Module 2: Sensors and signal processing
Lecture 1
Sensors and transducers

Measurement is an important subsystem of a mechatronics system. Its main function is to collect the information on system status and to feed it to the micro-processor(s) for controlling the whole system.

Measurement system comprises of sensors, transducers and signal processing devices. Today a wide variety of these elements and devices are available in the market. For a mechatronics system designer it is quite difficult to choose suitable sensors/transducers for the desired application(s). It is therefore essential to learn the principle of working of commonly used sensors/transducers. A detailed consideration of the full range of measurement technologies is, however, out of the scope of this course. Readers are advised to refer "Sensors for mechatronics" by Paul P.L. Regtien, Elsevier, 2012 [2] for more information.

Sensors in manufacturing are basically employed to automatically carry out the production operations as well as process monitoring activities. Sensor technology has the following important advantages in transforming a conventional manufacturing unit into a modern one.

1. Sensors alarm the system operators about the failure of any of the sub units of manufacturing system. It helps operators to reduce the downtime of complete manufacturing system by carrying out the preventative measures.
2. Reduces requirement of skilled and experienced labors.
3. Ultra-precision in product quality can be achieved.

Sensor

It is defined as an element which produces signal relating to the quantity being measured [1]. According to the Instrument Society of America, sensor can be defined as "*A device which provides a usable output in response to a specified measurand.*" Here, the output is usually an 'electrical quantity' and measurand is a 'physical quantity, property or condition which is to be measured'. Thus in the case of, say, a variable inductance displacement element, the quantity being measured is displacement and the sensor transforms an input of displacement into a change in inductance.

Transducer

It is defined as an element when subjected to some physical change experiences a related change [1] or an element which converts a specified measurand into a usable output by using a transduction principle.

It can also be defined as a device that converts a signal from one form of energy to another form.

A wire of Constantan alloy (copper-nickel 55-45% alloy) can be called as a sensor because variation in mechanical displacement (tension or compression) can be sensed as change in electric resistance. This wire becomes a transducer with appropriate electrodes and input-output mechanism attached to it. Thus we can say that 'sensors are transducers'.

Sensor/transducers specifications

Transducers or measurement systems are not perfect systems. Mechatronics design engineer must know the capability and shortcoming of a transducer or measurement system to properly assess its performance. There are a number of performance related parameters of a transducer or measurement system. These parameters are called as sensor specifications.

Sensor specifications inform the user to the about deviations from the ideal behavior of the sensors. Following are the various specifications of a sensor/transducer system.

1. Range

The range of a sensor indicates the limits between which the input can vary. For example, a thermocouple for the measurement of temperature might have a range of 25-225 °C.

2. Span

The span is difference between the maximum and minimum values of the input. Thus, the above-mentioned thermocouple will have a span of 200 °C.

3. Error

Error is the difference between the result of the measurement and the true value of the quantity being measured. A sensor might give a displacement reading of 29.8 mm, when the actual displacement had been 30 mm, then the error is –0.2 mm.

4. *Accuracy*

The accuracy defines the closeness of the agreement between the actual measurement result and a true value of the measurand. It is often expressed as a percentage of the full range output or full–scale deflection. A piezoelectric transducer used to evaluate dynamic pressure phenomena associated with explosions, pulsations, or dynamic pressure conditions in motors, rocket engines, compressors, and other pressurized devices is capable to detect pressures between 0.1 and 10,000 psig (0.7 KPa to 70 MPa). If it is specified with the accuracy of about ±1% full scale, then the reading given can be expected to be within ± 0.7 MPa.

5. *Sensitivity*

Sensitivity of a sensor is defined as the ratio of change in output value of a sensor to the per unit change in input value that causes the output change. For example, a general purpose thermocouple may have a sensitivity of 41 µV/°C.

6. *Nonlinearity*

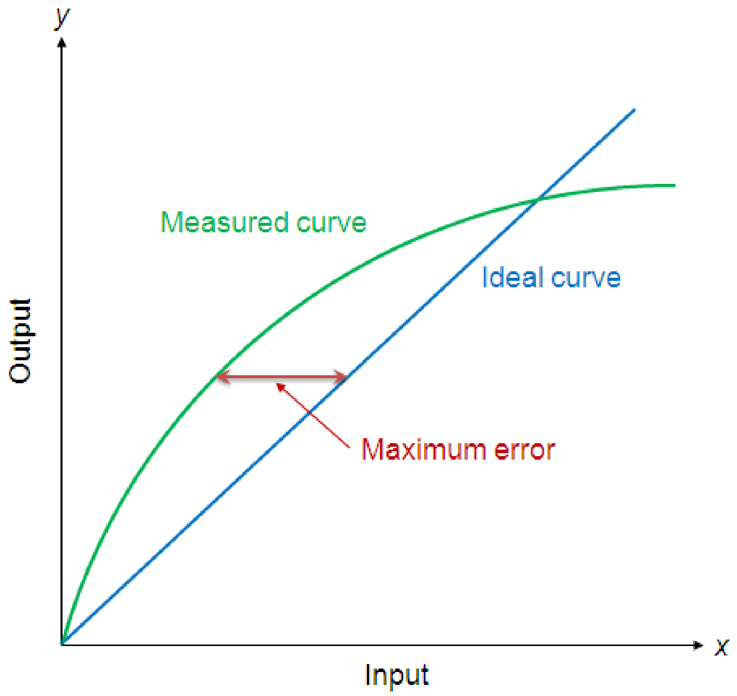

Figure 2.1.1 Non-linearity error

The nonlinearity indicates the maximum deviation of the actual measured curve of a sensor from the ideal curve. Figure 2.1.1 shows a somewhat exaggerated relationship between the ideal, or least squares fit, line and the actual measured or *calibration* line. Linearity is often specified in terms of *percentage of nonlinearity*, which is defined as:

Nonlinearity (%) = Maximum deviation in input ⁄ Maximum full scale input (2.1.1)

The static nonlinearity defined by Equation 2.1.1 is dependent upon environmental factors, including temperature, vibration, acoustic noise level, and humidity. Therefore it is important to know under what conditions the specification is valid.

7. Hysteresis

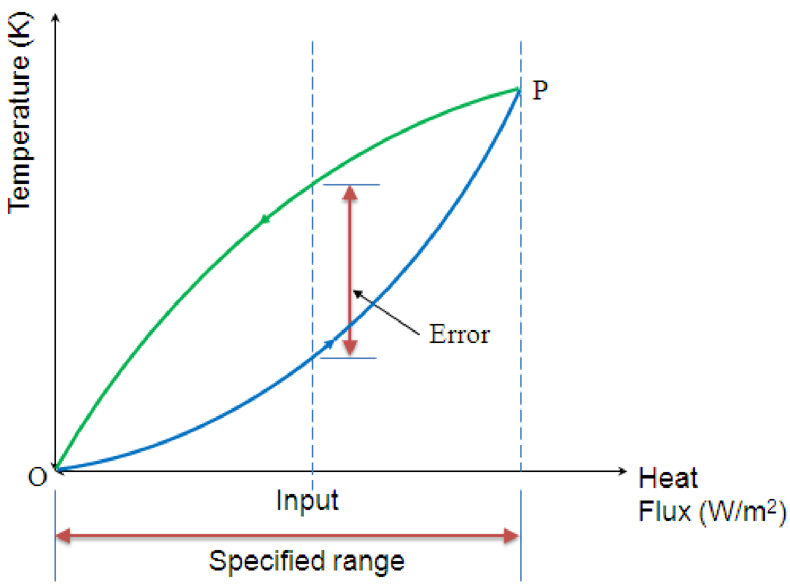

Figure 2.1.2 Hysteresis error curve

The hysteresis is an error of a sensor, which is defined as the maximum difference in output at any measurement value within the sensor's specified range when approaching the point first with increasing and then with decreasing the input parameter. Figure 2.1.2 shows the hysteresis error might have occurred during measurement of temperature using a thermocouple. The hysteresis error value is normally specified as a positive or negative percentage of the specified input range.

8. Resolution

Resolution is the smallest detectable incremental change of input parameter that can be detected in the output signal. Resolution can be expressed either as a proportion of the full-scale reading or in absolute terms. For example, if a LVDT sensor measures a displacement up to 20 mm and it provides an output as a number between 1 and 100 then the resolution of the sensor device is 0.2 mm.

9. Stability

Stability is the ability of a sensor device to give same output when used to measure a constant input over a period of time. The term ‘drift’ is used to indicate the change in output that occurs over a period of time. It is expressed as the percentage of full range output.

10.Dead band/time

The dead band or dead space of a transducer is the range of input values for which there is no output. The dead time of a sensor device is the time duration from the application of an input until the output begins to respond or change.

11.Repeatability

It specifies the ability of a sensor to give same output for repeated applications of same input value. It is usually expressed as a percentage of the full range output:

Repeatability = (maximum – minimum values given) X 100 ⁄ full range (2.1.2)

12.Response time

Response time describes the speed of change in the output on a step-wise change of the measurand. It is always specified with an indication of input step and the output range for which the response time is defined.

Classification of sensors

Sensors can be classified into various groups according to the factors such as measurand, application fields, conversion principle, energy domain of the measurand and thermodynamic considerations. These general classifications of sensors are well described in the references [2, 3].

Detail classification of sensors in view of their applications in manufacturing is as follows.

