sensor-based technologies include:** Photographic, thermal, electric field sensing, chemical, infrared and seismic. However, as can be the case with some sensors, seismic and infrared light sensors exist in both active and passive forms.

## Linearizing Devices:

- Nonlinearity is present in any physical device, to varying levels.
- If the level of nonlinearity in a system (component, device, or equipment) can be neglected without exceeding the error tolerance, then the system can be assumed linear.
- Linear system is one that can be expressed as one or more linear differential equations.
- Note that the principle of superposition holds for linear systems.

## Nonlinearities in a system can appear in two forms:

- Dynamic manifestation of nonlinearities
- Static manifestation of nonlinearities

## Cases:

- The useful operating region of a system can exceed the frequency range where the frequency response function is flat. The operating response of such a system is said to be dynamic.
  - Examples include a typical control system (e.g., automobile, aircraft, milling machine, robot), actuator (e.g., hydraulic motor), and controller (e.g., proportional-integral-derivative or PID control circuitry).
- Nonlinearities of such systems can manifest themselves in a dynamic form such as the jump phenomenon (also known as the fold catastrophe), limit cycles, and **frequency creation**.

### Solutions for dynamic manifestations of nonlinearity:

- Design changes, extensive adjustments, or reduction of the operating signal levels and bandwidths would be necessary in general, to reduce or eliminate.

### Is that a good Solution?

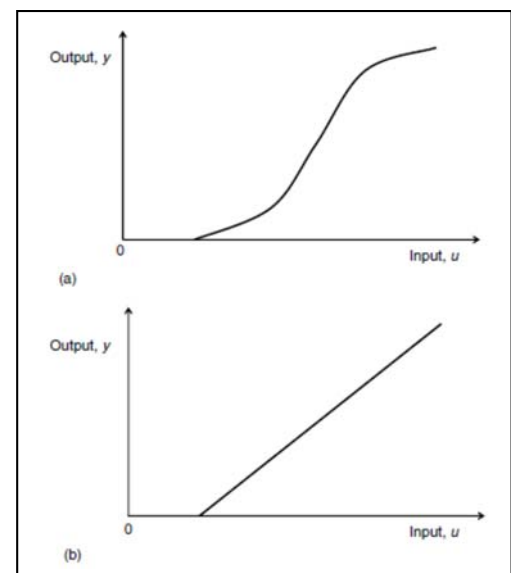
- In many instances, such changes would not be practical, and we may have to *somehow cope with the presence of these nonlinearities* under dynamic conditions.
- Design changes might involve:
  - Replacing conventional gear drives by devices such as harmonic drives to reduce backlash.
  - Replacing nonlinear actuators by linear actuators, and
  - Using components that have negligible Coulomb friction and that make small motion excursions.

### What is Coulomb Friction?

- Coulomb friction is a *simplified quantification* of the friction force that exists between two dry surfaces in contact with each other.
- All friction calculations are approximations, and this measurement is dependent only on the fundamental principles of motion.
- It assumes that the contact surfaces are fairly uniform and that the coefficient of friction that must be overcome for motion to begin is well-established for the materials in contact.

## What about Static Manifestations:

- Making design changes and adjustments, as in the case of dynamic devices.
- Since the response is static, and since we normally deal with an available device (fixed design) whose internal hardware cannot be modified,
- We should consider ways of linearizing the input/output characteristic by *modifying the output* itself.
  - Linearization using digital software
  - Linearization using digital (logic) hardware
  - Linearization using analog circuitry
- **In the software approach to linearization:**
  - Output of the device is read into a digital processor with software-programmable memory
  - *And the output is modified* according to the program instructions.
- **In the hardware approach:**
  - Output is read by a device with *fixed logic circuitry for processing (modifying)* the data.
- **In the analog approach:**
  - A *linearizing circuit is directly connected at the output of the device*, so that the *output of the linearizing circuit is proportional to the input* to the original device.



## Software based linearization:

Assuming that the nonlinear relationship between the input and the output of a nonlinear device is known, the input can be computed for a known value of the output.

In the software approach of linearization, a processor and memory that can be programmed using software (i.e., a digital computer) is used to compute the input using output data.

Analysis:

- Flexible - Linearization algorithm can be modified (e.g., improved, changed) simply by modifying the program stored in the RAM.
- Highly complex nonlinearities can be handled by the software method.
- Relatively slow.

## Linearization by Hardware Logic:

- Hardware logic method:
  - Linearization algorithm is permanently implemented in the IC form using appropriate digital logic circuitry for data processing and memory elements (e.g., flip-flops).
- However, *algorithm and numerical values of parameters* (except input values) cannot be modified without redesigning the IC chip, because a hardware device typically does not have programmable memory.
- Difficult to implement very complex linearization algorithms –Mass chip production, initial chip development cost? Testing for our needs only?
- Lack of Flexibility - A digital linearizing unit with a processor and a read-only memory (ROM), whose program cannot be modified, also lacks the flexibility of a programmable software device.

