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:

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

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

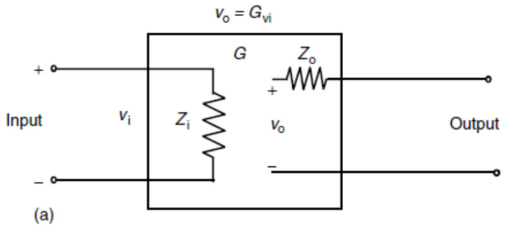
- O/C voltage at output is the output voltage present when there is no current flowing at the output port. This is the case if the output port is not connected to a load (impedance). *As soon as a load is connected at the output of the device, a current flows through it, and the output voltage drops 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.

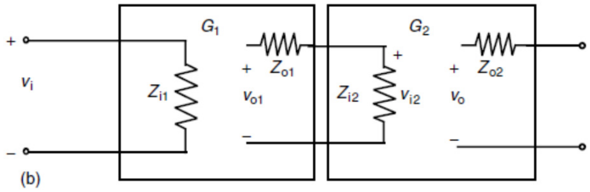
The output impedance: $Z_i = \frac{Rated\ input\ Volatge}{corresponding\ current\ through\ the\ input\ terminals}$

While Output terminals are maintained in O/C.

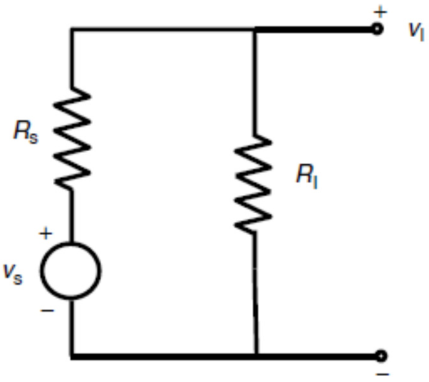
Z_0 and Z_i can be represented as shown in the diagram.

- 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:

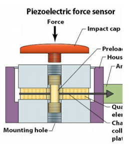


- When two electrical components are interconnected, current (and energy) flows between the two components and changes the original (unconnected) conditions. *This is known as the (electrical) loading effect, and it has to be minimized.*
- At the same time, adequate power and current would be needed 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.

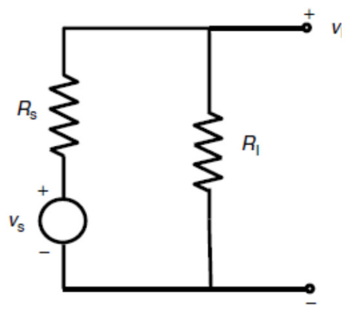


- *In such cases, the input impedance of the signal-conditioning unit might be inadequate to reduce loading effects;*
- *Also, the output signal level of these high impedance sensors is quite low for signal transmission, processing, actuation, and control.*
- *The solution for this problem is to introduce 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.*

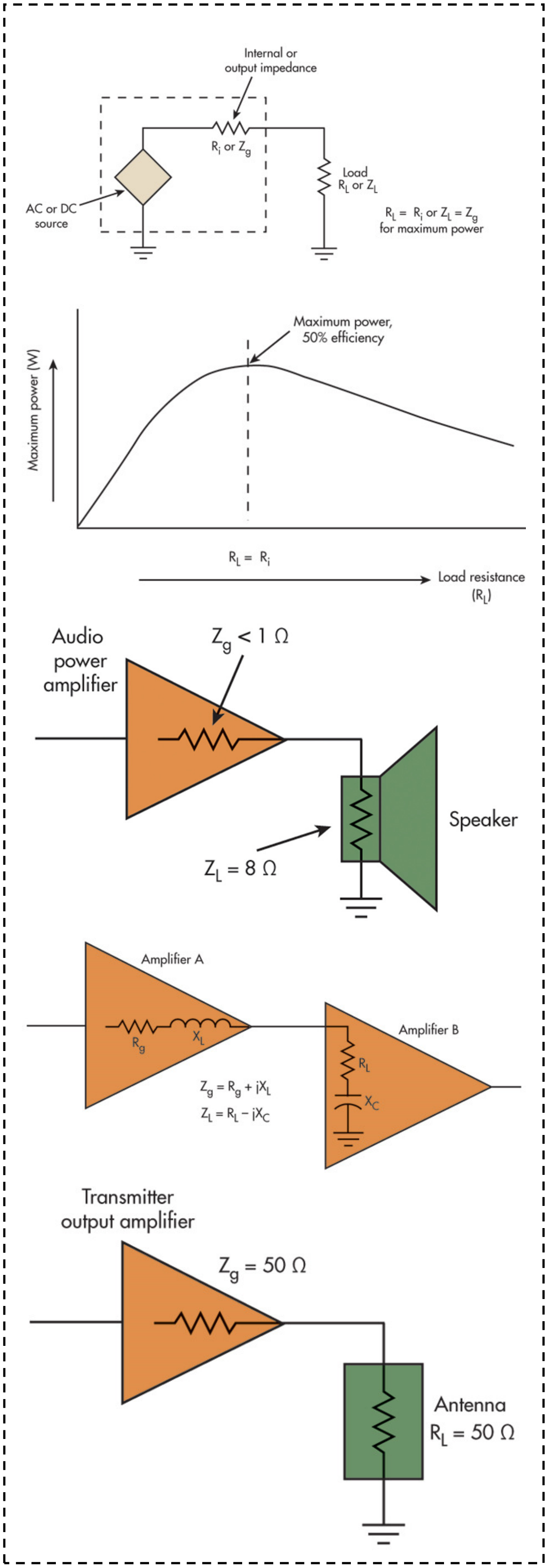
When connecting a device to a signal source, loading problems can be reduced by making sure that the device has a high input impedance.

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.

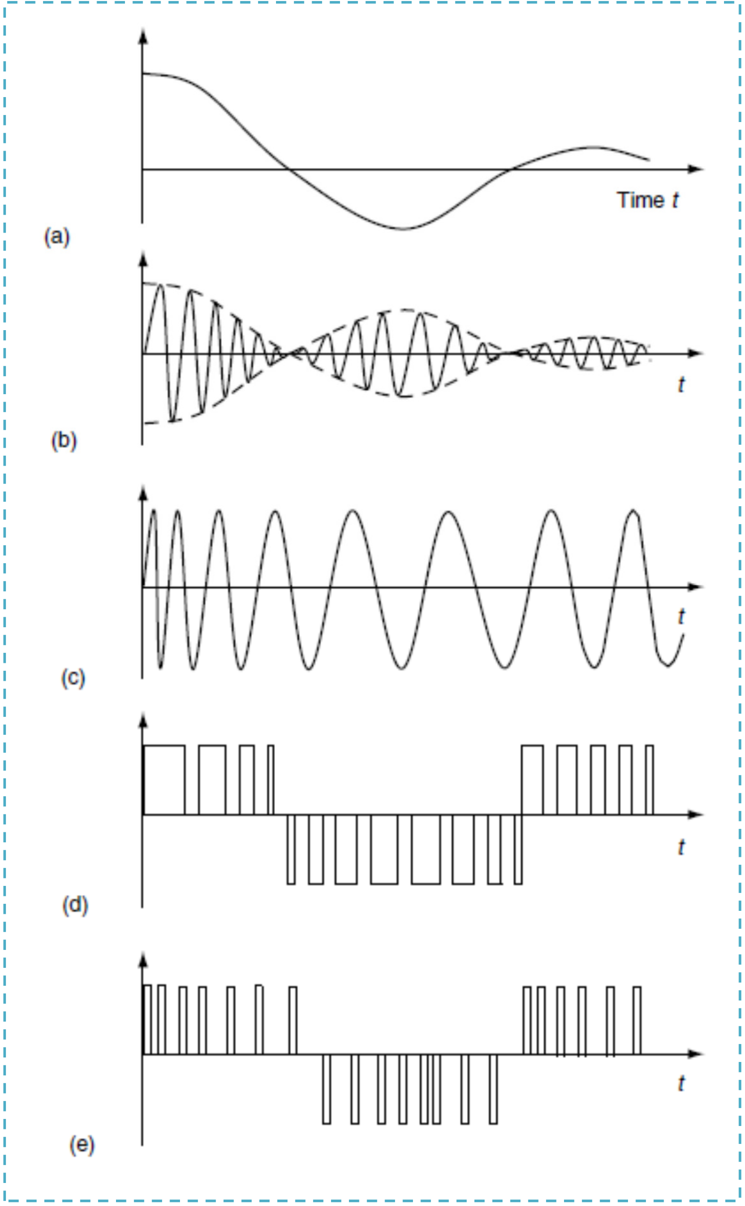
In many data acquisition systems, output impedance of the output amplifier is made equal to the transmission line impedance. When maximum power amplification is desired, conjugate matching is recommended. In this case, input and output impedances of the matching amplifier are made equal to the complex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



Using Complex Impedance:



Modulation:



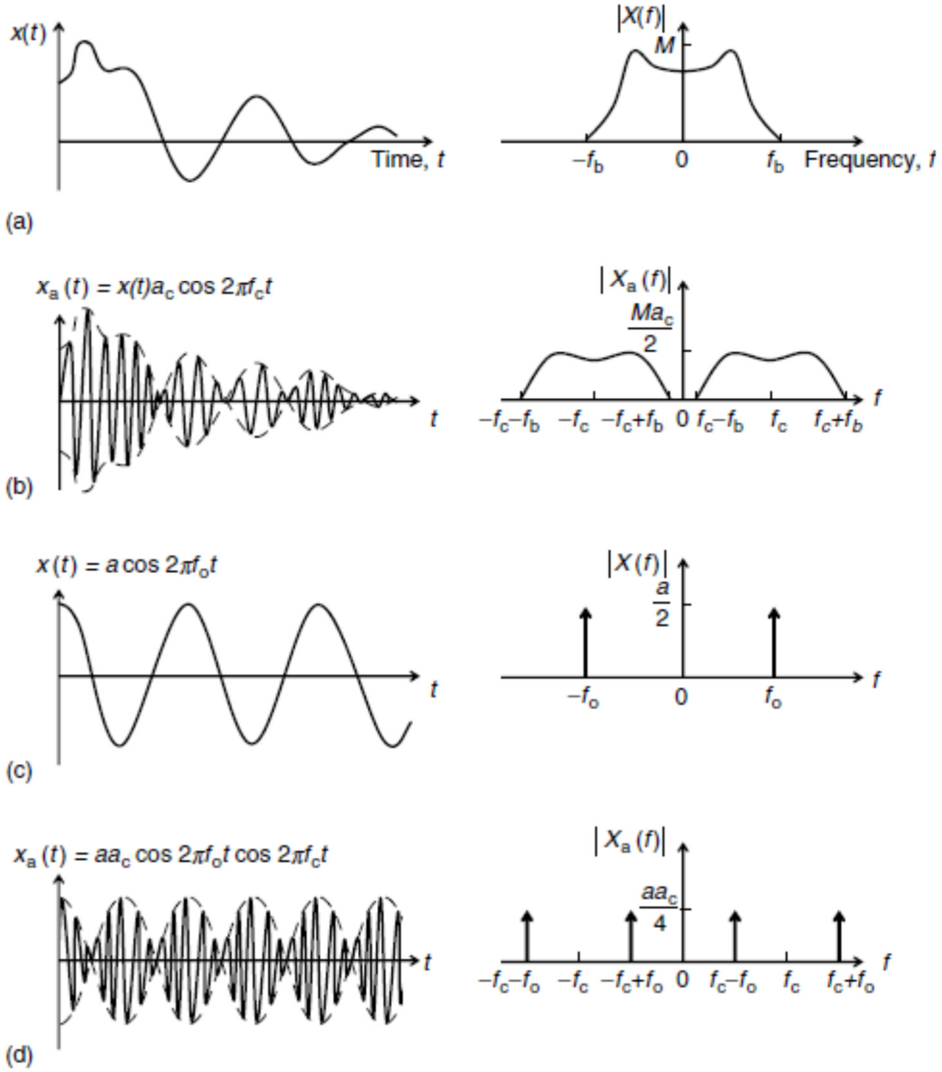
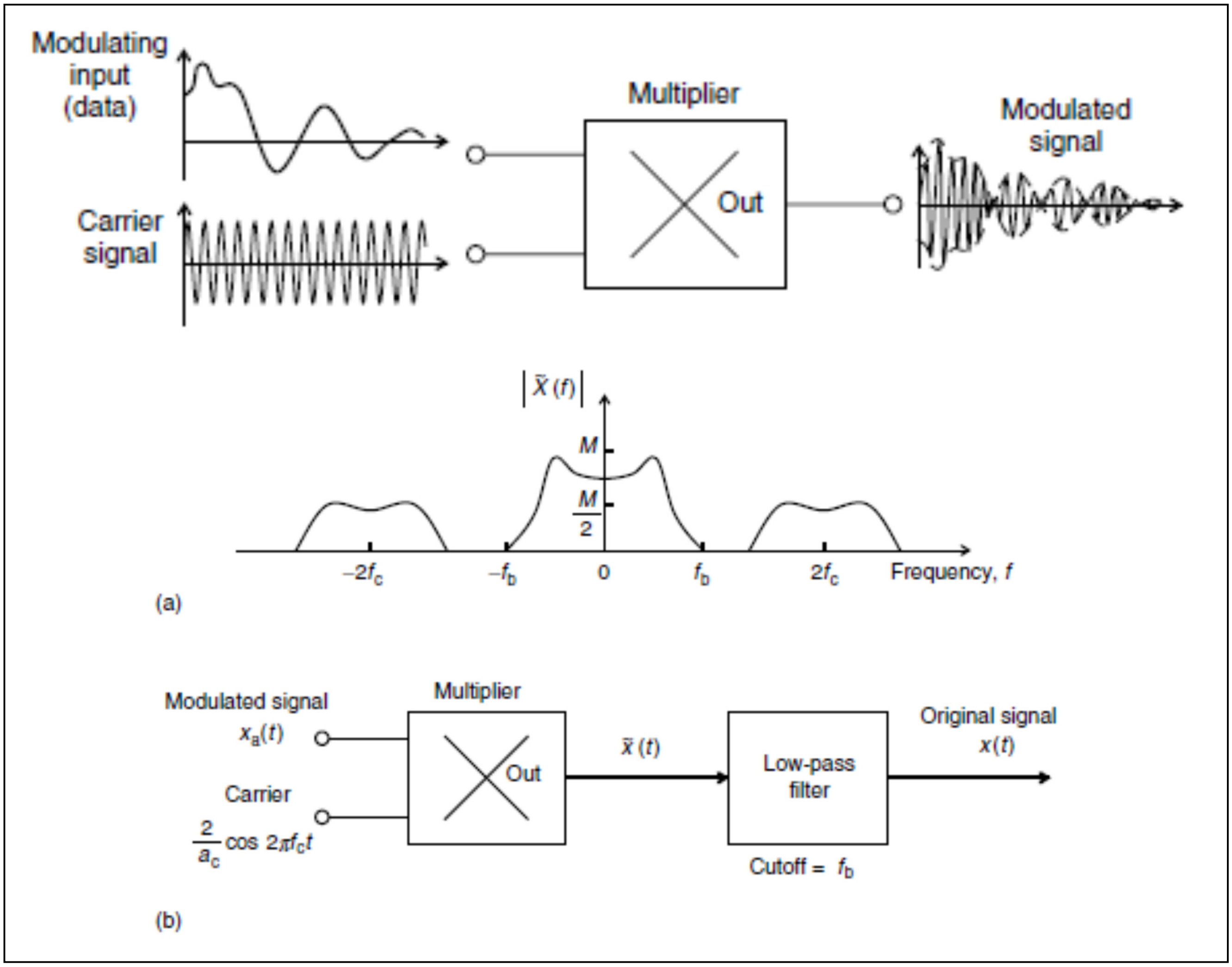