A. Displacement, position and proximity sensors
    - Potentiometer
    - Strain-gauged element
    - Capacitive element
    - Differential transformers
    - Eddy current proximity sensors
    - Inductive proximity switch
    - Optical encoders
    - Pneumatic sensors
    - Proximity switches (magnetic)
    - Hall effect sensors

B. Velocity and motion
    - Incremental encoder
    - Tachogenerator
    - Pyroelectric sensors

C. Force
    - Strain gauge load cell

D. Fluid pressure
    - Diaphragm pressure gauge
    - Capsules, bellows, pressure tubes
    - Piezoelectric sensors
    - Tactile sensor
    -

E. Liquid flow
    - Orifice plate
    - Turbine meter

F. Liquid level
    - Floats
    - Differential pressure

G. Temperature
    - Bimetallic strips
    - Resistance temperature detectors
    - Thermistors
    - Thermo-diodes and transistors
    - Thermocouples
    - Light sensors
    - Photo diodes
    - Photo resistors

- Photo transistor

Principle of operation of these transducers and their applications in manufacturing are presented in the next lectures.

Quiz:

1. Define sensors and list the various specifications that need to be carefully studied before using a Thermocouple for reading the temperature of a furnace.
2. Differentiate between span and range of a transducer system.
3. What do you mean by nonlinearity error? How it is different than Hysteresis error?
4. Explain the significance of the following information given in the specification of the following transducer,
   <u>Thermocouple</u>
   Sensitivity: nickel chromium/nickel aluminum thermocouple: 0.039 mV/ºC when the cold junction is at 0 ºC.

References:

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.
2. Regtien, P. P. L., Sensors for mechatronics, Elesevier, USA, 2012.
3. Tonshoff, H.K. and I. Inasaki, Sensors in manufacturing, Wiley-VCH, 2001.

Module 2: Sensors and signal processing
Lecture 2
Displacement and position sensors

Displacement sensors are basically used for the measurement of movement of an object. Position sensors are employed to determine the position of an object in relation to some reference point.

Proximity sensors are a type of position sensor and are used to trace when an object has moved with in particular critical distance of a transducer.

Displacement sensors

1. Potentiometer Sensors

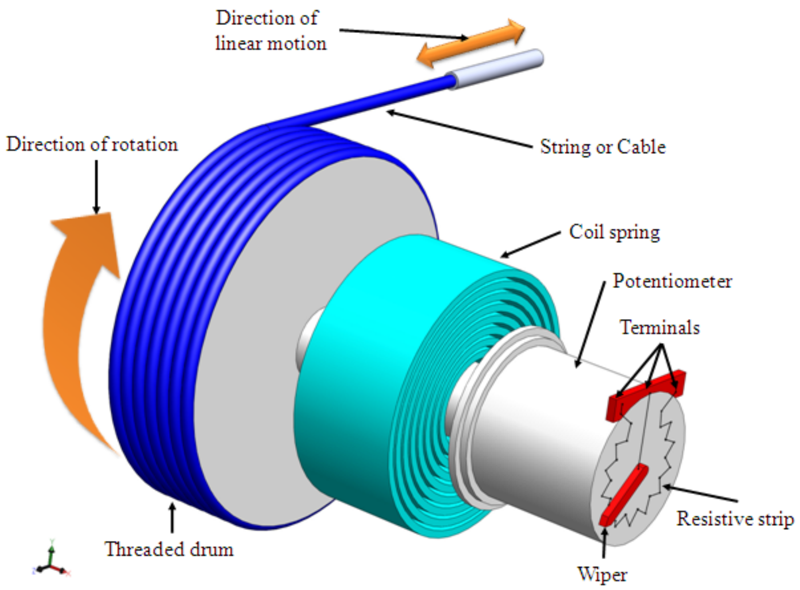

Figure 2.2.1 Schematic of a potentiometer sensor for measurement of linear displacement

Figure 2.2.1 shows the construction of a rotary type potentiometer sensor employed to measure the linear displacement. The potentiometer can be of linear or angular type. It works on the principle of conversion of mechanical displacement into an electrical signal. The sensor has a resistive element and a sliding contact (wiper). The slider moves along this conductive body, acting as a movable electric contact.

The object of whose displacement is to be measured is connected to the slider by using

- a rotating shaft (for angular displacement)
- a moving rod (for linear displacement)
- a cable that is kept stretched during operation

The resistive element is a wire wound track or conductive plastic. The track comprises of large number of closely packed turns of a resistive wire. Conductive plastic is made up of plastic resin embedded with the carbon powder. Wire wound track has a resolution of the order of ± 0.01 % while the conductive plastic may have the resolution of about 0.1 µm.

During the sensing operation, a voltage V_s is applied across the resistive element. A voltage divider circuit is formed when slider comes into contact with the wire. The output voltage (V_A) is measured as shown in the figure 2.2.2. The output voltage is proportional to the displacement of the slider over the wire. Then the output parameter displacement is calibrated against the output voltage V_A.

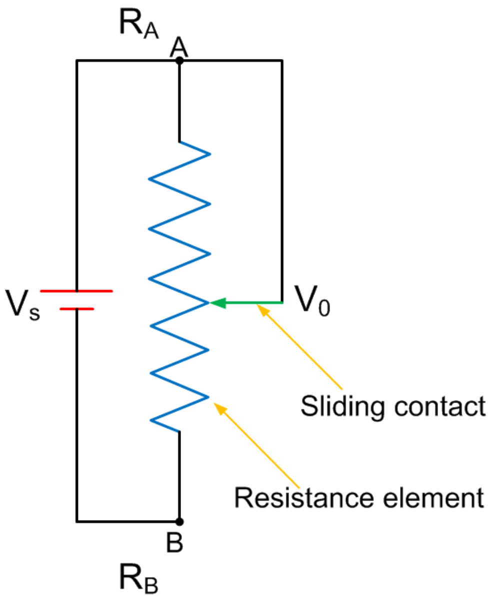

Figure 2.2.2 Potentiometer: electric circuit

$V_A = I\, R_A$ (2.2.1)

But $I = V_S / (R_A + R_B)$ (2.2.2)

Therefore $V_A = V_S\, R_A / (R_A + R_B)$ (2.2.3)

As we know that R = ρ L / A, where ρ is electrical resistivity, L is length of resistor and A is area of cross section

$V_A = V_S\, L_A / (L_A + L_B)$ (2.2.4)

Applications of potentiometer

These sensors are primarily used in the control systems with a feedback loop to ensure that the moving member or component reaches its commanded position.

These are typically used on machine-tool controls, elevators, liquid-level assemblies, forklift trucks, automobile throttle controls. In manufacturing, these are used in control of injection molding machines, woodworking machinery, printing, spraying, robotics, etc. These are also used in computer-controlled monitoring of sports equipment.

2. *Strain Gauges*

The strain in an element is a ratio of change in length in the direction of applied load to the original length of an element. The strain changes the resistance *R* of the element. Therefore, we can say,

$\Delta R/R \;\alpha\; \varepsilon$;

$$\Delta R/R = G\,\varepsilon \qquad (2.2.5)$$

where G is the constant of proportionality and is called as gauge factor. In general, the value of G is considered in between 2 to 4 and the resistances are taken of the order of 100 Ω.

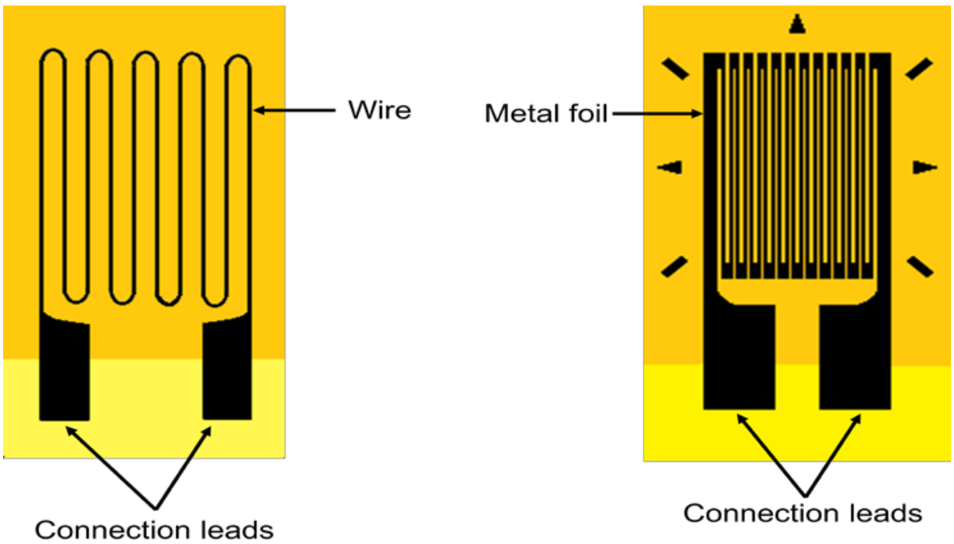

Figure 2.2.3 A pattern of resistive foils

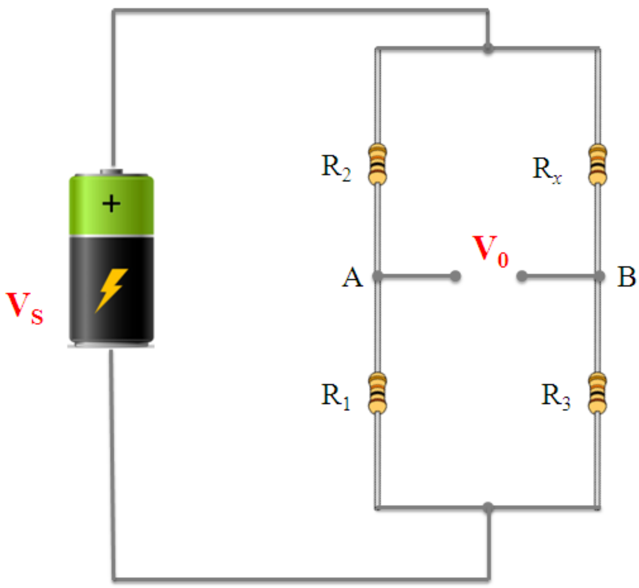

Figure 2.2.4 Wheatstone's bridge

Resistance strain gauge follows the principle of change in resistance as per the equation 2.2.5. It comprises of a pattern of resistive foil arranged as shown in Figure 2.2.3. These foils are made of Constantan alloy (copper-nickel 55-45% alloy) and are bonded to a backing material plastic (ployimide), epoxy or glass fiber reinforced epoxy. The strain gauges are secured to the workpiece by using epoxy or Cyanoacrylate cement Eastman 910 SL. As the workpiece undergoes change in its shape due to external loading, the resistance of strain gauge element changes. This change in resistance can be detected by a using a Wheatstone's resistance bridge as shown in Figure 2.2.4. In the balanced bridge we can have a relation,

$$R_2/ R_1 = R_x / R_3 \qquad (2.2.6)$$

where R_x is resistance of strain gauge element, R_2 is balancing/adjustable resistor, R_1 and R_3 are known constant value resistors. The measured deformation or displacement by the stain gauge is calibrated against change in resistance of adjustable resistor R_2 which makes the voltage across nodes A and B equal to zero.