## Analog Linearizing Circuitry

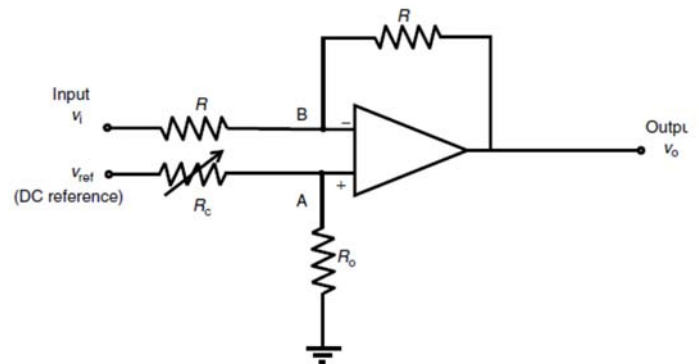
Three types of analog linearizing circuitry can be identified:

- Offsetting circuitry
- Circuitry that provides a proportional output
- Curve shapers

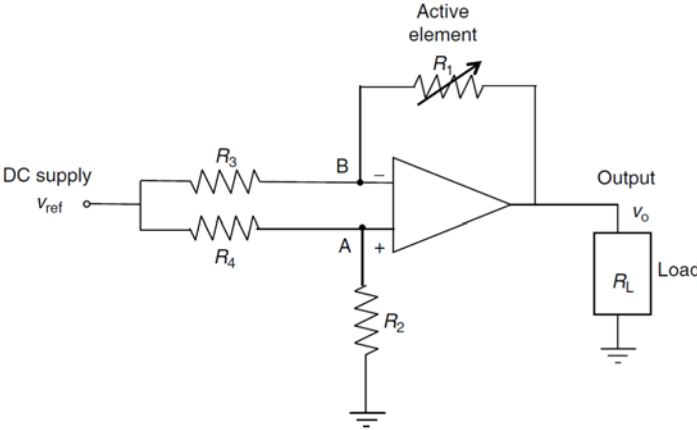
### Offsetting circuitry:

- An offset is a nonlinearity that can be easily removed using an analog device.
- Adding a dc offset of equal value to the response, in the opposite direction. Deliberate addition of an offset in this manner is known as offsetting.
- The associated removal of original offset is known as offset compensation.
- Example:
  - Results of ADC and DAC can be removed by analog offsetting.
  - Constant (dc) error components, such as steady-state errors in dynamic systems due to load changes, gain changes, and other disturbances, can be eliminated by offsetting.

Easiest Approach - Use Summer Op-Amp (Add or subtract)



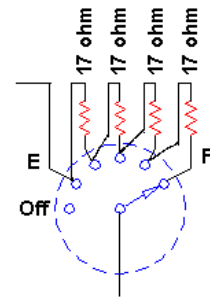
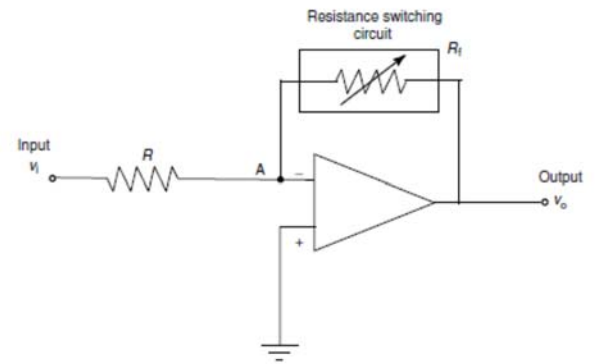
# Proportional-Output Circuitry:



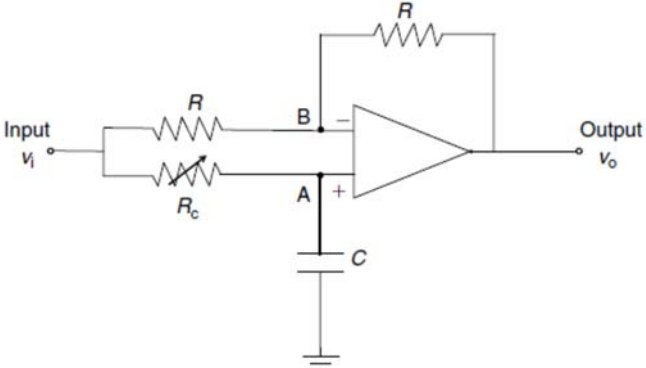
$$v_o = v_A - v_B = \frac{R_1 v_{\text{ref}}}{(R_1 + R_2)} - \frac{R_3 v_{\text{ref}}}{(R_3 + R_4)} = \frac{(R_1 R_4 - R_2 R_3)}{(R_1 + R_2)(R_3 + R_4)} v_{\text{ref}}.$$