FIGURE 2.22

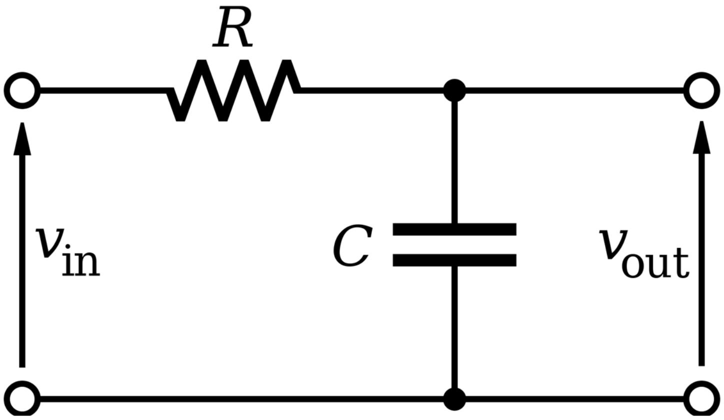
Illustration of the modulation theorem. (a) A transient data signal and its Fourier spectrum magnitude. (b) Amplitude-modulated signal and its Fourier spectrum magnitude. (c) A sinusoidal data signal. (d) Amplitude modulation by a sinusoidal signal.

Modulation and De-Modulation:



Consider the modulated signal above:

Low Pass Filter with a cut-off:



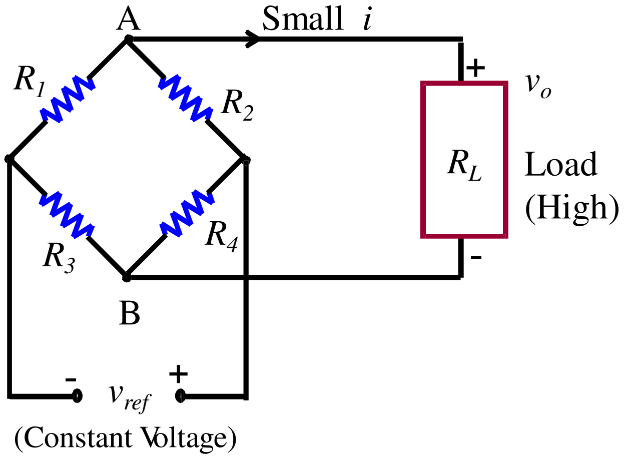
What if you applied a sine wave to this filter?

What if you applied a Step Function to this filter?

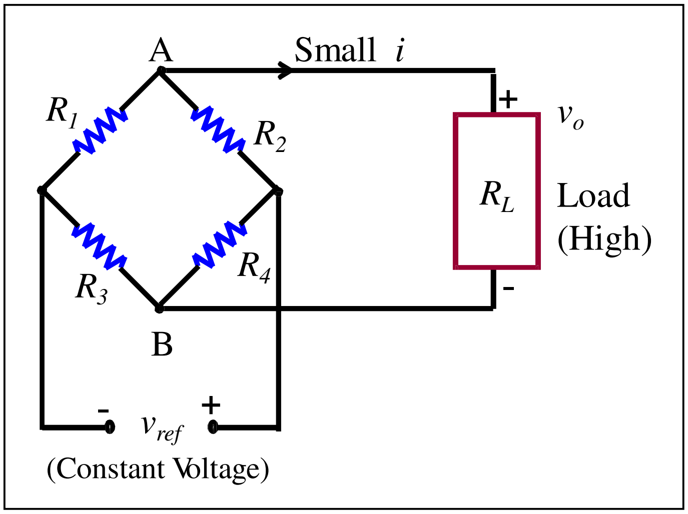
Bridge Circuits:

Bridge circuits are used to make a form of measurement:

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

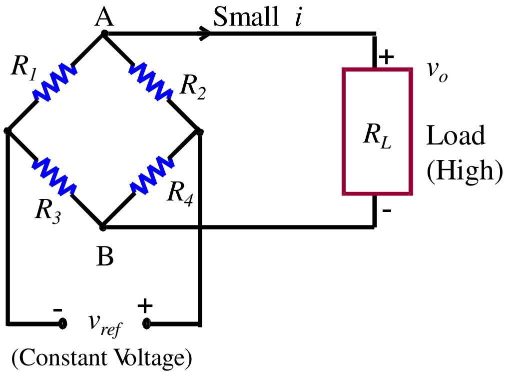


Continuing

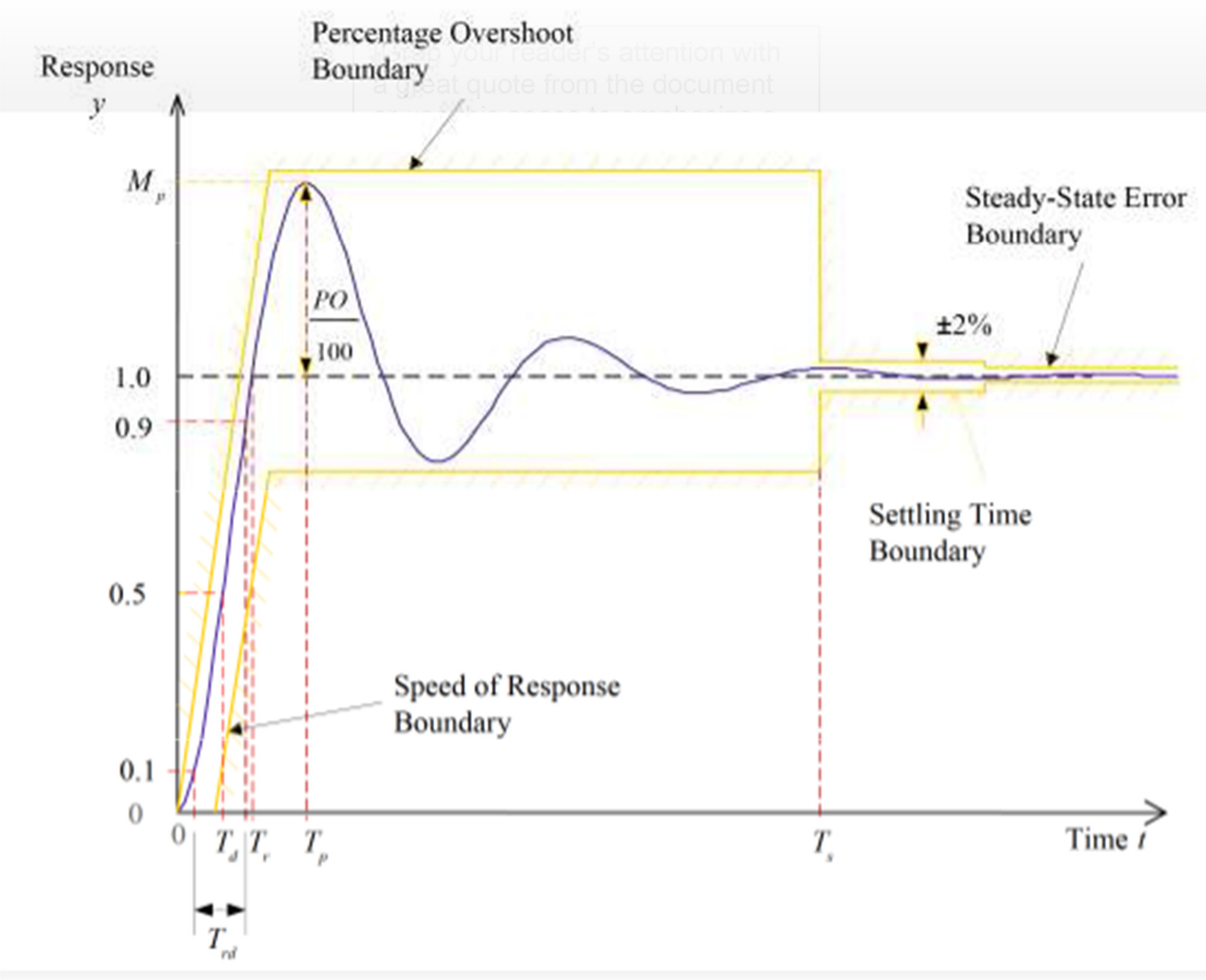


Example:

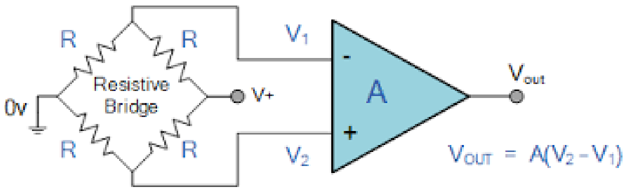
Suppose that in Figure on the right, at first $R_1 = R_2 = R_3 = R_4$. Now increase R_1 by δR, decrease R_2 by δR. This will represent two active elements that act in reverse, as in the case of two strain gage elements mounted on the top and the bottom surfaces of a beam in bending. Show that the bridge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

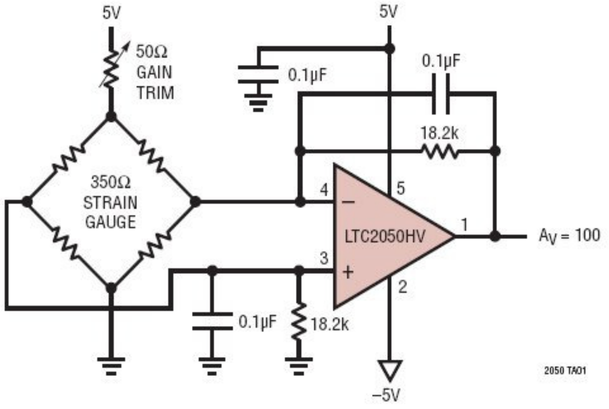


Solution:


Response
y
Percentage Overshoot
Boundary
M_p
PO/100
Steady-State Error
Boundary
±2%
1.0
0.9
0.5
0.1
0
Settling Time
Boundary
Speed of Response
Boundary
0
T_d
T_r
T_p
T_s
Time t
T_{rd}

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).