Applications of strain gauges

Strain gauges are widely used in experimental stress analysis and diagnosis on machines and failure analysis. They are basically used for multi-axial stress fatigue testing, proof testing, residual stress and vibration measurement, torque measurement, bending and deflection measurement, compression and tension measurement and strain measurement.

Strain gauges are primarily used as sensors for machine tools and safety in automotives. In particular, they are employed for force measurement in machine tools, hydraulic or pneumatic press and as impact sensors in aerospace vehicles.

3. *Capacitive element based sensor*

Capacitive sensor is of non-contact type sensor and is primarily used to measure the linear displacements from few millimeters to hundreds of millimeters. It comprises of three plates, with the upper pair forming one capacitor and the lower pair another. The linear displacement might take in two forms:

a. one of the plates is moved by the displacement so that the plate separation changes
b. area of overlap changes due to the displacement.

Figure 2.2.5 shows the schematic of three-plate capacitive element sensor and displacement measurement of a mechanical element connected to the plate 2.

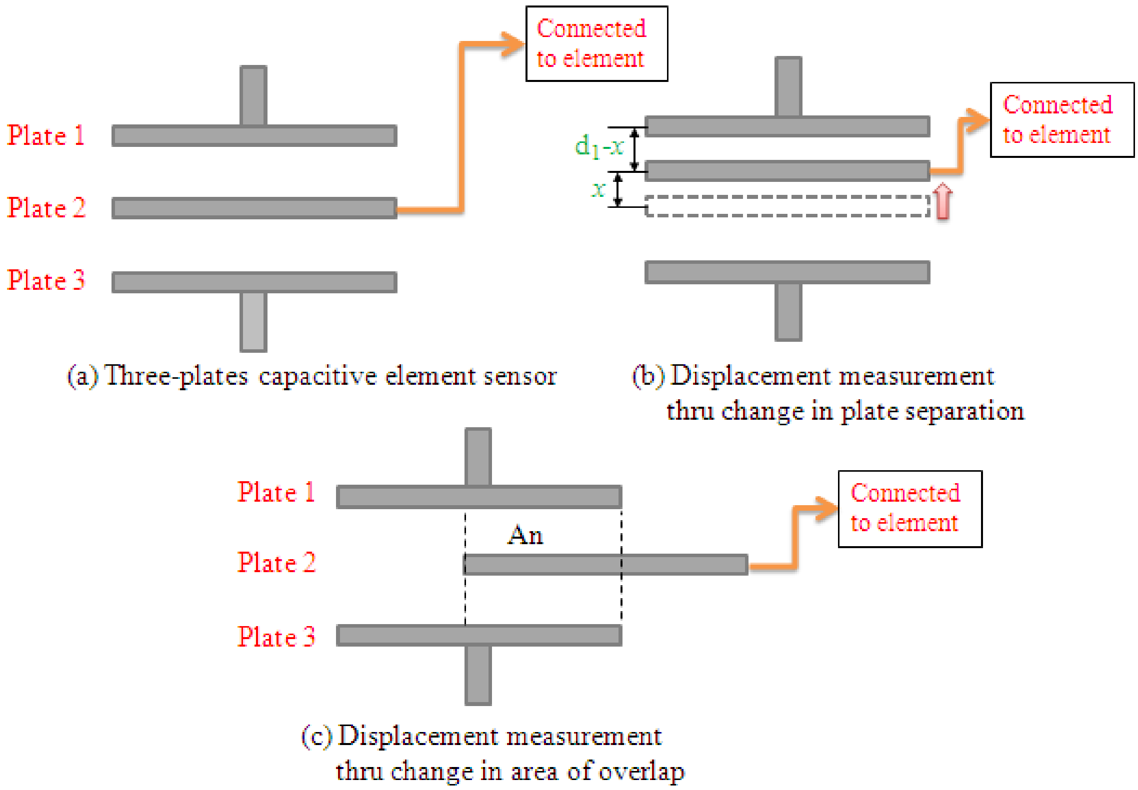

Figure 2.2.5 Displacement measurement using capacitive element sensor

The capacitance C of a parallel plate capacitor is given by,

$$C = \varepsilon_r \varepsilon_o A / d \qquad (2.2.7)$$

where ε_r is the relative permittivity of the dielectric between the plates, ε_o permittivity of free space, *A* area of overlap between two plates and *d* the plate separation.

As the central plate moves near to top plate or bottom one due to the movement of the element/workpiece of which displacement is to be measured, separation in between the plate changes. This can be given as,

$$C_1 = (\varepsilon_r \varepsilon_o A) / (d + x) \quad (2.2.8)$$

$$C_2 = (\varepsilon_r \varepsilon_o A) / (d - x) \quad (2.2.9)$$

When C1 and C2 are connected to a Wheatsone's bridge, then the resulting out-of-balance voltage would be in proportional to displacement x.

Capacitive elements can also be used as proximity sensor. The approach of the object towards the sensor plate is used for induction of change in plate separation. This changes the capacitance which is used to detect the object.

Applications of capacitive element sensors

- Feed hopper level monitoring
- Small vessel pump control
- Grease level monitoring
- Level control of liquids
- Metrology applications
  - to measure shape errors in the part being produced
  - to analyze and optimize the rotation of spindles in various machine tools such as surface grinders, lathes, milling machines, and air bearing spindles by measuring errors in the machine tools themselves
- Assembly line testing
  - to test assembled parts for uniformity, thickness or other design features
  - to detect the presence or absence of a certain component, such as glue etc.

4. *Linear variable differential transformer (LVDT)*

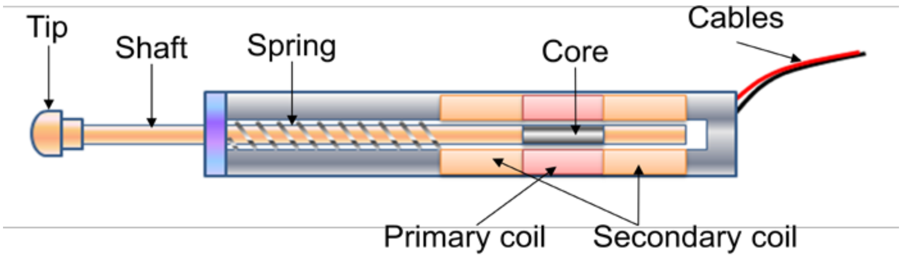

Figure 2.2.6 Construction of a LVDT sensor

Linear variable differential transformer (LVDT) is a primary transducer used for measurement of linear displacement with an input range of about ± 2 to ± 400 mm in general. It has non-linearity error ± 0.25% of full range. Figure 2.2.6 shows the construction of a LVDT sensor. It has three coils symmetrically spaced along an insulated tube. The central coil is primary coil and the other two are secondary coils. Secondary coils are connected in series in such a way that their outputs oppose each other. A magnetic core attached to the element of which displacement is to be monitored is placed inside the insulated tube.

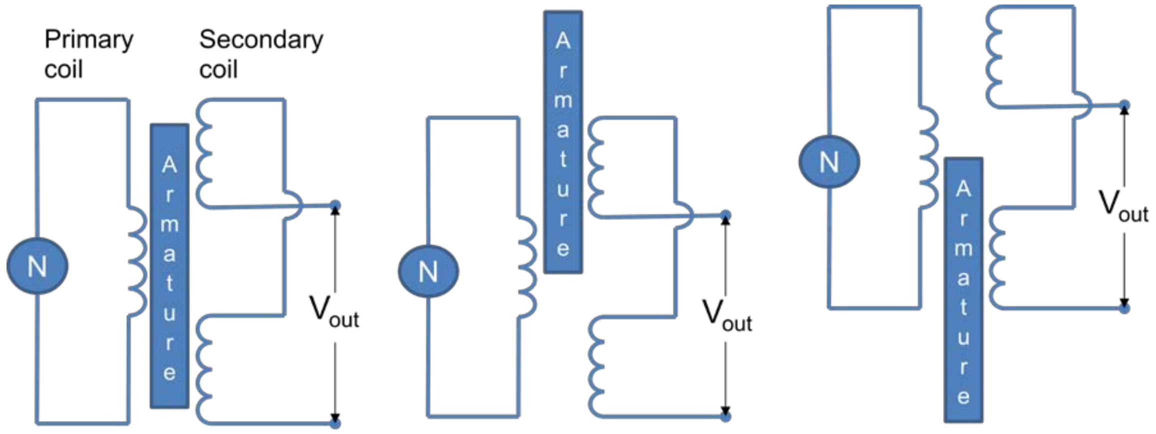

Figure 2.2.7 Working of LVDT sensor

Due to an alternating voltage input to the primary coil, alternating electro-magnetic forces (emfs) are generated in secondary coils. When the magnetic core is centrally placed with its half portion in each of the secondary coil regions then the resultant voltage is zero. If the core is displaced from the central position as shown in Figure 2.2.7, say, more in secondary coil 1 than in coil 2, then more emf is generated in one coil i.e. coil 1 than the other, and there is a resultant voltage from the coils. If the magnetic core is further displaced, then the value of resultant voltage increases in proportion with the displacement. With the help of signal processing devices such as low pass filters and demodulators, precise displacement can be measured by using LVDT sensors.