## Curve Shaping Circuitry:

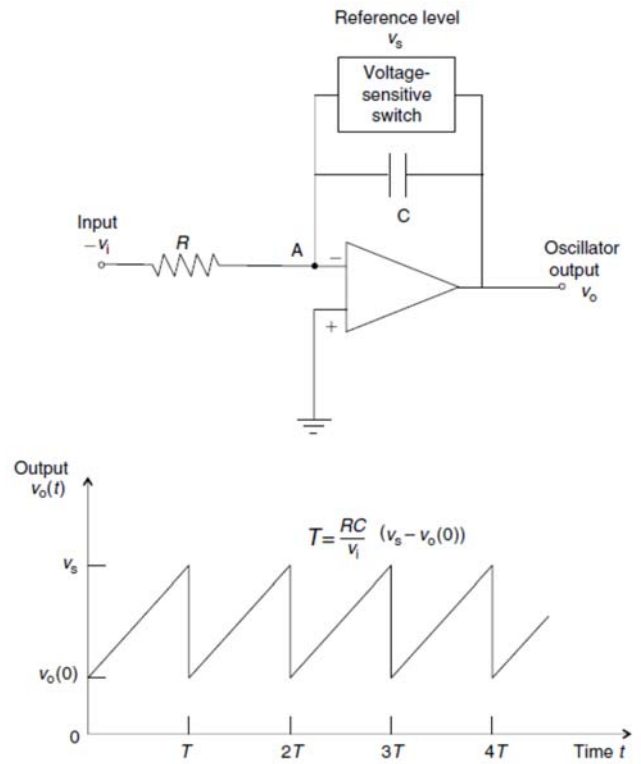
- Sort of like an amplifier with adjustable gain.
- Adjustable Feedback resistor  $R_f$
- Bank of resistors and automatic switching can be deployed using Zener diodes.



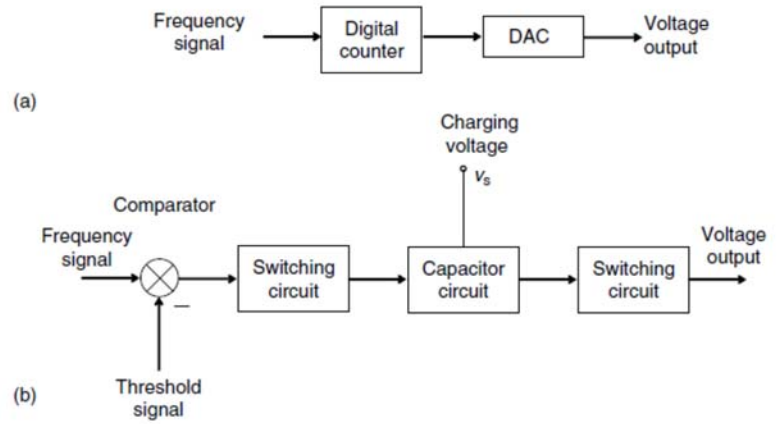
**Phase Shifters:**



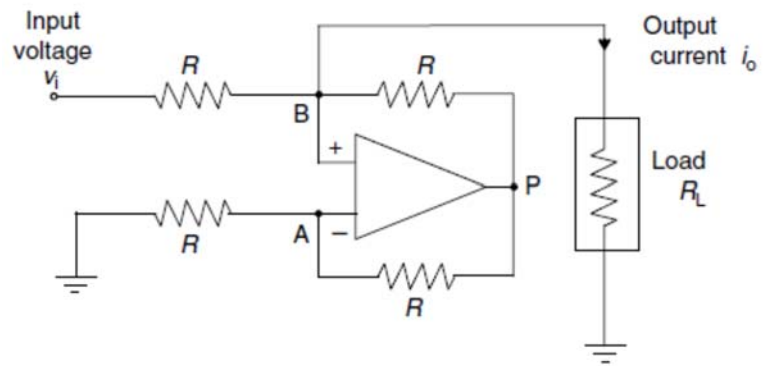
## Voltage to Frequency Converter:



## Frequency to Voltage Convertor



## Voltage to Current Convertor:



## Chapter-4

Motion Transducers: By motion, we particularly mean one or more of the following four kinematic variables:

- Displacement (including position, distance, proximity, size or gage)
- Velocity (rate of change of displacement)
- Acceleration (rate of change of velocity)
- Jerk (rate of change of acceleration)

### Examples:

- Rotating speed of a work-piece and the feed rate of a tool are measured in controlling machining operations.
- Displacements and speeds (both angular and translator) at joints (revolute and prismatic) of robotic manipulators or kinematic linkages are used in controlling manipulator trajectory.
- In high-speed ground transit vehicles, acceleration and jerk measurements can be used for active suspension control to obtain improved ride quality.
- Angular speed is a crucial measurement that is used in the control of rotating machinery, such as turbines, pumps, compressors, motors, transmission units or gear boxes, and generators in power generating plants.
- Proximity sensors (to measure displacement) and accelerometers (to measure acceleration) are the two most common types of measuring devices used in machine protection systems for condition monitoring, fault detection, diagnostic, and online (often real-time) control of large and complex machinery.