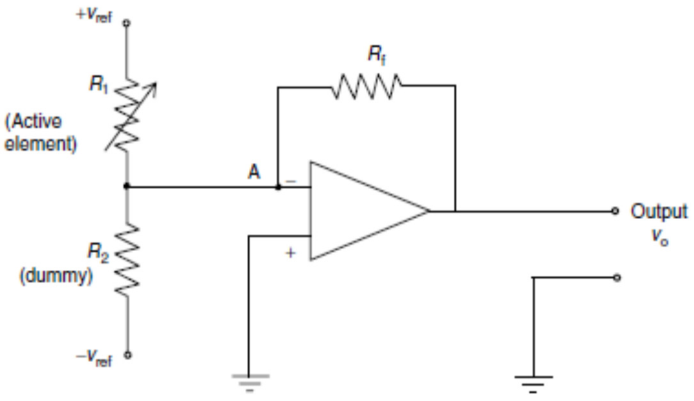
- This is typically an instrumentation amplifier, which is essentially a sophisticated differential amplifier.

- 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 resistanceR_f.



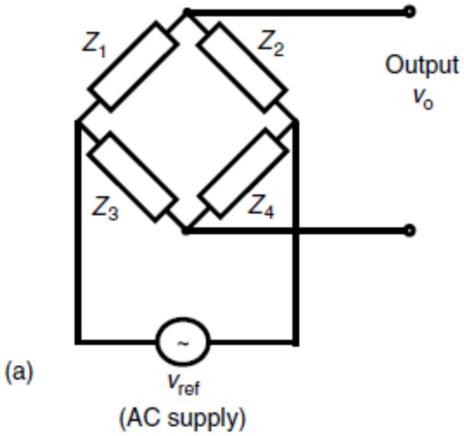
To get the output equation, we use the two basic facts for an unsaturated op-amp;

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).

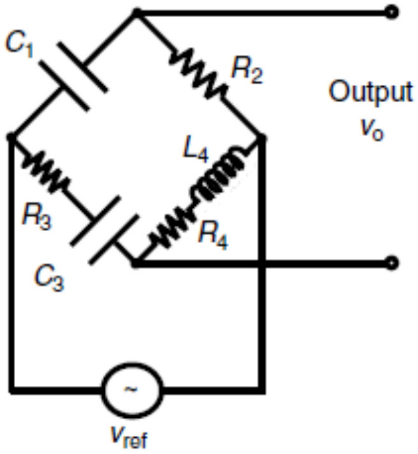
Hence, voltage at node A is zero and the current balance equation at node A is given by:

Impedance Bridges:

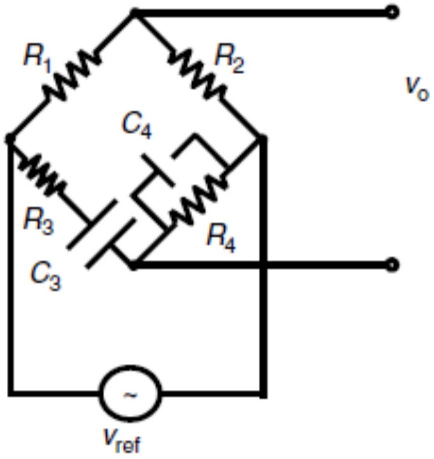
- AC Bridge
- Contains four impedances: $Z_1, Z_2, Z_3\ and\ Z_4$



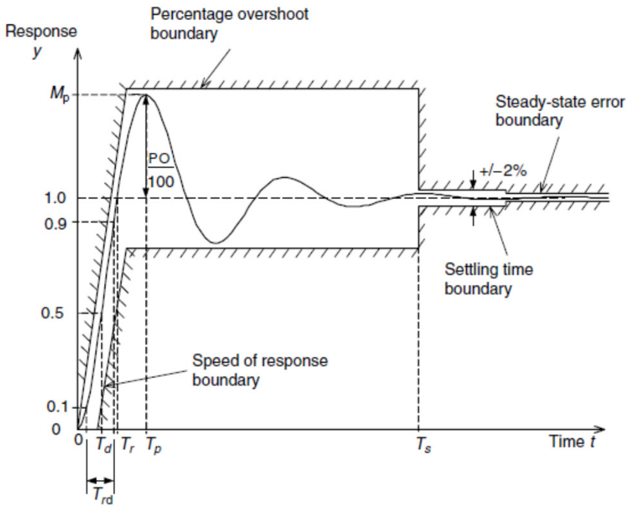
Owen Bridge:



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+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:

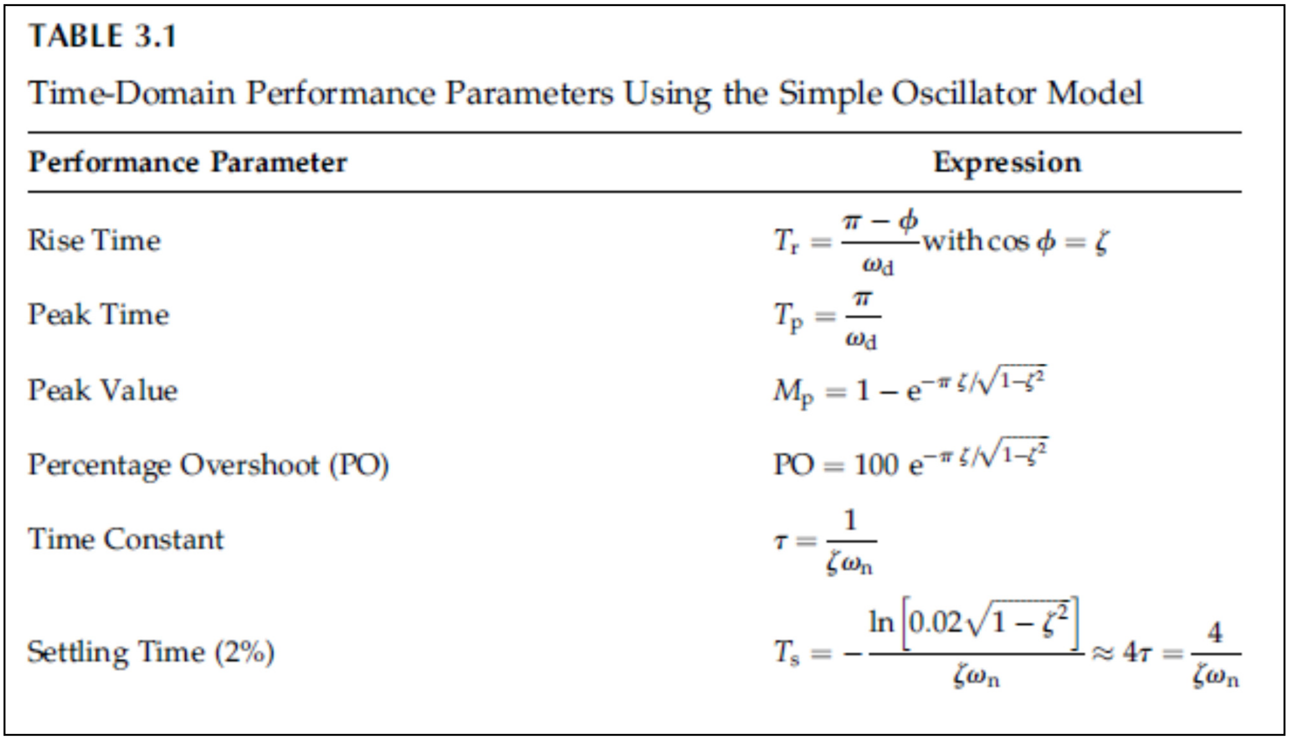


TABLE 3.1

Time-Domain Performance Parameters Using the Simple Oscillator Model

Performance Parameter	Expression
Rise Time	$T_r = \dfrac{\pi - \phi}{\omega_d}$ with $\cos\phi = \zeta$
Peak Time	$T_p = \dfrac{\pi}{\omega_d}$
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	$\tau = \dfrac{1}{\zeta\omega_n}$
Settling Time (2%)	$T_s = -\dfrac{\ln\left[0.02\sqrt{1-\zeta^2}\right]}{\zeta\omega_n} \approx 4\tau = \dfrac{4}{\zeta\omega_n}$

An automobile weighs 1000 kg. The equivalent stiffness at each wheel, including the suspension system, is approximately 60.0×10^3 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:

- Error = (instrument reading) – (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,

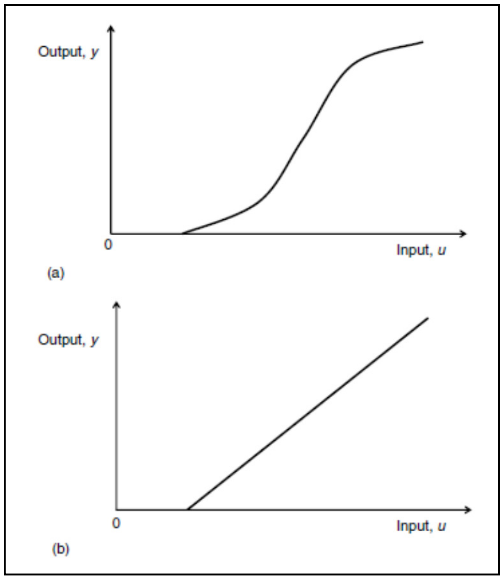
- We should consider ways of linearizing the input/output characteristic by ***modifying the output*** itself.

    - 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

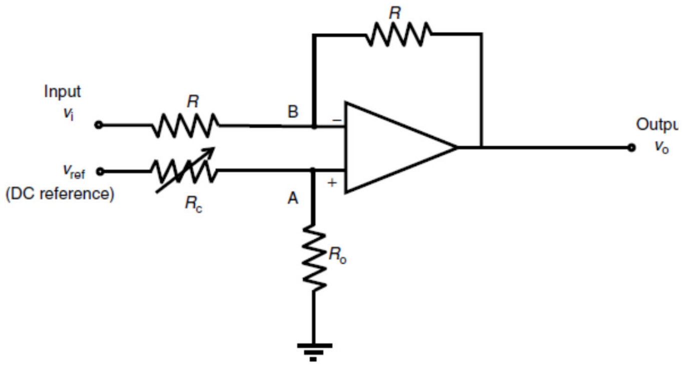
Three types of analog linearizing circuitry can be identified:

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

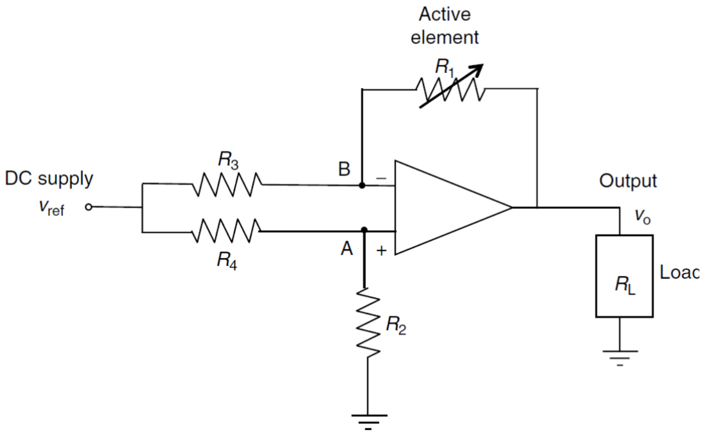
Offsetting circuitry:

- 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)



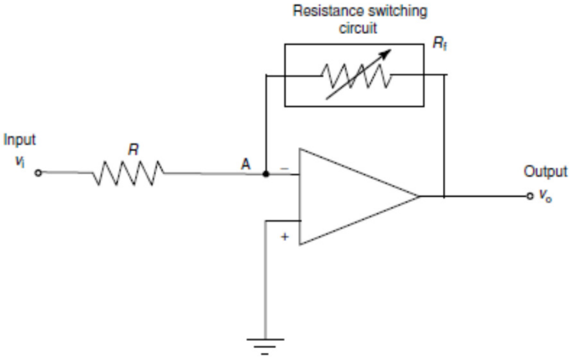
Proportional-Output Circuitry:

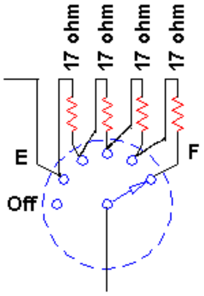


$$v_o = v_A - v_B = \frac{R_1 v_{\mathrm{ref}}}{(R_1 + R_2)} - \frac{R_3 v_{\mathrm{ref}}}{(R_3 + R_4)} = \frac{(R_1 R_4 - R_2 R_3)}{(R_1 + R_2)(R_3 + R_4)} v_{\mathrm{ref}}.$$

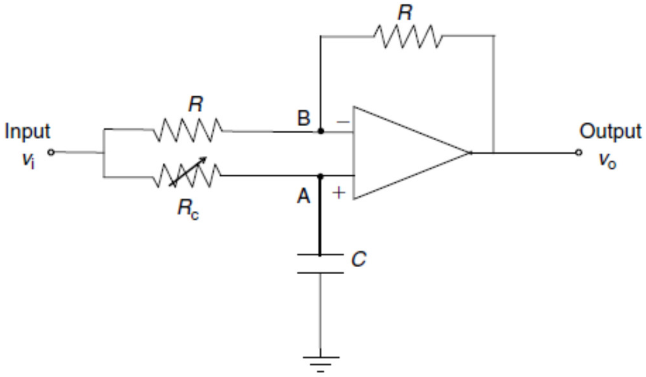
Curve Shaping Circuitry:

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

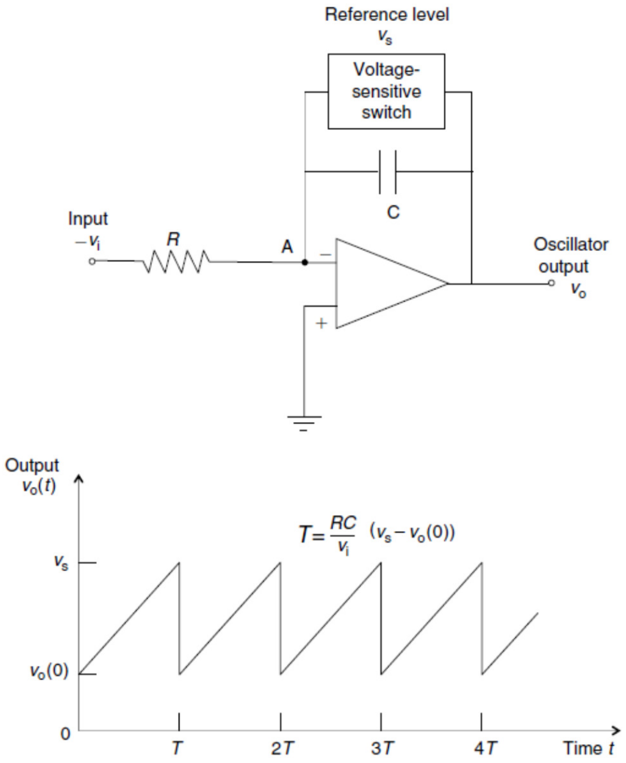




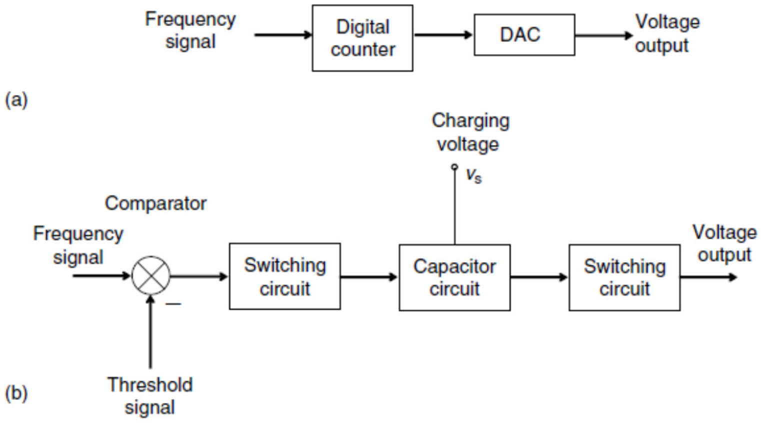
Phase Shifters:



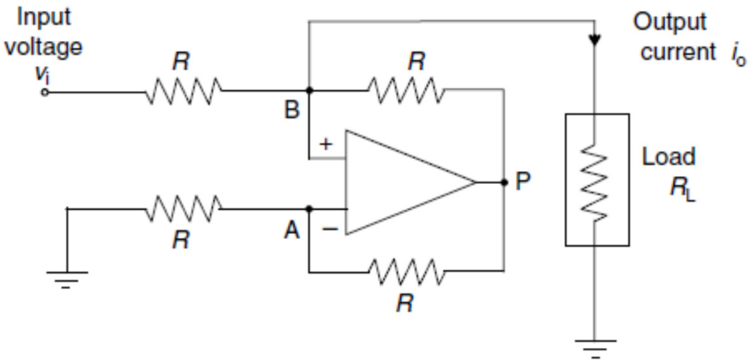
Voltage to Frequency Convertor:



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:

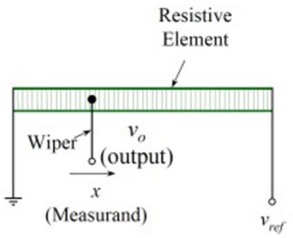
- *Signal characteristics: (e.g., steady, highly transient, periodic, NB, BB)*
- *The required frequency content of the processed signal*
- *The signal-to-noise ratio (SNR) of the measurement*
- *Processing capabilities (e.g., analog or digital processing, limitations of the digital processor and interface; 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*

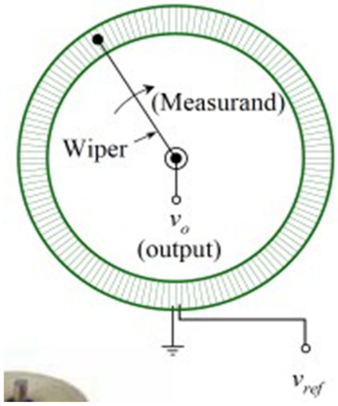
Motion Transducers:

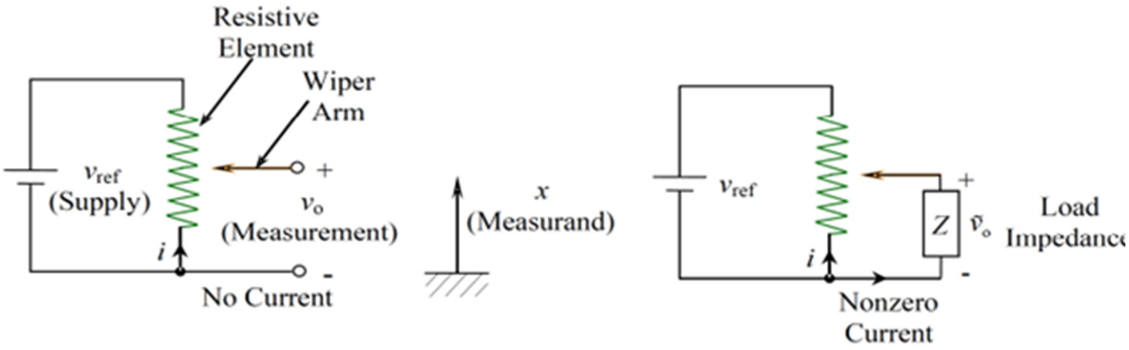
- Potentiometers (resistively coupled)
- Variable inductance (electromagnetically coupled)
- Variable capacitance
- Eddy current
- Piezoelectric

Potentiometer:

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

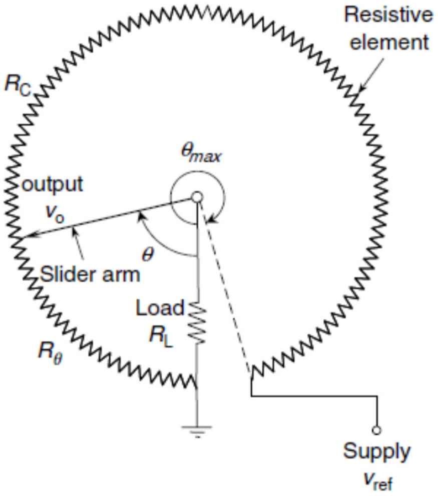


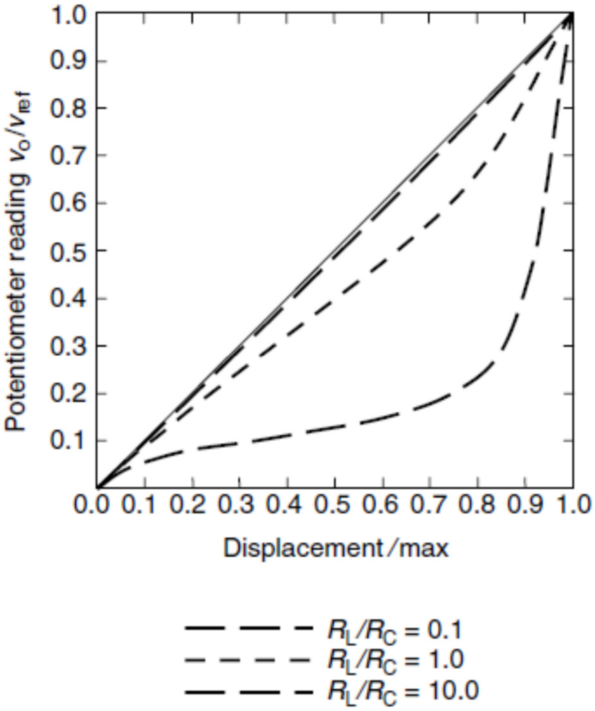




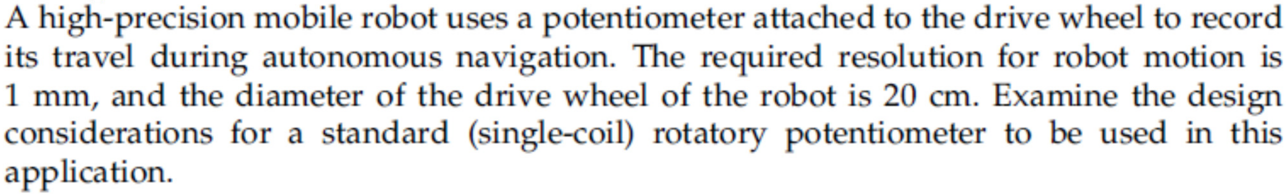
Loading Nonlinearity:

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




Potentiometer reading v_o/v_{ref}
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Displacement / max
$R_L/R_C = 0.1$
$R_L/R_C = 1.0$
$R_L/R_C = 10.0$

Example:

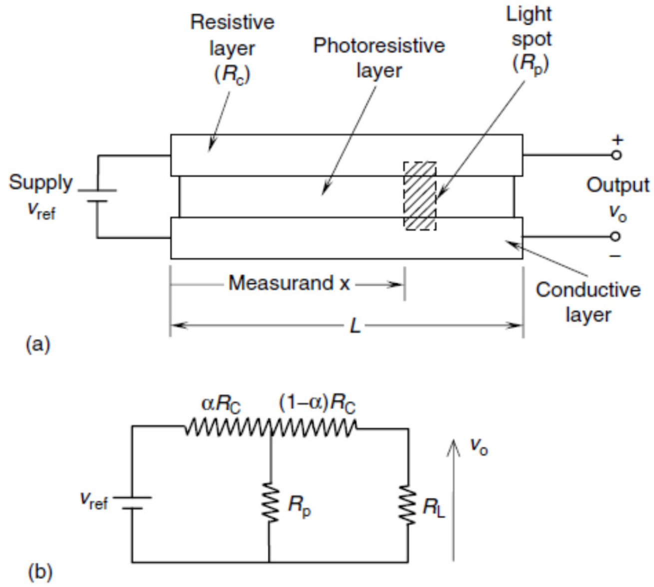


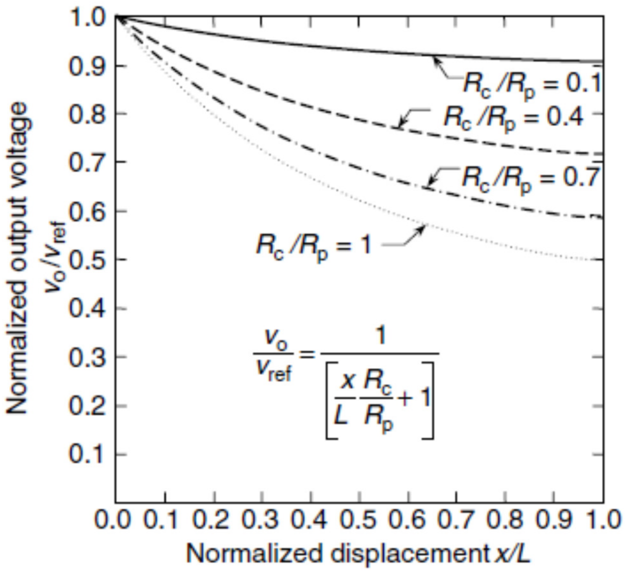
A high-precision mobile robot uses a potentiometer attached to the drive wheel to record its travel during autonomous navigation. The required resolution for robot motion is 1 mm, and the diameter of the drive wheel of the robot is 20 cm. Examine the design considerations for a standard (single-coil)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

Solution:

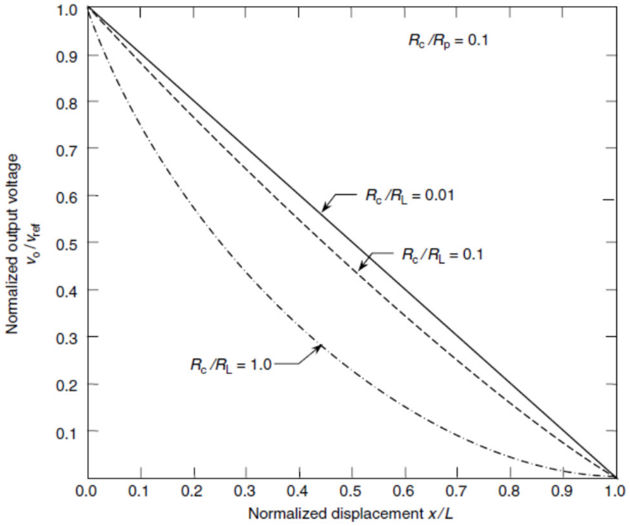
Optical Potentiometer:

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



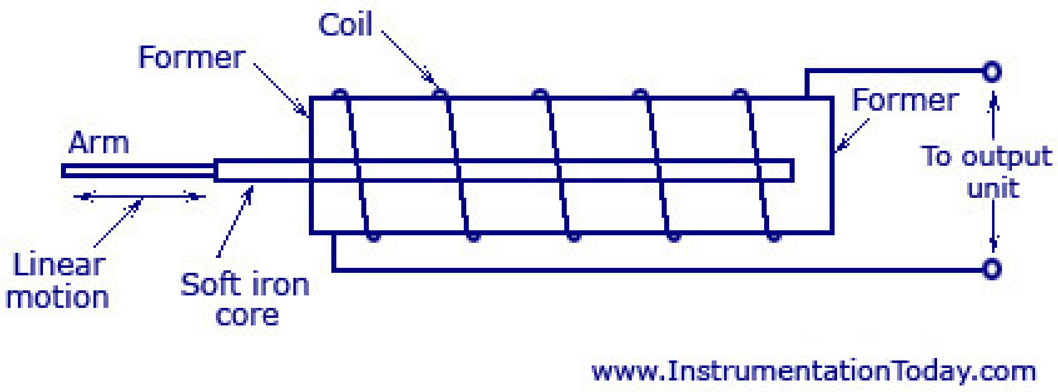


$$\frac{v_o}{v_{ref}}\left\{\frac{R_c}{R_L}+1+0.1\frac{x}{L}\left[\left(1-\frac{x}{L}\right)\frac{R_c}{R_L}+1\right]\right\}=1$$



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.



- 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.

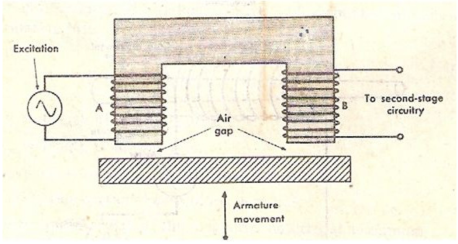
- This is the basis of electromagnetic induction, and it is the principle of operation of electrical generators and variable-inductance transducers.

- ***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.

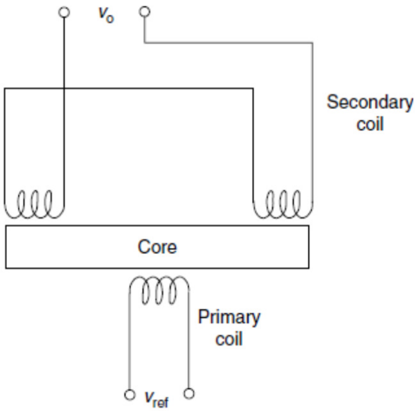
Mutual-induction transducers:



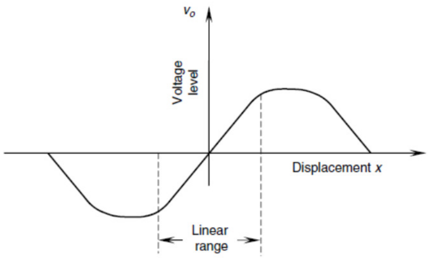
- Arrangement of a mutual-induction transducer constitutes two coils, the primary winding and the secondary winding. One of the coils (primary winding) carries an alternating-current (ac) excitation, which induces a steady ac voltage in the other coil (secondary winding).
- The level (amplitude, rms-value, 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).

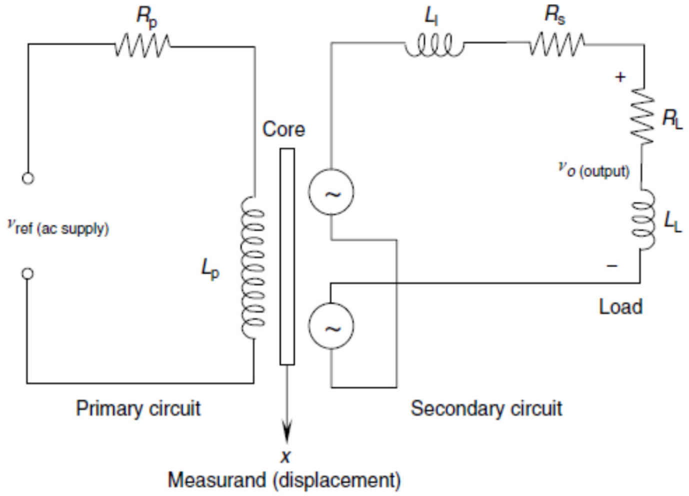
Linear-Variable Differential Transformer (LVDT)



- 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.



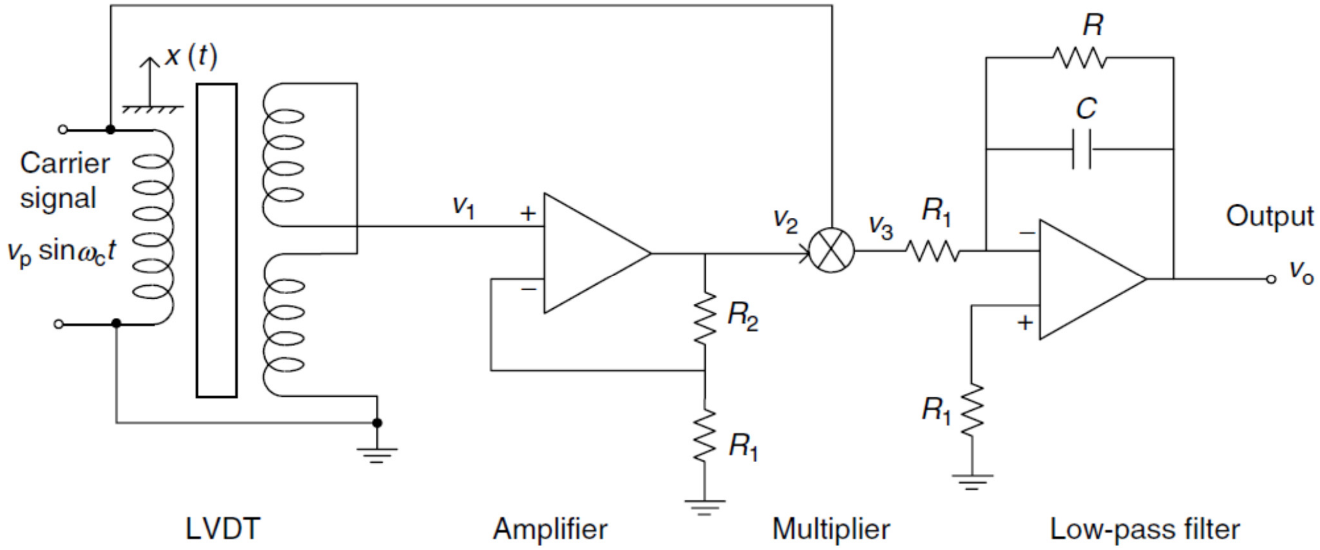
Linear-Variable Differential Transformer (LVDT) Equivalent Circuit.



Signal Conditioning:

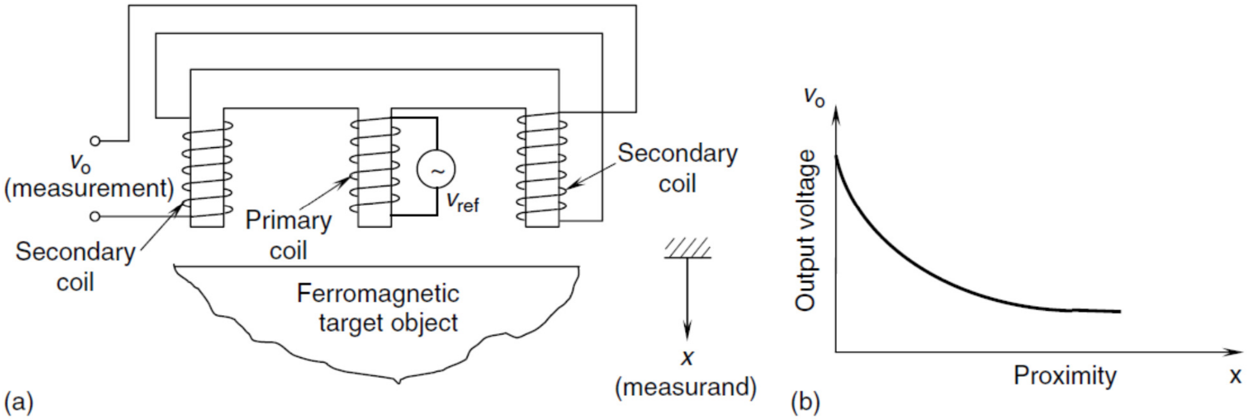
- Signal Amplification – increase signal strength so we ca interpret it.
- Filtering – need exactly the signals we require for interpreting it properly.
- Improving SNR – filter out unwanted so actual signal quality is better and Noise (unwanted) signal is suppresses.

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

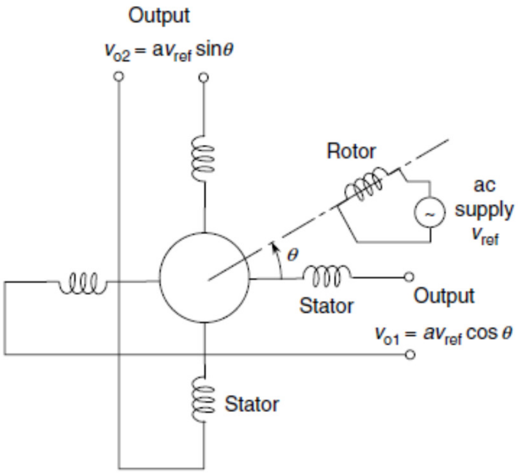
    - Level detection (e.g., in the filling, bottling, and chemical process industries)

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 90^0 apart.



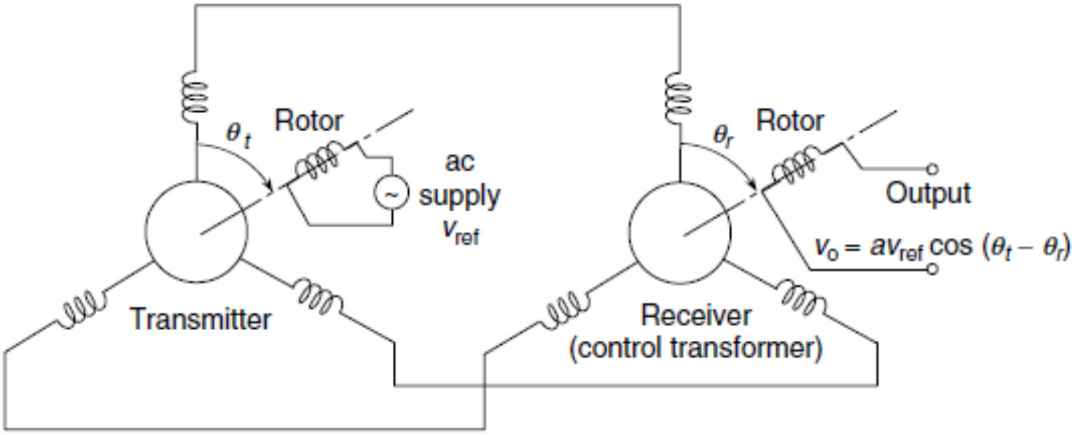
- If the angular position of the rotor with respect to one pair of stator windings is denoted by θ, the induced voltage in this pair of windings is given by:

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.

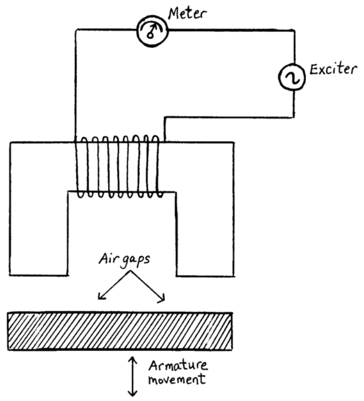
Synchro Transformer:

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 120^0 apart around the rotor shaft.



Self-Induction Transducers:

- Unlike mutual-induction transducers, only a single coil is employed.
- This coil is activated by an ac supply voltage V_{ref} of sufficiently high frequency.
- The current produces a magnetic flux, which is linked back with the coil.
- The level of flux linkage (or self-inductance) can be varied by moving a ferromagnetic object within the magnetic field.