LVDT exhibits good repeatability and reproducibility. It is generally used as an absolute position sensor. Since there is no contact or sliding between the constituent elements of the sensor, it is highly reliable. These sensors are completely sealed and are widely used in Servomechanisms, automated measurement in machine tools.

A rotary variable differential transformer (RVDT) can be used for the measurement of rotation. Readers are suggested to prepare a report on principle of working and construction of RVDT sensor.

Applications of LVDT sensors

- Measurement of spool position in a wide range of servo valve applications
- To provide displacement feedback for hydraulic cylinders
- To control weight and thickness of medicinal products viz. tablets or pills
- For automatic inspection of final dimensions of products being packed for dispatch
- To measure distance between the approaching metals during Friction welding process
- To continuously monitor fluid level as part of leak detection system
- To detect the number of currency bills dispensed by an ATM

Quiz:

1. Explain the principle of working of LVDT.
2. Describe the working of RVDT with a neat sketch.
3. List the applications of potentiometer sensor in/around your home and office/university.

References

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.

Module 2: Sensors and signal processing
Lecture 3
Displacement, position and proximity sensors

1. *Eddy current proximity sensors*

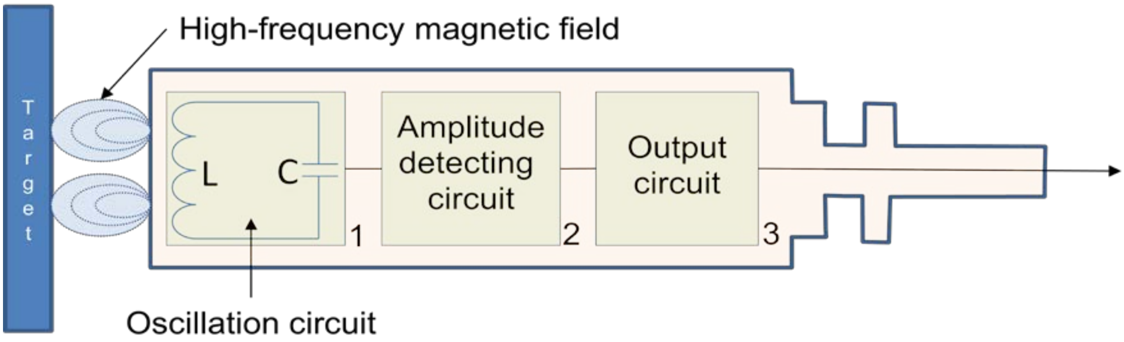

Figure 2.3.1 Schematic of Inductive Proximity Sensor

Eddy current proximity sensors are used to detect non-magnetic but conductive materials. They comprise of a coil, an oscillator, a detector and a triggering circuit. Figure 2.3.1 shows the construction of eddy current proximity switch. When an alternating current is passed thru this coil, an alternative magnetic field is generated. If a metal object comes in the close proximity of the coil, then eddy currents are induced in the object due to the magnetic field. These eddy currents create their own magnetic field which distorts the magnetic field responsible for their generation. As a result, impedance of the coil changes and so the amplitude of alternating current. This can be used to trigger a switch at some pre-determined level of change in current.

Eddy current sensors are relatively inexpensive, available in small in size, highly reliable and have high sensitivity for small displacements.

Applications of eddy current proximity sensors

- Automation requiring precise location
- Machine tool monitoring
- Final assembly of precision equipment such as disk drives
- Measuring the dynamics of a continuously moving target, such as a vibrating element,
- Drive shaft monitoring
- Vibration measurements

2. *Inductive proximity switch*

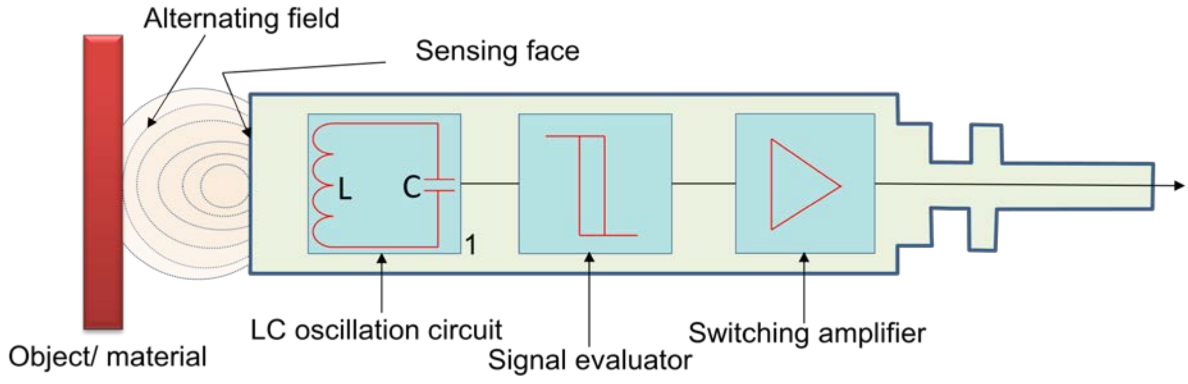

Figure 2.3.2 Schematic of Inductive Proximity Switch

Inductive proximity switches are basically used for detection of metallic objects. Figure 2.3.2 shows the construction of inductive proximity switch. An inductive proximity sensor has four components; the coil, oscillator, detection circuit and output circuit. An alternating current is supplied to the coil which generates a magnetic field. When, a metal object comes closer to the end of the coil, inductance of the coil changes. This is continuously monitored by a circuit which triggers a switch when a preset value of inductance change is occurred.

Applications of inductive proximity switches

- Industrial automation: counting of products during production or transfer
- Security: detection of metal objects, arms, land mines

3. *Optical encoders*

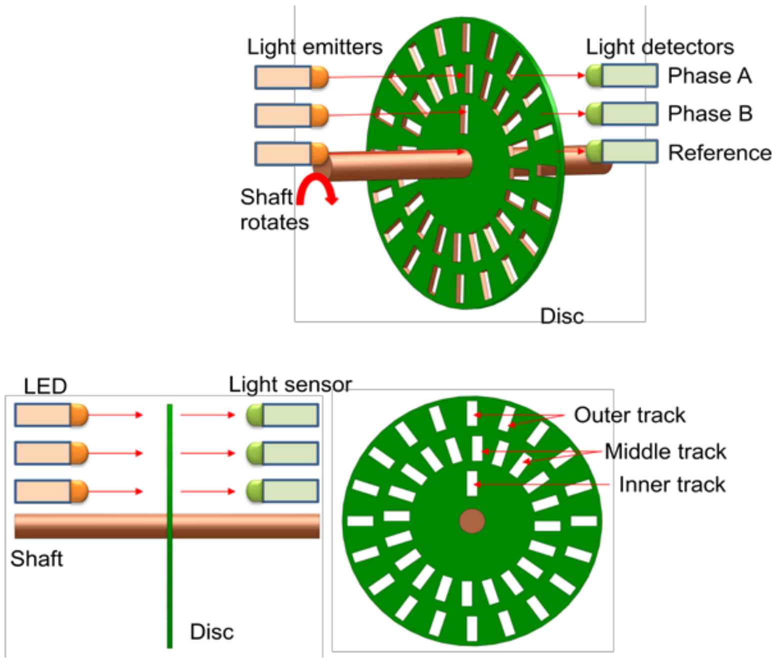

Figure 2.3.3 Construction and working of optical encoder

Optical encoders provide digital output as a result of linear / angular displacement. These are widely used in the Servo motors to measure the rotation of shafts. Figure 2.3.3 shows the construction of an optical encoder. It comprises of a disc with three concentric tracks of equally spaced holes. Three light sensors are employed to detect the light passing thru the holes. These sensors produce electric pulses which give the angular displacement of the mechanical element e.g. shaft on which the Optical encoder is mounted. The inner track has just one hole which is used locate the 'home' position of the disc. The holes on the middle track offset from the holes of the outer track by one-half of the width of the hole. This arrangement provides the direction of rotation to be determined. When the disc rotates in clockwise direction, the pulses in the outer track lead those in the inner; in counter clockwise direction they lag behind. The resolution can be determined by the number of holes on disc. With 100 holes in one revolution, the resolution would be,

$360^o/100 = 3.6^o$.