**Question:** *Is there a need for separate transducers to measure the four kinematic variables above, because any one variable is related to the other through simple integration or differentiation.*

**Answer:** Very limited and depends on many factors:

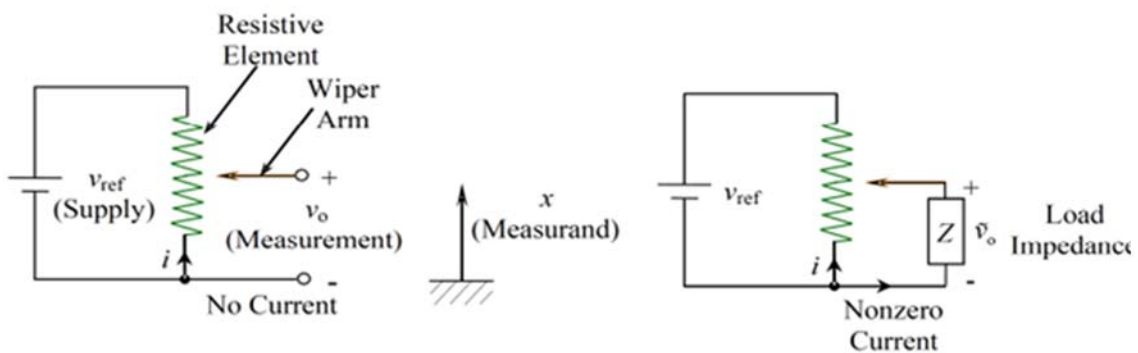
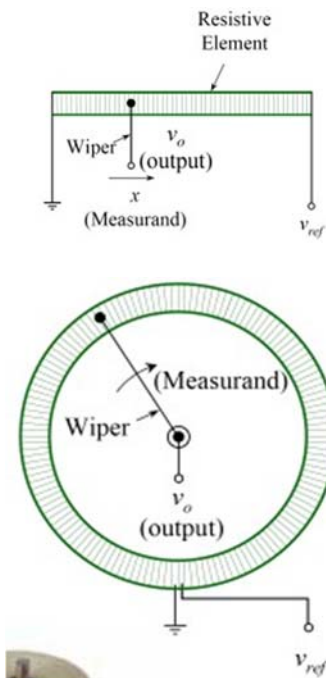
- *Signal characteristics: (e.g., steady, highly transient, periodic, NB, BB)*
- *The required frequency content of the processed signal*
- *The signal-to-noise ratio (SNR) of the measurement*
- *Processing capabilities (e.g., analog or digital processing, limitations of the digital processor and interface; processing speed, sampling rate, and buffer size)*
- *Controller requirements and the nature of the plant (e.g., time constants, delays, complexity, hardware limitations)*
- *Required accuracy as the end objective (on which processing requirements and Hardware costs depend)*

## Motion Transducers:

- Potentiometers (resistively coupled)
- Variable inductance (electromagnetically coupled)
- Variable capacitance
- Eddy current
- Piezoelectric

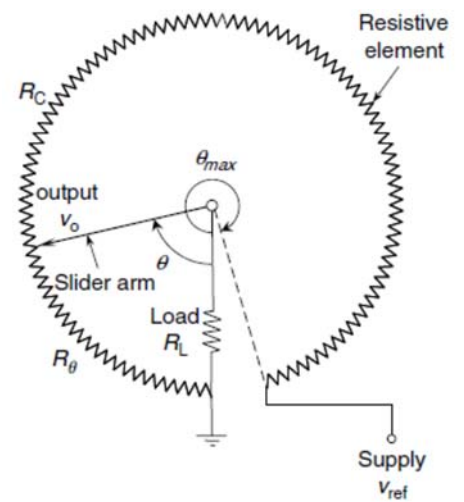
## Potentiometer:

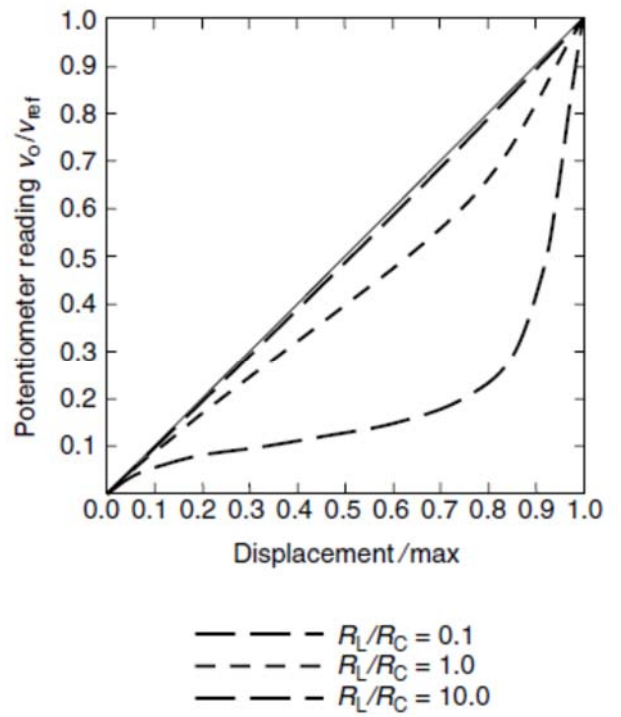
- Uniform coil of wire or a film of high resistive material- Carbon, platinum, or conductive plastic.



## Loading Nonlinearity:

- What is the significance of the electrical loading nonlinearity error caused by a purely resistive load connected to the pot?





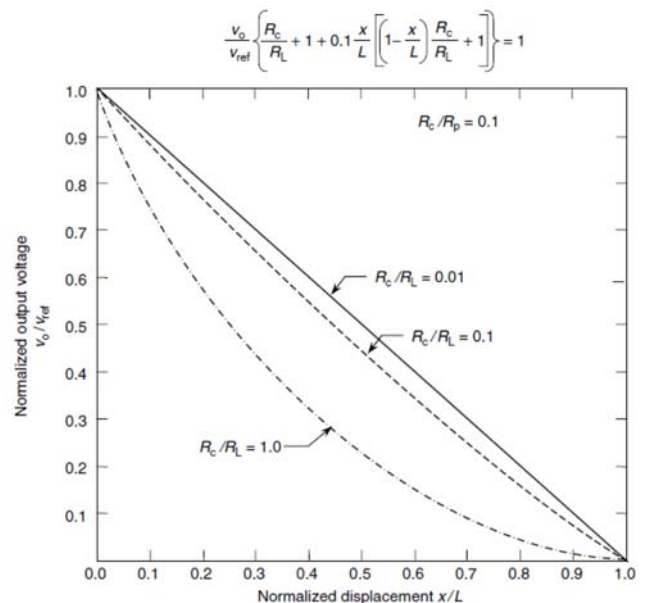
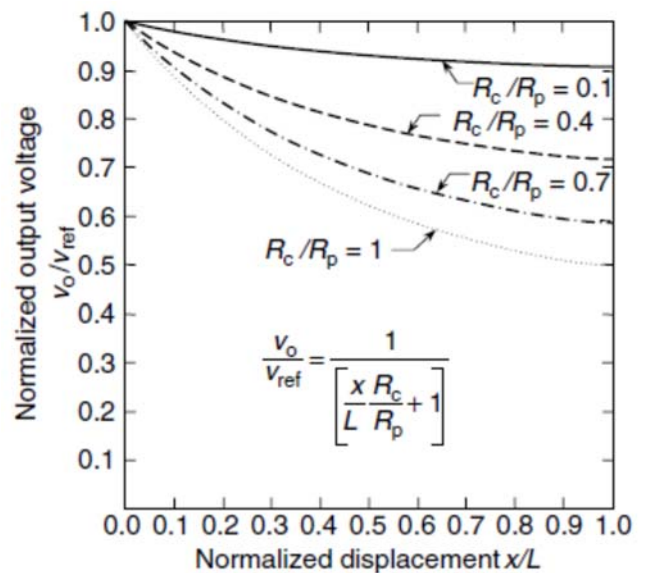
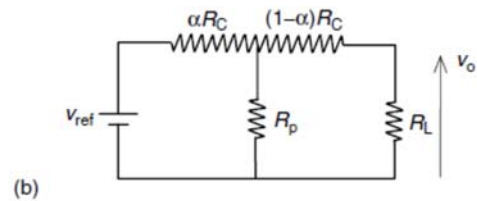
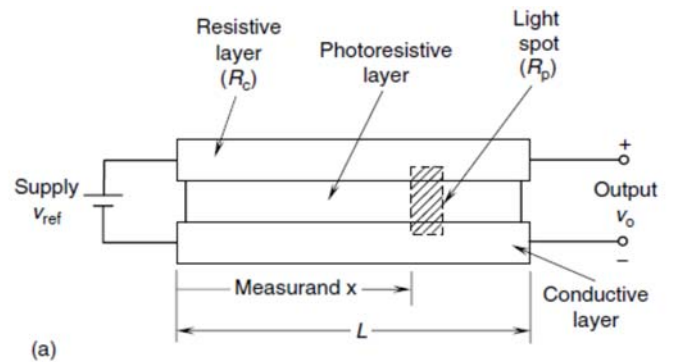
**Example:**

A high-precision mobile robot uses a potentiometer attached to the drive wheel to record its travel during autonomous navigation. The required resolution for robot motion is 1 mm, and the diameter of the drive wheel of the robot is 20 cm. Examine the design considerations for a standard (single-coil) rotatory potentiometer to be used in this application.