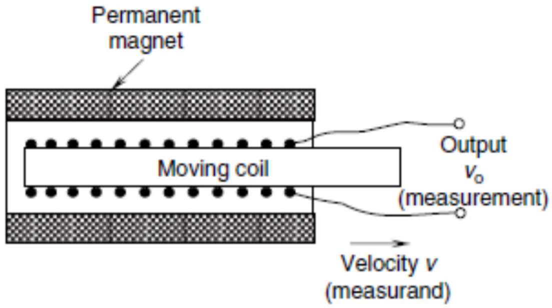


A simple self-inductance arrangement wherein a change in the air gap changes the pickup output.

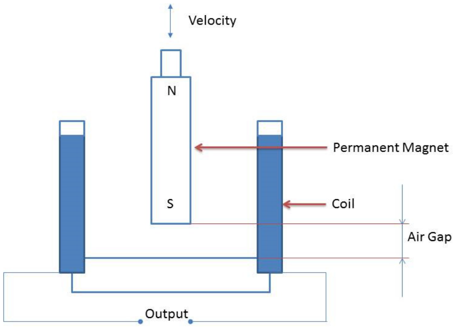
- This movement changes the reluctance of the flux linkage path and also the inductance in the coil.
- The change in self-inductance, which can be measured using an inductance-measuring circuit represents the measurand (displacement of the object).
- Note that self-induction transducers are usually variable-reluctance devices as well.

Permanent-Magnet Transducers:

A distinctive feature of permanent magnet transducers is that they have a permanent magnet to generate a uniform and steady magnetic field.

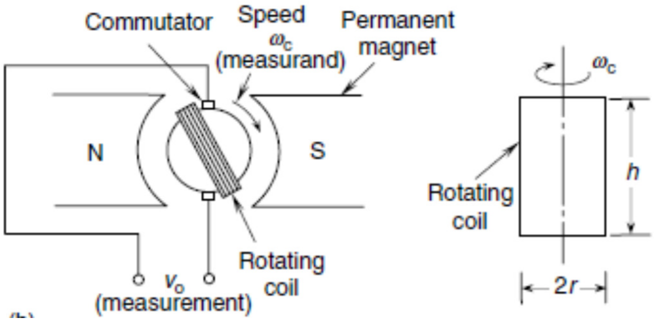


Moving Magnet Type velocity Transducer

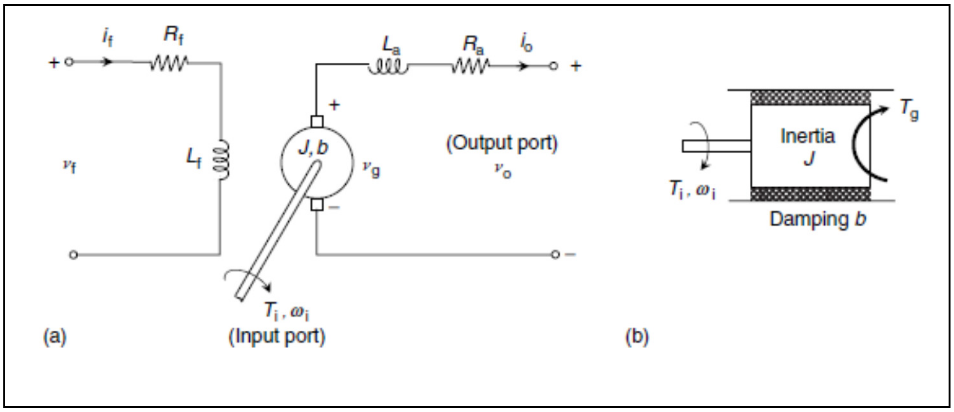


- A relative motion between the magnetic field and an electrical conductor induces a voltage, which is proportional to the speed at which the conductor crosses the magnetic field (i.e., the rate of change of flux linkage).
- In some designs, a unidirectional magnetic field generated by a dc supply (i.e., an electromagnet) is used in place of a permanent magnet.
- Permanent-magnet transducers are not variable-reluctance devices in general.

DC Tachometer



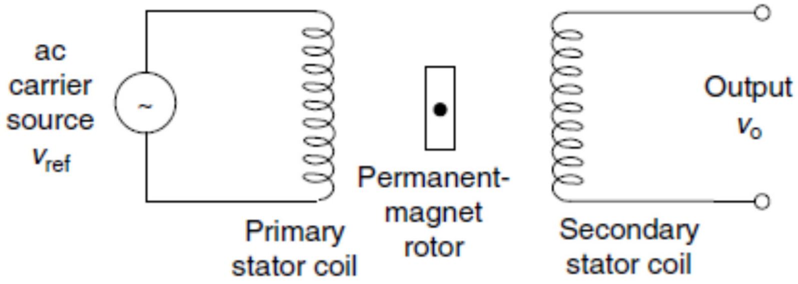
Modeling and Design Example:



Finally, i_0 in Equation (5) is eliminated using Equation (6). This gives the matrix transfer function relation:

$$\begin{bmatrix} v_{\mathrm{o}} \\ i_{\mathrm{o}} \end{bmatrix} = \begin{bmatrix} K + (R_a + sL_a)(b + sJ)/K & -(R_a + sL_a)/K \\ -(b + sJ)/K & 1/K \end{bmatrix} \begin{pmatrix} \boldsymbol{\omega}_{\mathrm{i}} \\ T_{\mathrm{i}} \end{pmatrix}.$$

Permanent-Magnet AC Tachometer:



(a)

- When the rotor is stationary or moving in a quasi-static manner, the output voltage is a constant amplitude signal much like the reference voltage, as in an electrical transformer.

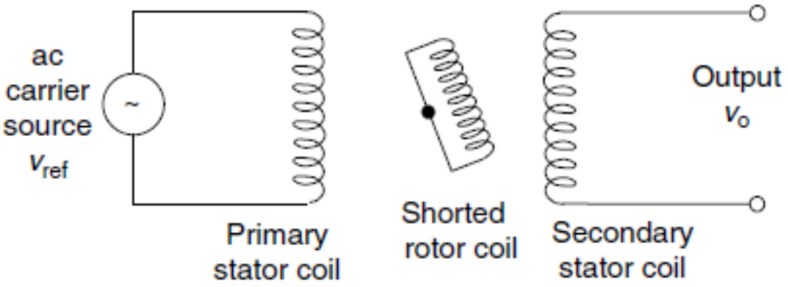
- As the rotor moves at a finite speed, an additional induced voltage, which is proportional to the rotor speed, is generated in the secondary coil.

- This is due to the rate of change of flux linkage into the secondary coil as a result of the rotating magnet. The overall output from the secondary coil is an amplitude-modulated signal whose amplitude is proportional to the rotor speed.

- For transient velocities, it becomes necessary to demodulate this signal in order to extract the transient velocity signal (i.e., the modulating signal) from the overall (modulated) output.

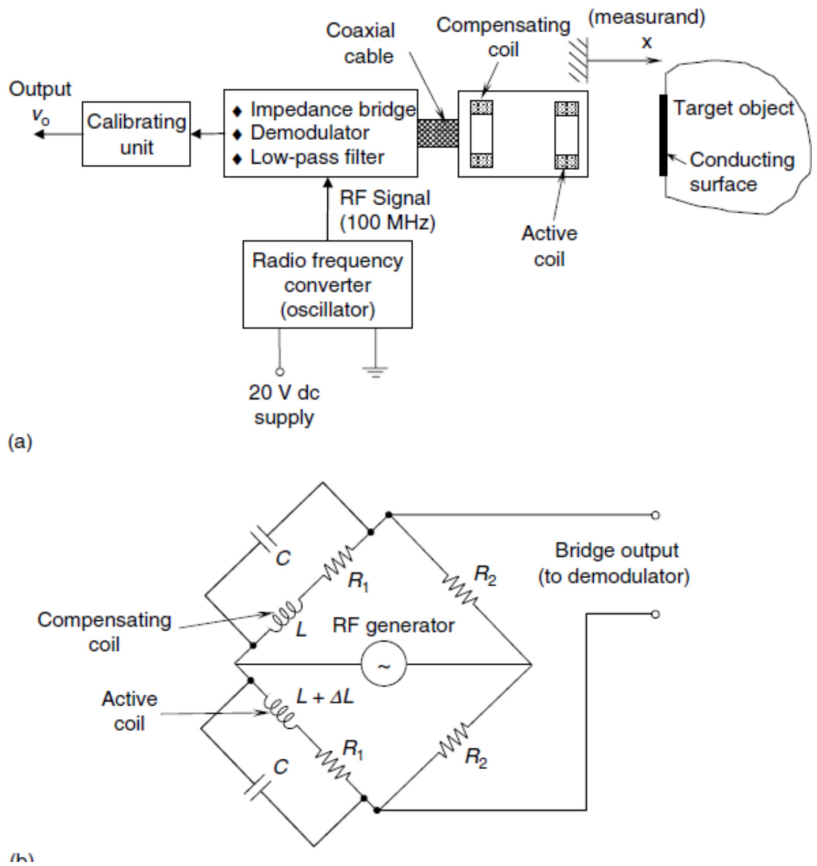
- The direction of velocity is determined from the phase angle of the modulated signal with respect to the carrier signal.

AC Induction Tachometer:



- Primary stator coil is powered by an ac supply which induces a voltage in the rotor coil and it is a modulated signal.
- High frequency (carrier) component of this induced signal is due to the direct transformer action of the primary ac.
- The other (modulating) component is induced by the speed of rotation of the rotor, and its magnitude is proportional to the speed of rotation.
- The non-energized stator (secondary) coil provides the output of the tachometer. This voltage output is a result of both the stator (primary) field and the speed of rotor coil. As a result, the tachometer output has a carrier ac component whose frequency is the same as the primary signal frequency, and a modulating component, which is proportional to the speed of rotation. Demodulation would be needed to extract the component that is proportional to the angular speed of the rotor.

Eddy Current Transducers:



- If a conducting (i.e., low-resistivity) medium is subjected to a fluctuating magnetic field, eddy currents are generated in the medium.

- The strength of eddy currents increases with the strength of the magnetic field and the frequency of the magnetic flux.

- This principle is used in eddy current proximity sensors.

- When the target object is moved close to the sensor, eddy currents are generated in the conducting medium because of the radio-frequency magnetic flux from the active coil.

- The ***magnetic field of the eddy currents opposes the primary field***, which generates these currents.

- Hence, the ***inductance of the active coil increases***, ***creating an imbalance in the bridge***. The resulting ***output from the bridge is an amplitude-modulated signal containing the radio-frequency carrier***. This signal can be demodulated by removing the carrier.

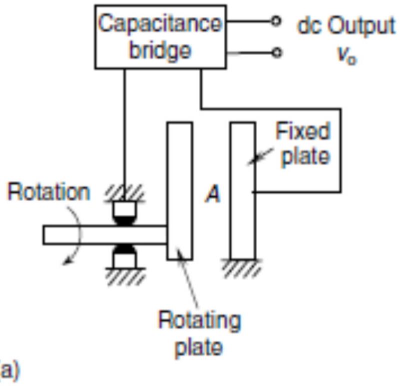
- The resulting signal (modulating signal) measures transient displacement of the target object.

-------End – of – Inductive- Sensors ----

Variable-Capacitance Transducers:

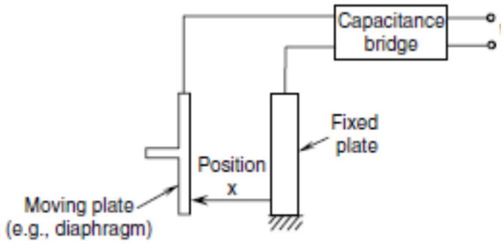
Variable-inductance devices and variable-capacitance devices are variable-reactance devices.