4. *Pneumatic Sensors*

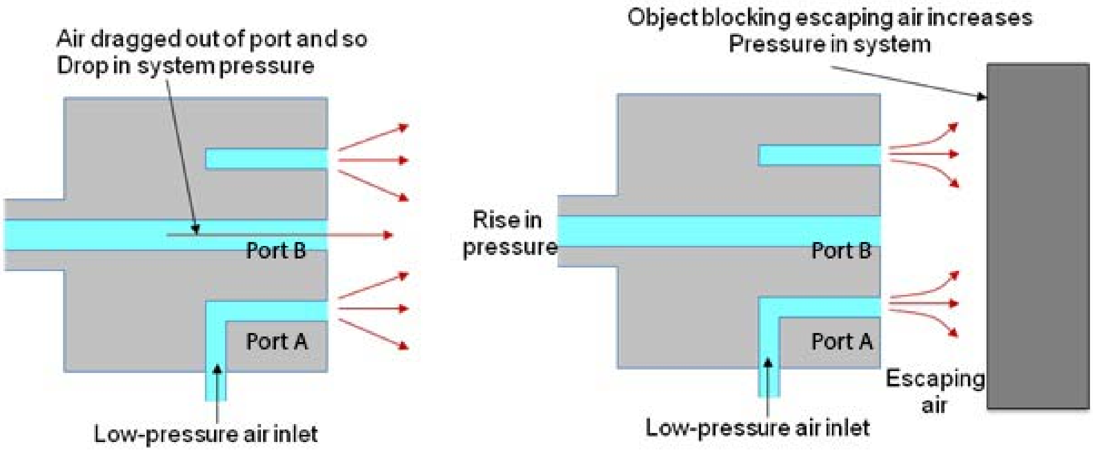

Figure 2.3.4 Working of Pneumatic Sensors [1]

Pneumatic sensors are used to measure the displacement as well as to sense the proximity of an object close to it. The displacement and proximity are transformed into change in air pressure. Figure 2.3.4 shows a schematic of construction and working of such a sensor. It comprises of three ports. Low pressure air is allowed to escape through port A. In the absence of any obstacle / object, this low pressure air escapes and in doing so, reduces the pressure in the port B. However when an object obstructs the low pressure air (Port A), there is rise in pressure in output port B. This rise in pressure is calibrated to measure the displacement or to trigger a switch. These sensors are used in robotics, pneumatics and for tooling in CNC machine tools.

5. *Proximity Switches*

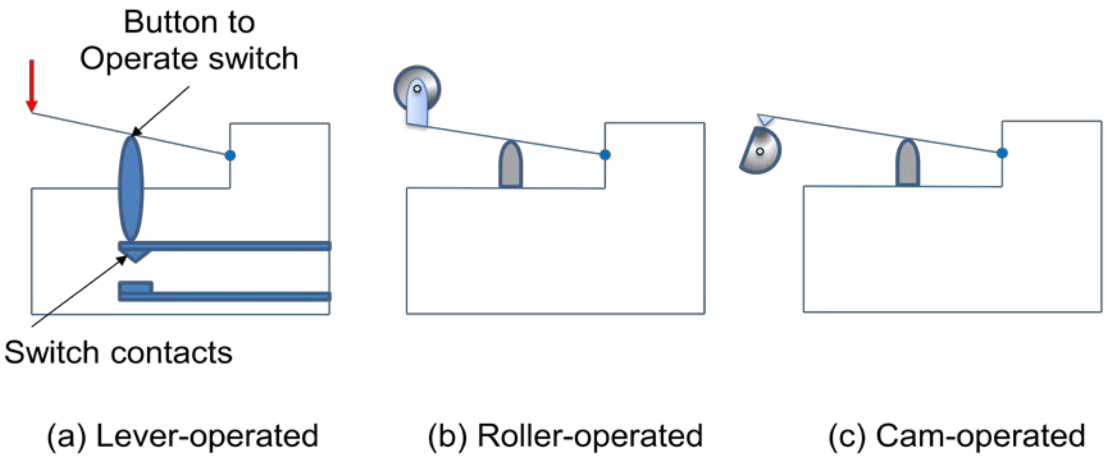

Figure 2.3.5 Configurations of contact type proximity switch [1]

Figure 2.3.5 shows a number of configurations of contact-type proximity switch being used in manufacturing automation. These are small electrical switches which require physical contact and a small operating force to close the contacts. They are basically employed on conveyor systems to detect the presence of an item on the conveyor belt.

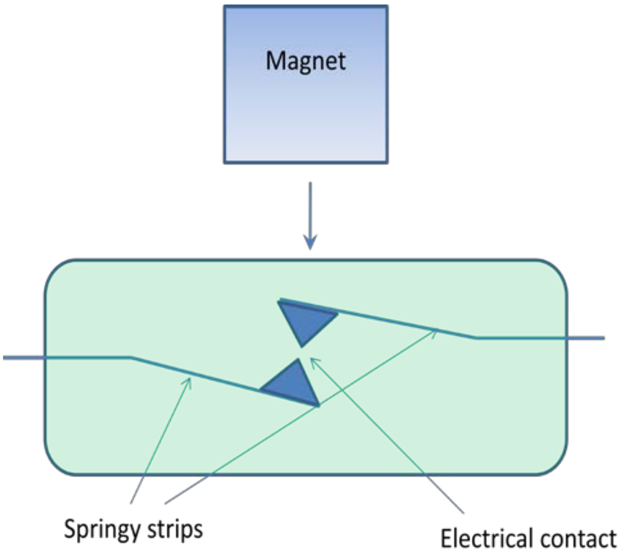

Figure 2.3.6 Reed Switch [1]

Magnet based Reed switches are used as proximity switches. When a magnet attached to an object brought close to the switch, the magnetic reeds attract to each other and close the switch contacts. A schematic is shown in Figure 2.3.6.

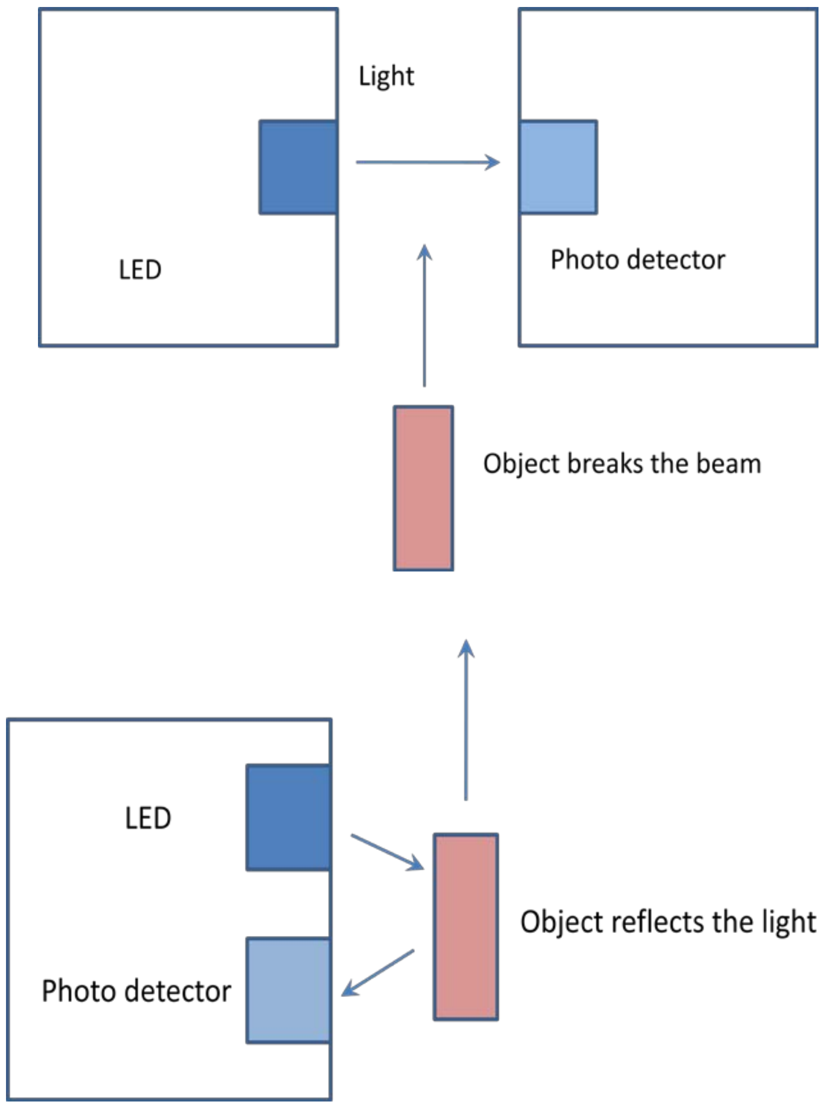

Figure 2.3.7 LED based proximity sensors [1]

Photo emitting devices such as Light emitting diodes (LEDs) and photosensitive devices such as photo diodes and photo transistors are used in combination to work as proximity sensing devices. Figure 2.3.7 shows two typical arrangements of LEDs and photo diodes to detect the objects breaking the beam and reflecting light.