Solution:

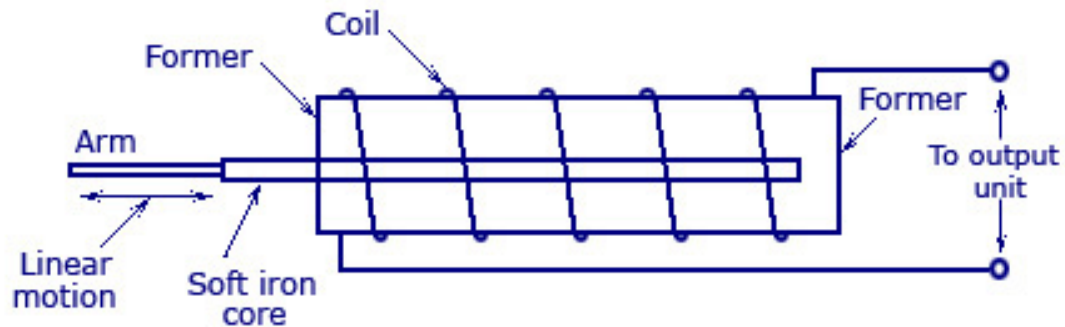
## Optical Potentiometer:

The optical potentiometer, shown is a displacement sensor. A layer of photoresistive material is sandwiched between a layer of ordinary resistive material and a layer of conductive material.



## Variable Inductance Transducers:

- When the flux linkage (defined as magnetic flux density times the number of turns in the conductor) through an electrical conductor changes, *a voltage in proportion to the rate of change of flux* is induced in the conductor.



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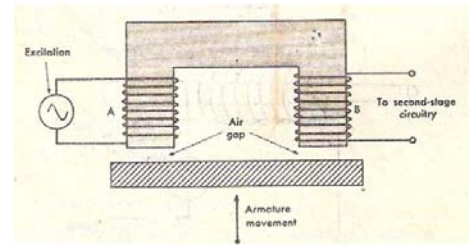
- This voltage in turn, generates a magnetic field, which opposes the original (primary) field. Hence, a mechanical force is necessary to sustain the change of flux linkage.
- If the change in flux linkage is brought about by a relative motion, the associated mechanical energy is directly converted (induced) into electrical energy.
- This is the basis of electromagnetic induction, and it is the principle of operation of electrical generators and variable-inductance transducers.
- *The induced voltage or change in inductance may be used as a measure of the motion.*

Three primary types can be identified as:

- Mutual-induction transducers
- Self-induction transducers
- Permanent-magnet transducers.

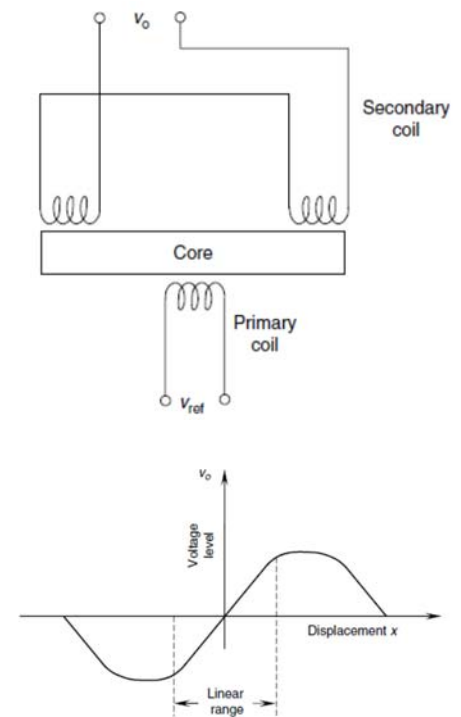
## Mutual-induction transducers:

- Arrangement of a mutual-induction transducer constitutes two coils, the primary winding and the secondary winding. One of the coils (primary winding) carries an alternating-current (ac) excitation, which induces a steady ac voltage in the other coil (secondary winding).
- The level (amplitude, rms-value, etc.) of the induced voltage depends on the flux linkage between the coils.
- None of these transducers employ contact sliders or slip-rings and brushes as do resistively coupled transducers (potentiometer) which results in increased design life and low mechanical loading.
- In mutual-induction transducers, a change in the flux linkage is effected by one of two common techniques.
  - One technique is to *move an object made of ferromagnetic material within the flux path between the primary coil and the secondary coil.*
  - The other common way to *change the flux linkage is to move one coil with respect to the other.*
  - Motion can be measured by using the secondary signal (i.e., induced voltage in the secondary coil).