Capacitive Rotation Sensor:

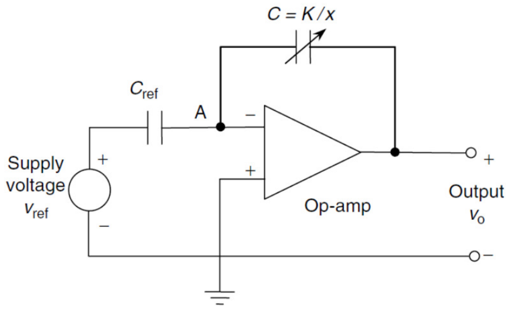


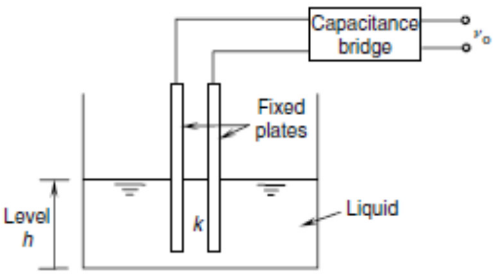
(a)

Capacitive Displacement Sensor:



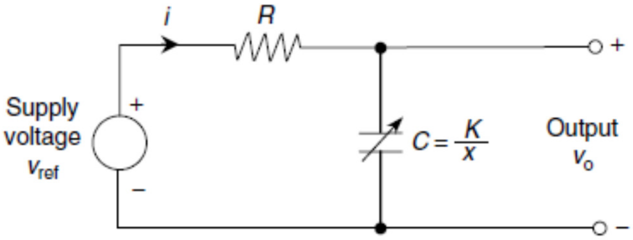
(b)



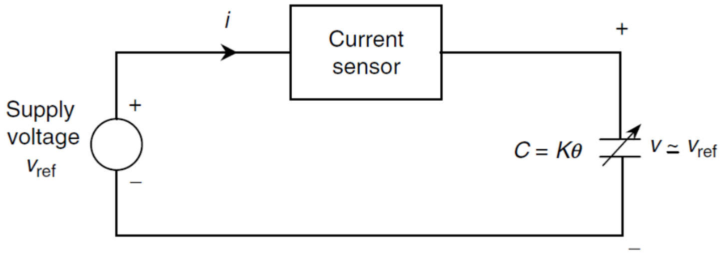


Example:

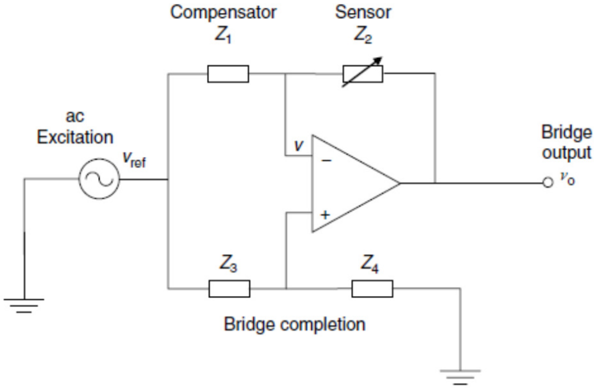
Consider the circuit shown, examine how this arrangement could be used to measure displacements.



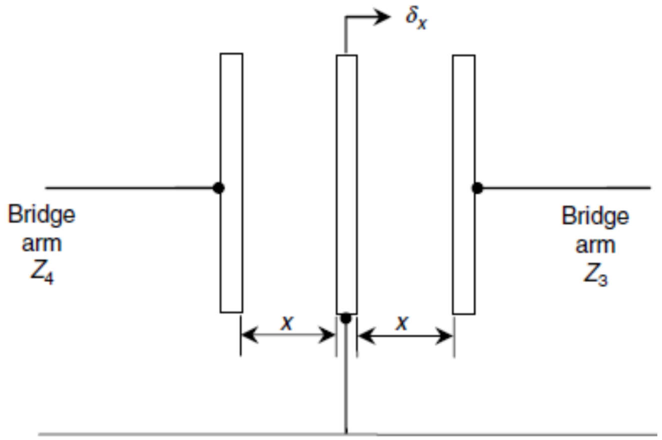
Capacitive Angular Velocity Sensor:



Capacitive-Bridge Circuit:

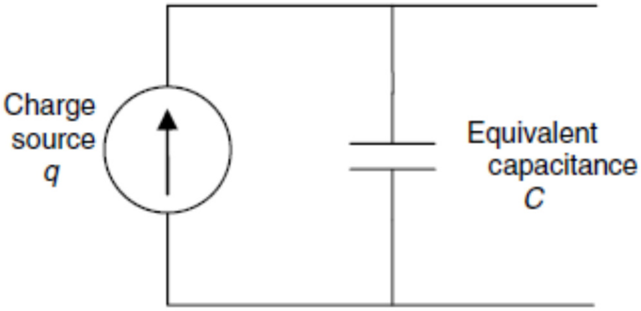


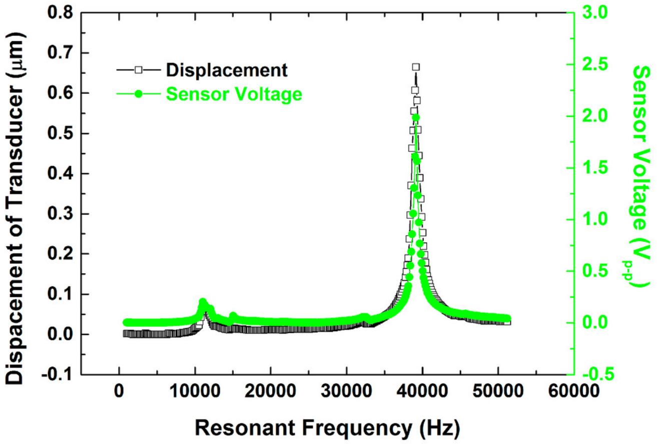
Differential (Push–Pull) Displacement Sensor:



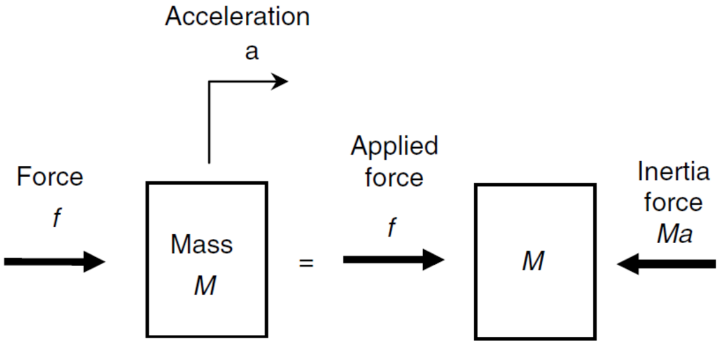
Piezoelectric Sensors:

Some substances, such as barium titanate, single-crystal quartz, and lead zirconatetitanate (PZT) ***can generate an electrical charge and an associated potential difference when they are subjected to mechanical stress or strain***. This piezoelectric effect is used in piezoelectric transducers.



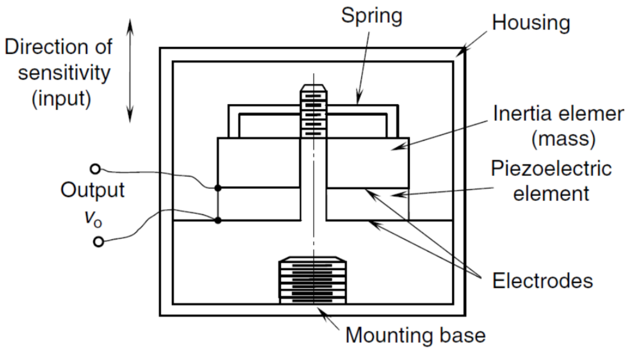


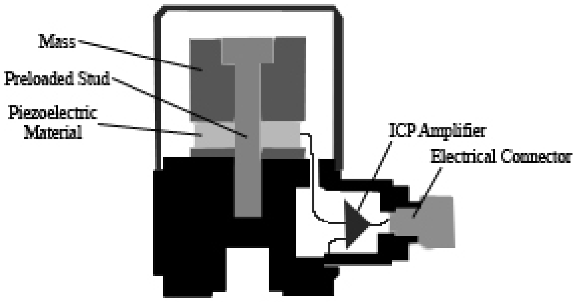
Accelerometers:



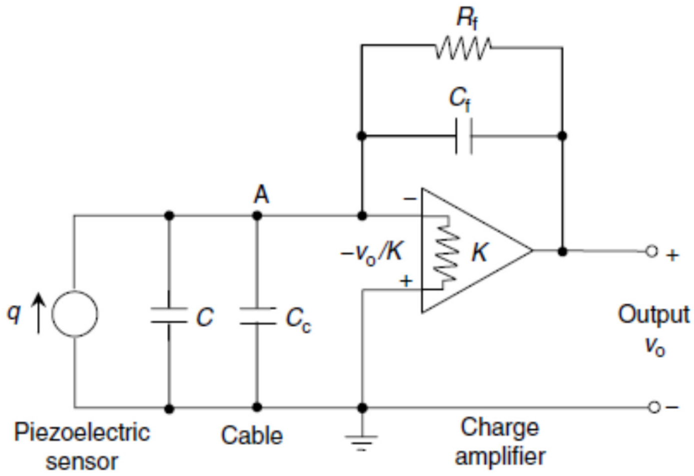
Piezoelectric Accelerometer:

A piezoelectric velocity transducer is simply a piezoelectric accelerometer with a built-in integrating amplifier in the form of a miniature integrated circuit.





Charge Amplifier:



Piezoelectric signals cannot be read using low-impedance devices. The two primary reasons for this are:

1. High output impedance in the sensor results in small output signal levels and large loading errors.
2. The charge can quickly leak out through the load.

A charge amplifier is commonly used as the signal-conditioning device for piezoelectric sensors, in order to overcome these problems to a great extent.

- Because of impedance transformation, the impedance at the ***output of the charge amplifier becomes much smaller than the output impedance of the piezoelectric sensor***. This virtually eliminates loading error and provides a low-impedance output for purposes such as signal communication, acquisition, recording, processing, and control.
- Also, by using a charge amplifier circuit with a ***relatively large time constant, the speed of charge leakage can be decreased***.

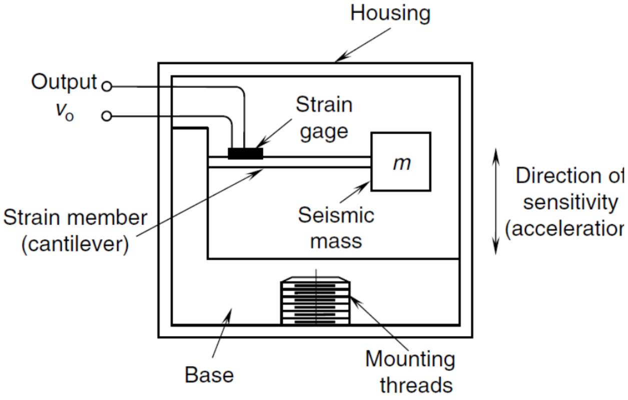
For example, consider a piezoelectric sensor and charge amplifier combination, as represented by the circuit above. Let us examine how the rate of charge leakage is reduced by using this arrangement.

Strain Gages:

- Many types of force and torque sensors are based on strain-gage measurements.
- Although strain gages measure strain, the measurements can be directly related to stress and force. Therefore, it is appropriate to discuss strain gages under force and torque sensors.
- Note, however, that strain gages may be used in a somewhat indirect manner (using auxiliary front-end elements) to measure other types of variables, including displacement, acceleration, pressure, and temperature.

Equations for Strain-Gage Measurements:

Examples:

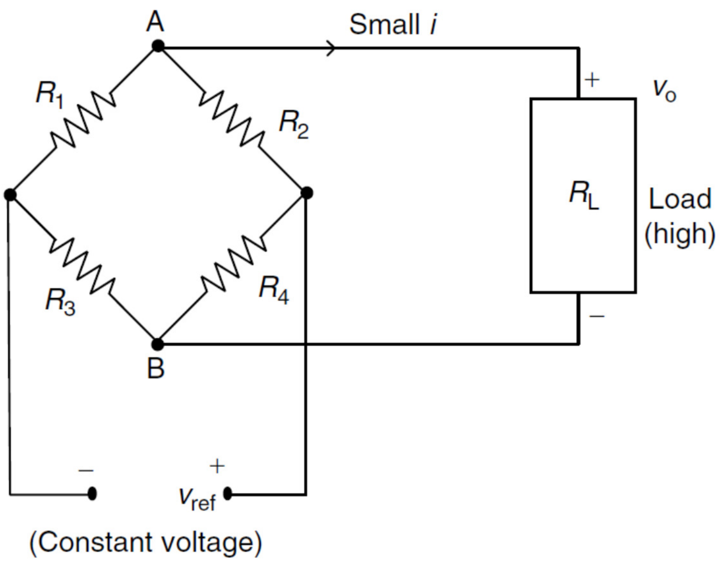


- Acceleration may be measured by first converting it into an inertia force of a suitable mass (seismic mass) element, then subjecting a cantilever (strain member) to that inertia force and, finally, measuring the strain at a high-sensitivity location of the cantilever element.
- Temperature may be measured by measuring the thermal expansion or deformation in a bimetallic element.
- Thermistors are temperature sensors made of semiconductor material whose resistance changes with temperature. Resistance temperature detectors (RTDs) operate by the same principle, except that they are made of metals, not of semiconductor material.
- Note that these temperature sensors, and the piezoelectric sensors, should not be confused with strain gages.
- Resistance strain gages are based on resistance change as a result of strain, or the piezo-resistive property of materials.

A direct way to obtain strain-gage measurement is:

- To apply a constant dc voltage across a series-connected pair of strain-gage element (of resistance R) and a suitable (complementary) resistor R_c, and
- To measure the output voltage V_0 across the strain gage under open-circuit conditions (using a voltmeter with high input impedance).
- It is known as a potentiometer circuit or ballast circuit.