6. *Hall effect sensor*

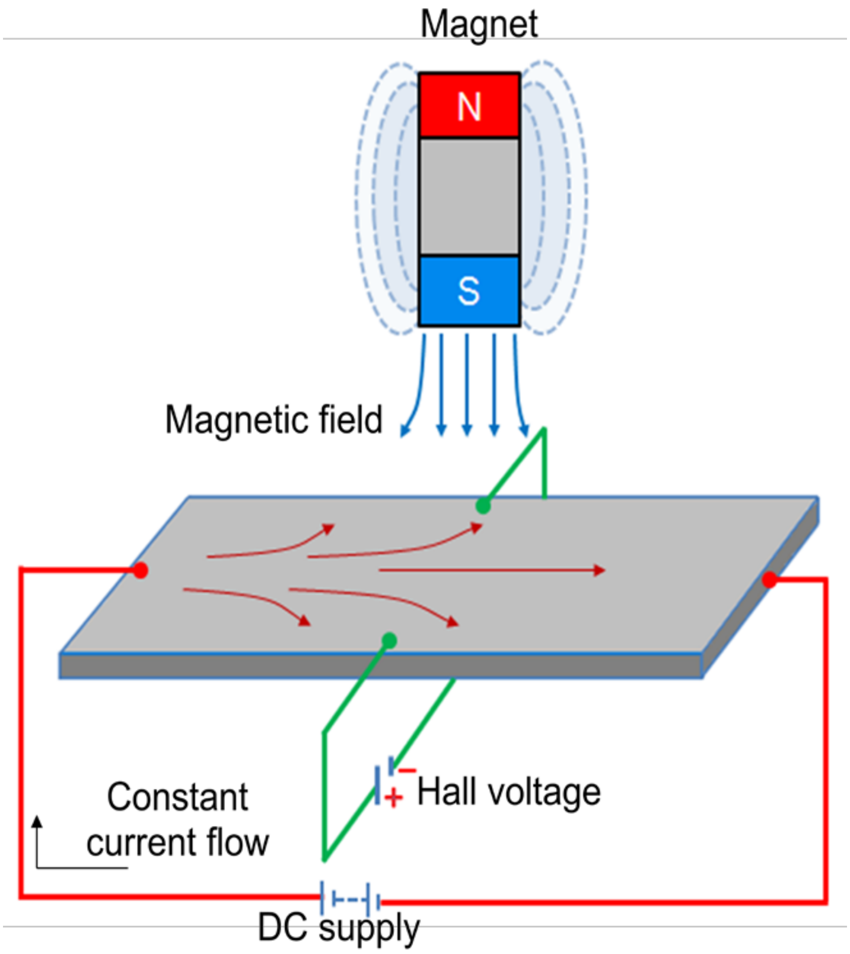

Figure 2.3.8 Principle of working of Hall effect sensor

Figure 2.3.8 shows the principle of working of Hall effect sensor. Hall effect sensors work on the principle that when a beam of charge particles passes through a magnetic field, forces act on the particles and the current beam is deflected from its straight line path. Thus one side of the disc will become negatively charged and the other side will be of positive charge. This charge separation generates a potential difference which is the measure of distance of magnetic field from the disc carrying current.

The typical application of Hall effect sensor is the measurement of fluid level in a container. The container comprises of a float with a permanent magnet attached at its top. An electric circuit with a current carrying disc is mounted in the casing. When the fluid level increases, the magnet will come close to the disc and a potential difference generates. This voltage triggers a switch to stop the fluid to come inside the container.

These sensors are used for the measurement of displacement and the detection of position of an object. Hall effect sensors need necessary signal conditioning circuitry. They can be operated at 100 kHz. Their non-contact nature of operation, good immunity to environment contaminants and ability to sustain in severe conditions make them quite popular in industrial automation.

Quiz:

1. To detect non-conducting metallic objects which sensor would be useful?
2. If a digital optical encoder has 7 tracks, then the minimum angular motion that can be measured by this device _________________.
3. Explain in brief two applications of "Reed switch".
4. Explain the principle of working of Hall effect sensor.

References

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.

Module 2: Sensors and signal processing
Lecture 4

Velocity, motion, force and pressure sensors

1. *Tachogenerator*

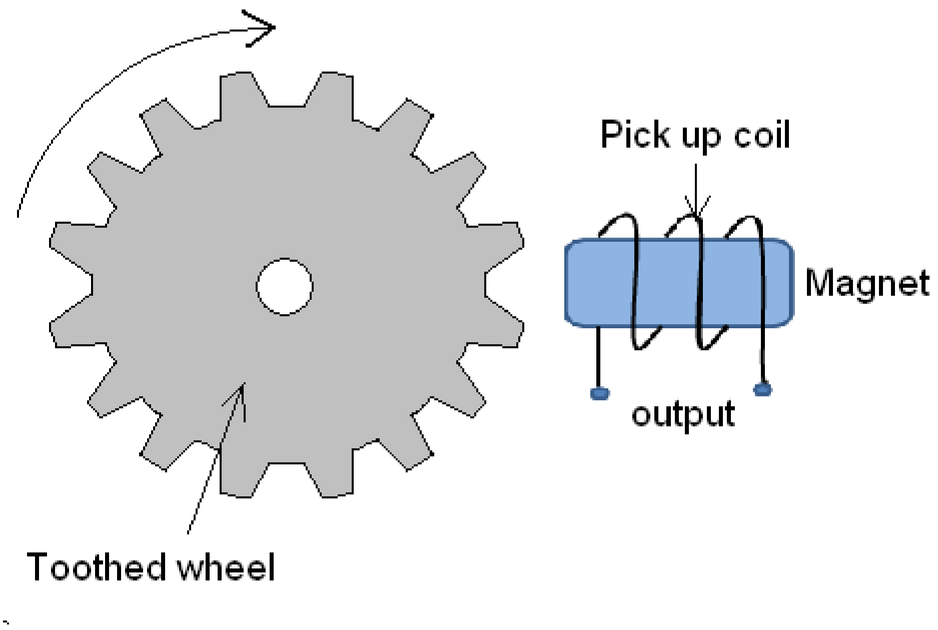

Figure 2.4.1 Principle of working of Techogenerator [1]

Tachogenerator works on the principle of variable reluctance. It consists of an assembly of a toothed wheel and a magnetic circuit as shown in figure 2.4.1. Toothed wheel is mounted on the shaft or the element of which angular motion is to be measured. Magnetic circuit comprising of a coil wound on a ferromagnetic material core. As the wheel rotates, the air gap between wheel tooth and magnetic core changes which results in cyclic change in flux linked with the coil. The alternating emf generated is the measure of angular motion. A pulse shaping signal conditioner is used to transform the output into a number of pulses which can be counted by a counter.

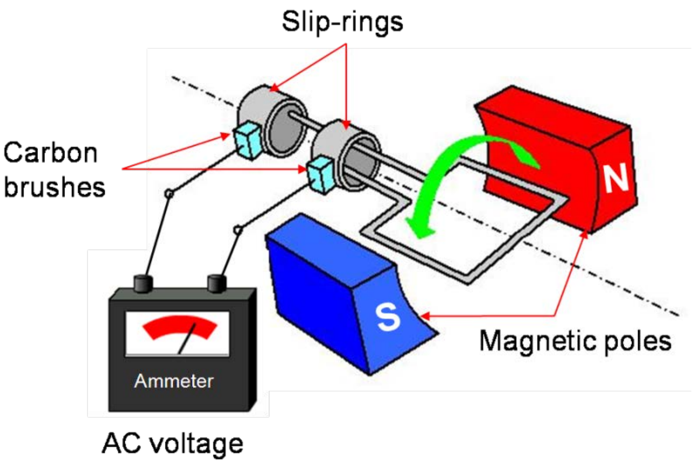

Figure 2.4.2 Construction and working of AC generator

An alternating current (AC) generator can also be used as a techognerator. It comprises of rotor coil which rotates with the shaft. Figure 2.4.2 shows the schematic of AC generator. The rotor rotates in the magnetic field produced by a stationary permanent magnet or electromagnet. During this process, an alternating emf is produced which is the measure of the angular velocity of the rotor. In general, these sensors exhibit nonlinearity error of about ± 0.15% and are employed for the rotations up to about 10000 rev/min.

2. *Pyroelectric sensors*

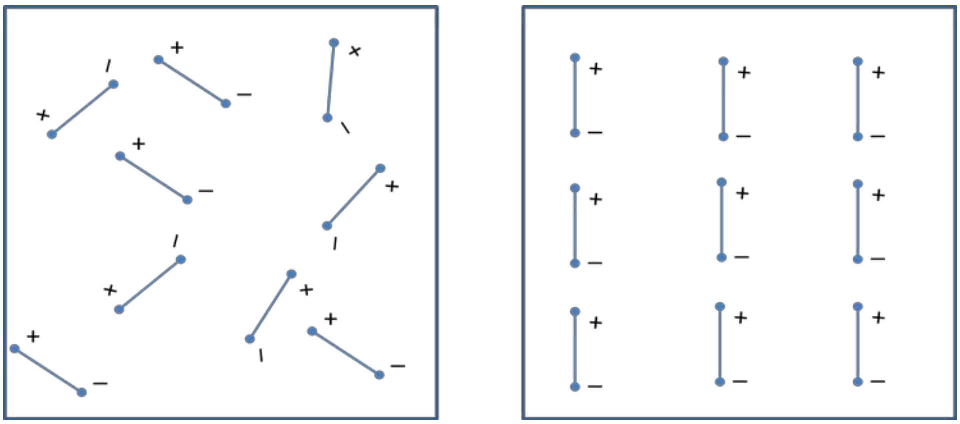

Figure 2.4.3 Principle of pyroelectricity

These sensors work on the principle of *pyroelectricity*, which states that a crystal material such as Lithium tantalite generates charge in response to heat flow. In presence of an electric field, when such a crystal material heats up, its electrical dipoles line up as shown in figure 2.4.3. This is called as polarization. On cooling, the material retains its polarization. In absence of electric field, when this polarized material is subjected to infra red irradiation, its polarization reduces. This phenomenon is the measure of detection of movement of an object.