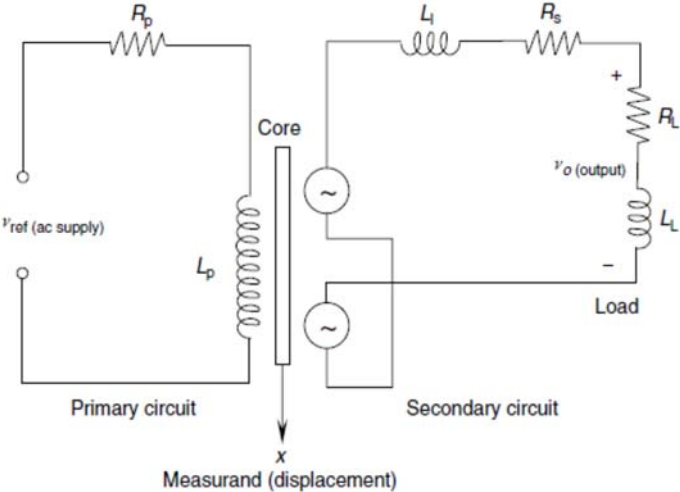


## Linear-Variable Differential Transformer (LVDT)

- As the core moves, the reluctance of the flux path between the primary and the secondary coils changes.
- The *degree of flux linkage* depends on the axial position of the core.
- Since the two secondary coils are connected in series opposition, so that the potentials induced in the two secondary coil segments oppose each other, it is seen that the *net induced voltage is zero when the core is centered between the two secondary winding segments. This is known as the null position.* When the core is displaced from this position, a nonzero induced voltage is generated. At steady state, the amplitude  $V_0 \propto$  Core displacement  $x$  in the linear (operating) region. Consequently,  $V_0$  may be used as a *measure of the displacement.*
- Note that because of opposed secondary windings, the LVDT provides the direction as well as the magnitude of displacement.



**Linear-Variable Differential Transformer (LVDT) Equivalent Circuit.**



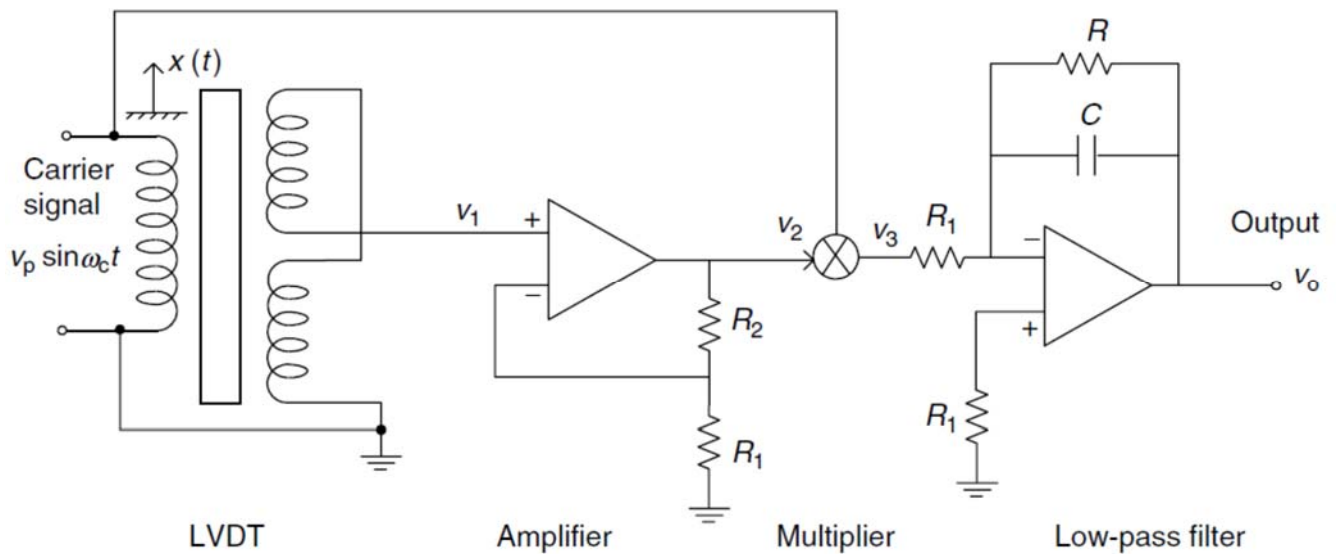


## Signal Conditioning:

- Signal Amplification – increase signal strength so we can interpret it.
- Filtering – need exactly the signals we require for interpreting it properly.
- Improving SNR – filter out unwanted so actual signal quality is better and Noise (unwanted) signal is suppressed.