Bridge Sensitivity:



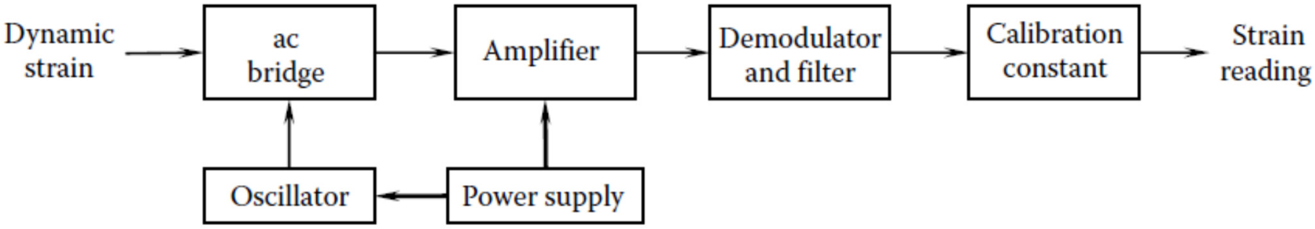
- Strain-gage measurements are calibrated with respect to a balanced bridge.
- When the strain gages in the bridge deform, the balance is upset.
- If one of the arms of the bridge has a variable resistor, it can be changed to restore balance.
- The amount of this change measures the amount by which the resistance of the strain gages changed, thereby measuring the applied strain.
- This is known as the *null-balance method* of strain measurement.

The Bridge Constant and the Calibration Constant:

If more than one strain-gage is active, the bridge output may be expressed as:

Assignment: Study Example 5.2 on page 363 Textbook Version2.

Data Acquisition:



For measuring dynamic strains:

- Either the servo null-balance method or the imbalance output method should be employed (see Chapter 2).
- A schematic diagram for the imbalance output method is shown in Figure above.
- In this method, the output from the active bridge is directly measured as a voltage signal and calibrated to provide the measured strain. Figure above corresponds to the use of an ac bridge.

- The bridge is powered by an ac voltage. The supply frequency should be about 10 times the maximum frequency of interest in the dynamic strain signal (bandwidth). A supply frequency in the order of 1 kHz is typical. This signal is generated by an oscillator and is fed into the bridge. The transient component of the output from the bridge is very small (typically <1 mV and possibly a few microvolts).

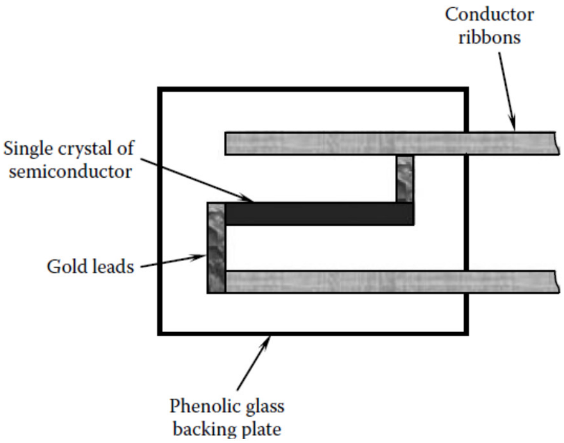
- This signal has to be amplified, demodulated (especially if the signals are transient), and filtered to provide the strain reading.

- The calibration constant of the bridge should be known in order to convert the output voltage to strain. Strain-gauge bridges powered by dc voltages are common.

- However, they have the advantages of simplicity with regard to the necessary circuitry and portability. The advantages of ac bridges include improved stability (reduced drift) and accuracy, and reduced power consumption

Accuracy Considerations:

Semiconductor Strain Gauges:



- Low-strain applications (e.g., dynamic torque measurement), the *sensitivity of foil gauges* is not adequate to produce an acceptable strain-gauge signal.
- SC strain gauges are particularly useful in such situations. The strain element of an SC strain-gauge is made of a *single crystal of piezoresistive material such as silicon, doped with a trace impurity such as boron*.
- The gauge factor (sensitivity) of an SC strain gauge is about two orders of magnitude higher than that of a metallic foil gauge (typically, 40–200), as seen for silicon, from the data given below

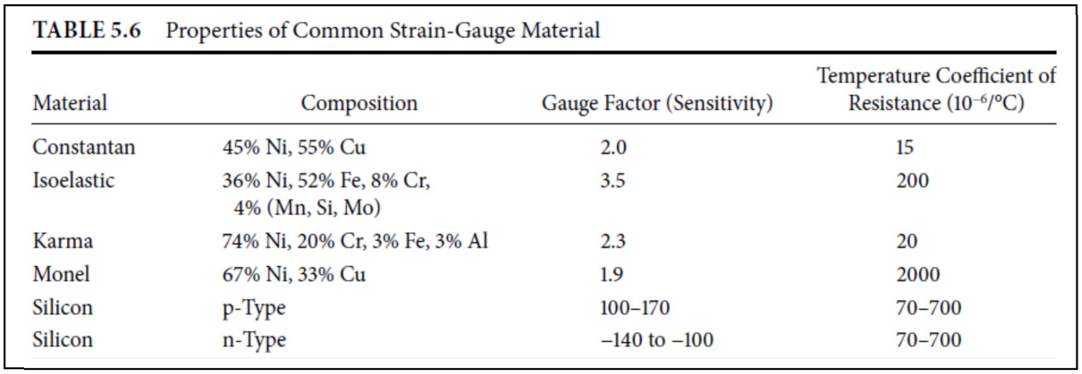
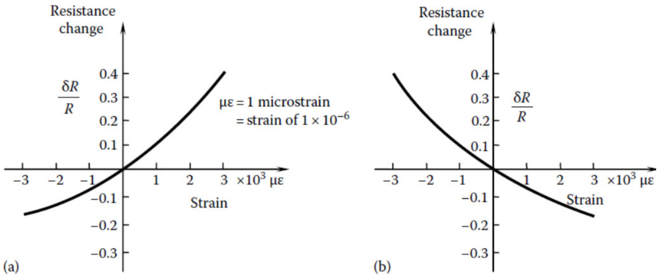


TABLE 5.6 Properties of Common Strain-Gauge Material

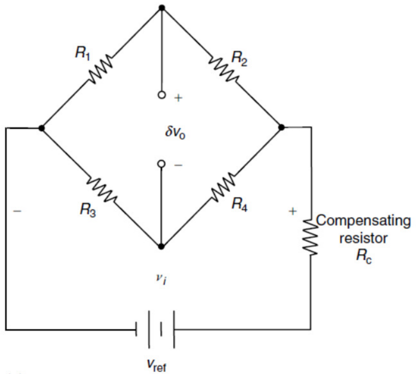
Material	Composition	Gauge Factor (Sensitivity)	Temperature Coefficient of Resistance (10^{-6}/°C)
Constantan	45% Ni, 55% Cu	2.0	15
Isoelastic	36% Ni, 52% Fe, 8% Cr, 4% (Mn, Si, Mo)	3.5	200
Karma	74% Ni, 20% Cr, 3% Fe, 3% Al	2.3	20
Monel	67% Ni, 33% Cu	1.9	2000
Silicon	p-Type	100–170	70–700
Silicon	n-Type	–140 to –100	70–700

- High resistivity - ∴ low power consumption and lower heat generation.
- Major dvantage of SC strain gauges is that they *deform elastically to fracture*. *Negligible mechanical hysteresis*, *smaller and lighter, providing less cross-sensitivity, and negligible error from mechanical loading*.
- Max-Measureable SC strain gauge is typically 0.003 m/m (i.e., 3000 με).
- Strain-gauge R - can be an order of magnitude greater for an SC strain gauge; for example, several hundred ohms for a metal foil strain gauge (typically, 120 or 350 Ω), while several thousand ohms (5000 Ω) for an SC strain gauge. Disad. associated with SC strain gauges & adv. of foil gauges.
    - *The strain–resistance relationship is more nonlinear.*
    - *Brittle and hard to mount on curvy surface*
    - *The maximum strain that can be measured is one to two orders of magnitude smaller (typically, <0.001 m/m).*
    - *Cost more and have much larger temperature sensitivity.*

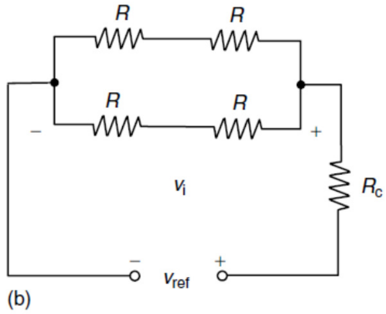


Automatic (Self) Compensation for Temperature:

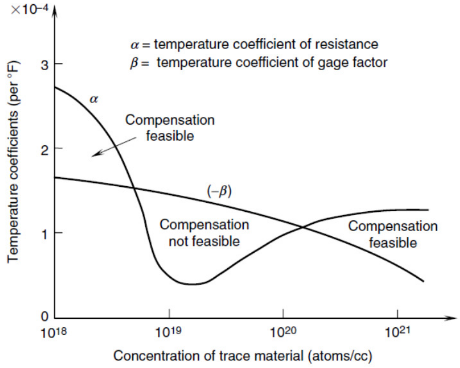
In foil gages the change in resistance due to temperature variations is typically small. Then the linear (first-order) approximation for the contribution from each arm of the bridge to the output signal, as given by Equation



(a)



(b)



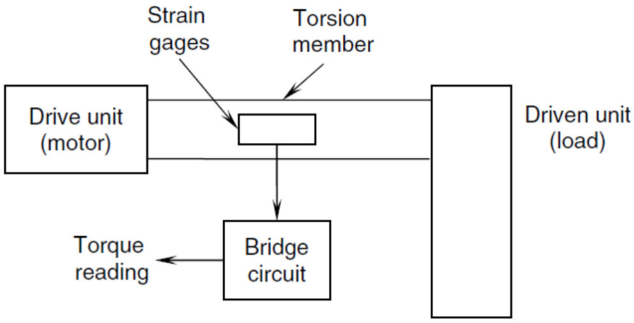
Torque Sensors:

A **torque sensor** or **torque transducer** or **torquemeter** is a device for measuring and recording the torque on a rotating system, such as an engine, crankshaft, gearbox, transmission, rotor, a bicycle crank or cap torque tester.

- Static torque is relatively easy to measure.
- Dynamic torque, on the other hand, is not easy to measure, since it generally requires transfer of some effect (electric or magnetic) from the shaft being measured to a static system.

Commonly, torque sensors or torque transducers use strain gauges applied to a rotating shaft or axle. With this method, a means to power the strain gauge bridge is necessary, as well as a means to receive the signal from the rotating shaft. This can be accomplished using slip rings, wireless telemetry, or rotary transformers. Newer types of torque transducers add conditioning electronics and an A/D converter to the rotating shaft. Stator electronics then read the digital signals and convert those signals to a high-level analog output signal, such as +/-10VDC.

Strain-Gage Torque Sensors:



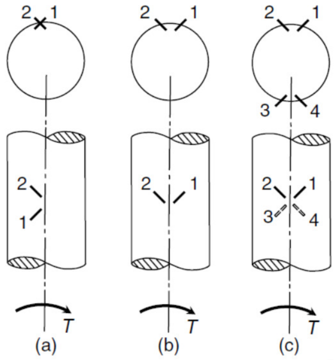
Simple method of torque sensing is:

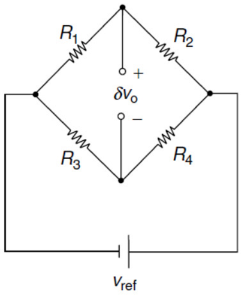
- To connect a torsion member between the drive unit and the (driven) load in series, as shown in diagram, and to measure the torque in the torsion member.
- If a circular shaft (solid or hollow) is used as the torsion member, the torque–strain relationship becomes relatively simple, and is given by:

From Last Page: $\boldsymbol{T} = \frac{8GJ}{kS_s r}\frac{\delta v_0}{v_{ref}}$**;**

- S_s is the gage factor (or sensitivity) of the strain gages and
- The bridge constant k depends on the number of active strain-gages used.

Strain gages are assumed to be mounted along a principal direction and three possible configurations are:





Strain-gage bridge

Configuration	(a)		(b)		(c)
Bridge constant (k)	2		2		4
Axial loads compensated	Yes		Yes		Yes
Bending loads compensated	Yes		Yes		Yes

Example 5.11

Consider a rigid load, which has a polar moment of inertia J_L and driven by a motor with a rigid rotor, which has inertia J_m. A torsional member of stiffness K_s is connected between the rotor and the load, as shown in Figure 5.49a, to measure the torque transmitted to the load.

(a) Determine the transfer function between the motor torque T_m and the twist angle θ of the torsion member. What is the torsional natural frequency ω_n of the system? Discuss why the system bandwidth depends on ω_n. Show that the bandwidth can be improved by increasing K_s, by decreasing J_m, or by decreasing J_L. Give some advantages and disadvantages of introducing a gearbox at the motor output.

(b) If a torsion member of stiffness 0.5 K_s is mounted at the load end of the shaft (in series) by what percentage the original torsional bandwidth of the system (representative of the allowable operating frequency range for the torque sensor) is reduced?