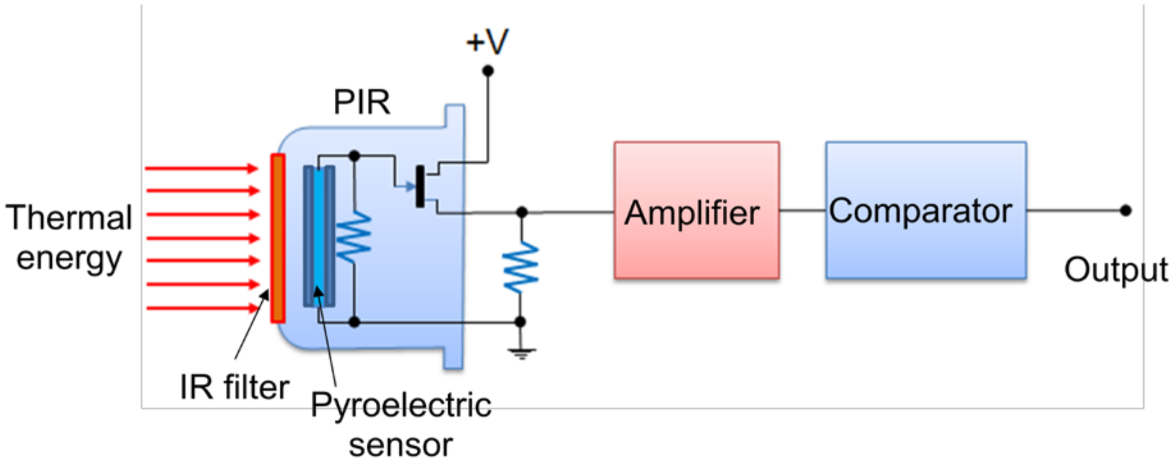

Figure 2.4.4 Construction and working a Pyroelectric sensor

Pyroelectric sensor comprises of a thick element of polarized material coated with thin film electrodes on opposite faces as shown in figure 2.4.4. Initially the electrodes are in electrical equilibrium with the polarized material. On incident of infra red, the material heats up and reduces its polarization. This leads to charge imbalance at the interface of crystal and electrodes. To balance this disequilibrium, measurement circuit supplies the charge, which is calibrated against the detection of an object or its movement.

Applications of Pyroelectric sensors [2]

- Intrusion detector
- Optothermal detector
- Pollution detector
- Position sensor
- Solar cell studies
- Engine analysis

3. Strain Gauge as force Sensor

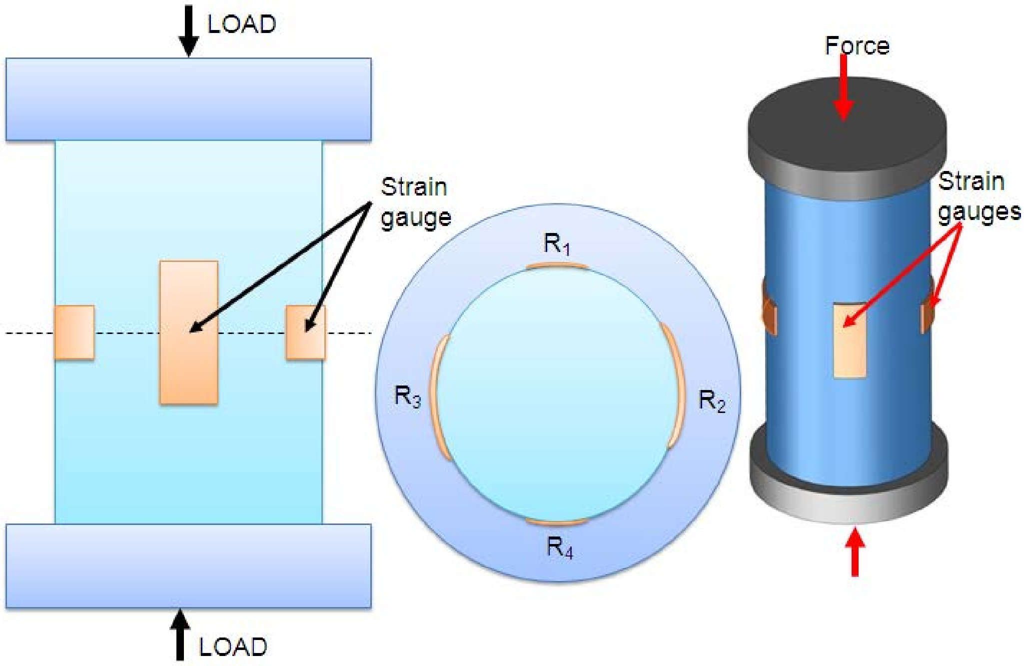

Figure 2.4.5 Strain gauge based Load cell

Strain gauge based sensors work on the principle of change in electrical resistance. When, a mechanical element subjects to a tension or a compression the electric resistance of the material changes. This is used to measure the force acted upon the element. The details regarding the construction of strain gauge transducer are already presented in Lecture 2 of Module 2.

Figure 2.4.5 shows a strain gauge load cell. It comprises of cylindrical tube to which strain gauges are attached. A load applied on the top collar of the cylinder compress the strain gauge element which changes its electrical resistance. Generally strain gauges are used to measure forces up to 10 MN. The non-linearity and repeatability errors of this transducer are ±0.03% and ±0.02% respectively.

4. *Fluid pressure*

Chemical, petroleum, power industry often need to monitor fluid pressure. Various types of instruments such as diaphragms, capsules, and bellows are used to monitor the fluid pressure. Specially designed strain gauges doped in diaphragms are generally used to measure the inlet manifold pressure in applications such as automobiles. A typical arrangement of strain gauges on a diaphragm is shown in figure 2.4.6. Application of pressurized fluid displaces the diaphragm. This displacement is measured by the stain gauges in terms of radial and/or lateral strains. These strain gauges are connected to form the arms of a Wheatstone bridge.

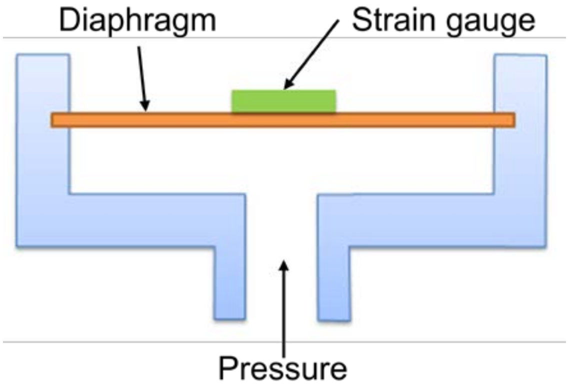

Figure 2.4.6 A diaphragm

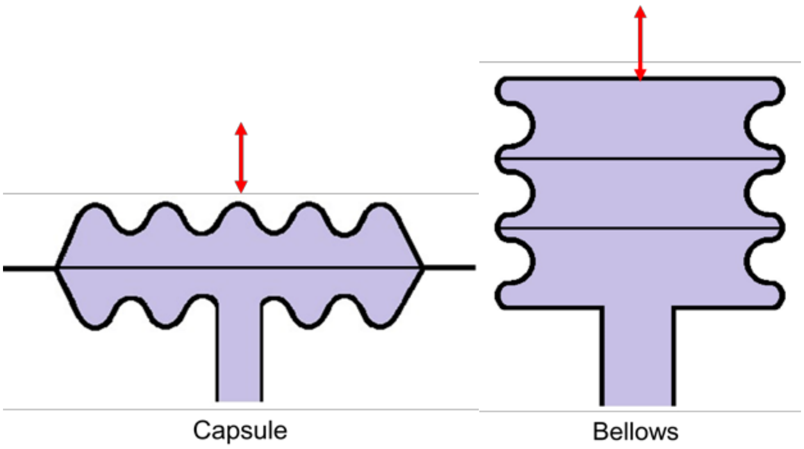

Figure 2.4.7 Schematic of Capsule and Bellow

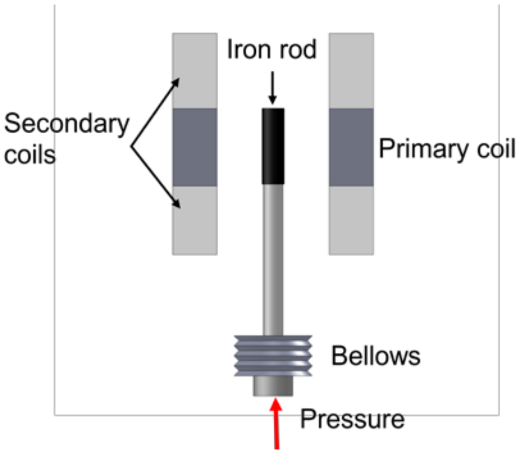

Figure 2.4.8 Bellow with a LVDT [1]

Capsule is formed by combining two corrugated diaphragms. It has enhanced sensitivity in comparison with that of diaphragms. Figure 2.4.7 shows a schematic of a Capsule and a Bellow. A stack of capsules is called as 'Bellows'. Bellows with a LVDT sensor measures the fluid pressure in terms of change in resultant voltage across the secondary coils of LVDT. Figure 2.4.8 shows a typical arrangement of the same.

5. *Tactile sensors*

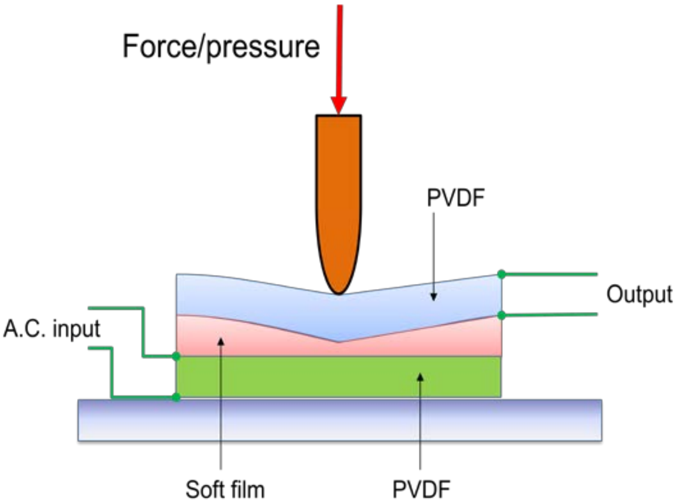

Figure 2.4.9 Schematic of a tactile sensor [1]

In general, tactile sensors are used to sense the contact of fingertips of a robot with an object. They are also used in manufacturing of 'touch display' screens of visual display units (VDUs) of CNC machine tools. Figure 2.4.9 shows the construction of piezo-electric polyvinylidene fluoride (PVDF) based tactile sensor. It has two PVDF layers separated by a soft film which transmits the vibrations. An alternating current is applied to lower PVDF layer which generates vibrations due to reverse piezoelectric effect. These vibrations are transmitted to the upper PVDF layer via soft film. These vibrations cause alternating voltage across the upper PVDF layer. When some pressure is applied on the upper PVDF layer the vibrations gets affected and the output voltage changes. This triggers a switch or an action in robots or touch displays.