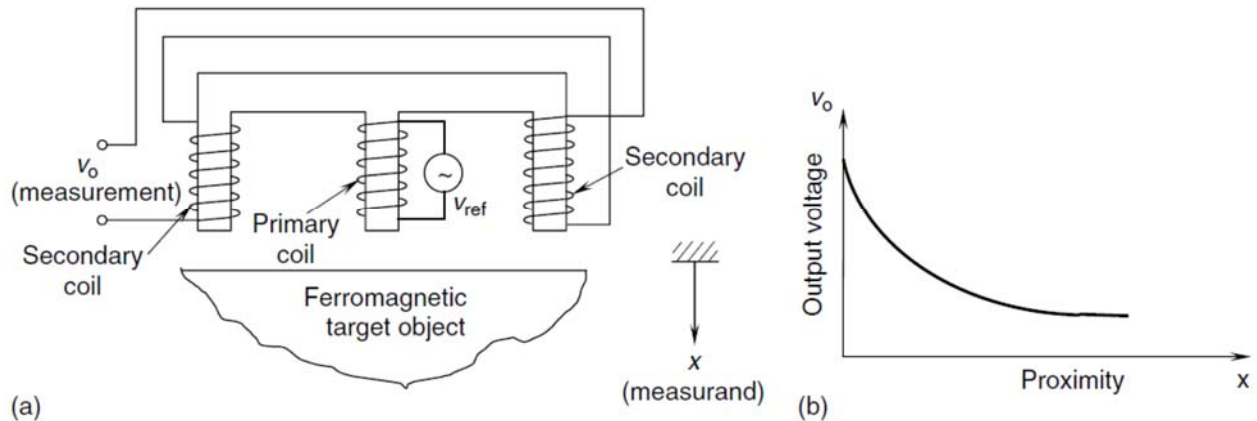
### Example:

Figure shows a schematic diagram of a simplified signal-conditioning system for an LVDT.



*See LVDT Example for more details.*

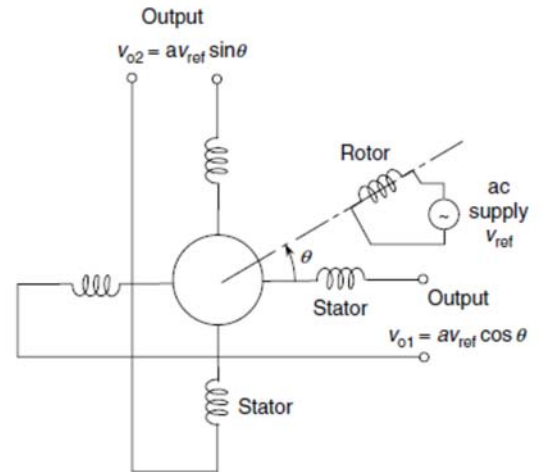
## Mutual Induction Proximity Sensor:



- Displacement transducer also operates on the mutual-induction principle.
- The insulating ***E-shaped*** core carries the primary winding in its middle limb. The two end limbs carry secondary windings, which are ***connected in series***. Unlike the LVDT and the RVDT, the two voltages induced in the secondary winding segments are additive in this case.
- Proximity sensors are used in a wide variety of applications pertaining to non-contacting displacement sensing and dimensional gaging. Few applications are:
  - Measurement and control of the gap between a robotic welding torch head and the work surface.
  - Gaging the thickness of metal plates in manufacturing operations (e.g., rolling and forming).
  - Angular speed measurement at steady state, by counting the number of rotations per unit time
  - Level detection (e.g., in the filling, bottling, and chemical process industries)

**Resolver:** This mutual-induction transducer is widely used for measuring angular displacements.

- Rotor contains the primary coil & It consists of a **single two-pole winding element** energized by an ac supply voltage  $V_{ref}$
- Rotor is directly attached to the object whose rotation is measured.
- **Stator** consists of two sets of windings placed  $90^\circ$  apart.
- If the angular position of the rotor with respect to one pair of stator windings is denoted by  $\theta$ , the induced voltage in this pair of windings is given by:



## **Demodulation:**

- As for differential transformers (i.e., LVDT and RVDT) transient displacement signals of a resolver can be extracted by demodulating its (modulated) outputs.
- This is accomplished by filtering out the carrier signal, thereby extracting the modulating signal.

### Synchro Transformer:

The “synchro” is somewhat similar in operation to the resolver. The main differences are that the synchro employs two identical rotor–stator pairs, and each stator has three sets of windings, which are placed  $120^\circ$  apart around the rotor shaft.