6. Piezoelectric sensor

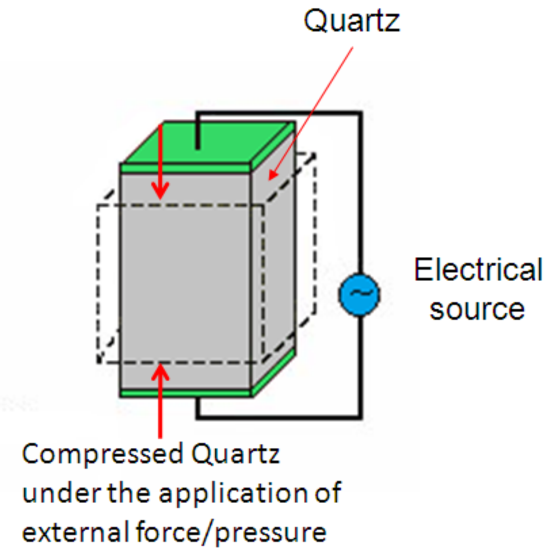

Figure 2.4.10 Principle of working of Piezoelectric sensor

Piezoelectric sensor is used for the measurement of pressure, acceleration and dynamic-forces such as oscillation, impact, or high speed compression or tension. It contains piezoelectric ionic crystal materials such as Quartz (Figure 2.4.10). On application of force or pressure these materials get stretched or compressed. During this process, the charge over the material changes and redistributes. One face of the material becomes positively charged and the other negatively charged. The net charge q on the surface is proportional to the amount x by which the charges have been displaced. The displacement is proportion to force. Therefore we can write,

$$q = kx = SF \qquad (2.4.1)$$

where k is constant and S is a constant termed the charge sensitivity.

7. Liquid flow

Liquid flow is generally measured by applying the Bernoulli's principle of fluid flow through a constriction. The quantity of fluid flow is computed by using the pressure drop measured. The fluid flow volume is proportional to square root of pressure difference at the two ends of the constriction. There are various types of fluid flow measurement devices being used in manufacturing automation such as Orifice plate, Turbine meter etc.

7.a Orifice plate:

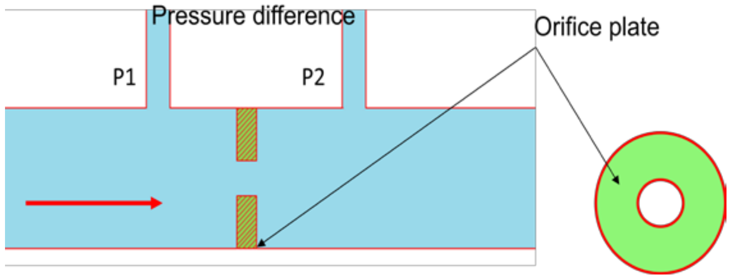

Figure 2.4.11 Orifice Plate [1]

Figure 2.4.11 shows a schematic of Orifice plate device. It has a disc with a hole at its center, through which the fluid flows. The pressure difference is measured between a point equal to the diameter of the tube upstream and a point equal to the half the diameter downstream. Orifice plate is inexpensive and simple in construction with no moving parts. It exhibits nonlinear behavior and does not work with slurries. It has accuracy of ± 1.5%.

7.b Turbine meter

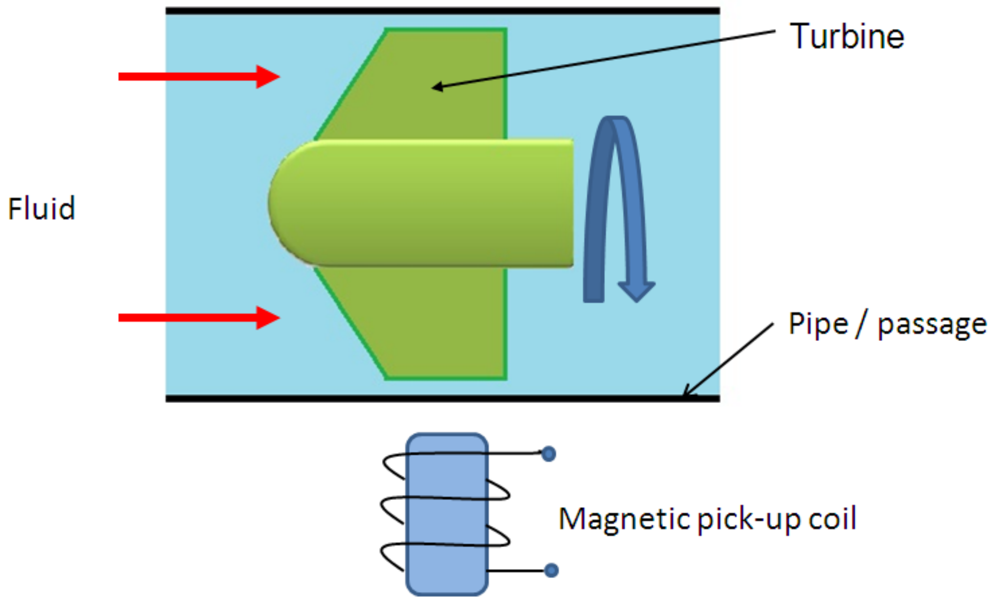

Figure 2.4.12 Schematic of turbine meter [1]

Turbine flow meter has an accuracy of ±0.3%. It has a multi blade rotor mounted centrally in the pipe along which the flow is to be measured. Figure 2.4.12 shows the typical arrangement of the rotor and a magnetic pick up coil. The fluid flow rotates the rotor. Accordingly the magnetic pick up coil counts the number of magnetic pulses generated due to the distortion of magnetic field by the rotor blades. The angular velocity is proportional to the number of pulses and fluid flow is proportional to angular velocity.

8. Fluid level

The level of liquid in a vessel or container can be measured,

a. directly by monitoring the position of liquid surface
b. indirectly by measuring some variable related to the height.

Direct measurements involve the use of floats however the indirect methods employ load cells. Potentiometers or LVDT sensors can be used along with the floats to measure the height of fluid column. Force sensed by the load cells is proportional to the height of fluid column.

Quiz:

1. PVDF piezoelectric polyvinylidene fluoride is used in the manufacture of ___________________________ sensor.
2. Suggest a suitable sensor to measure the level of sulphuric acid in a storage tank. The sensor must give an electric signal as output.
3. 'Bellows are more sensitive than capsules'. State true or false and justify your answer.
4. State the applications of pyroelectric sensors.

References

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.
2. Hossain A. and Rashid M. H., Pyroelectric Detectors and Their Applications, IEEE Trans. on Ind. Appl., 27 (5), 824-829, 1991.

Module 2: Sensors and signal processing
Lecture 5
Temperature and light sensors

Temperature conveys the state of a mechanical system in terms of expansion or contraction of solids, liquids or gases, change in electrical resistance of conductors, semiconductors and thermoelectric emfs. Temperature sensors such as bimetallic strips, thermocouples, thermistors are widely used in monitoring of manufacturing processes such as casting, molding, metal cutting etc. The construction details and principle of working of some of the temperature sensors are discussed in following sections.

1. *Bimetallic strips*

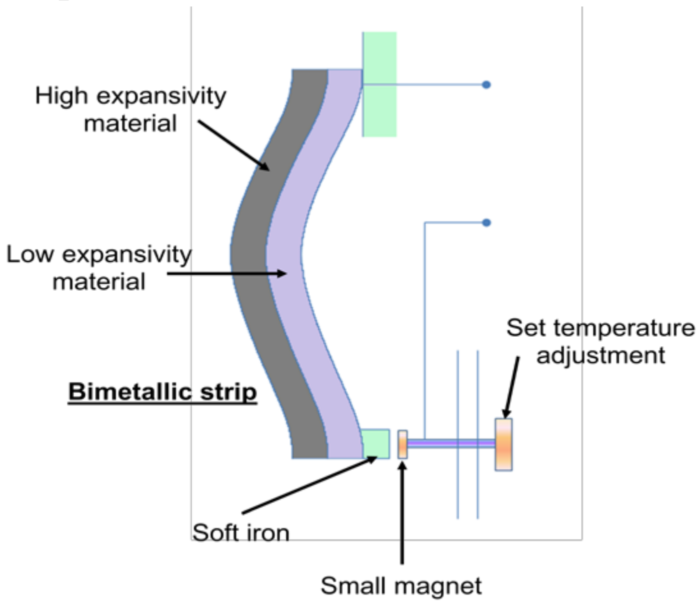

Figure 2.5.1 Construction and working of Bi-metallic strip

Bimetallic strips are used as thermal switch in controlling the temperature or heat in a manufacturing process or system. It contains two different metal strips bonded together. The metals have different coefficients of expansion. On heating the strips bend into curved strips with the metal with higher coefficient of expansion on the outside of the curve. Figure 2.5.1 shows a typical arrangement of a bimetallic strip used with a setting-up magnet. As the strips bend, the soft iron comes in closer proximity of the small magnet and further touches. Then the electric circuit completes and generates an alarm. In this way bimetallic strips help to protect the desired application from heating above the pre-set value of temperature.

2. *Resistance temperature detectors (RTDs)*

RTDs work on the principle that the electric resistance of a metal changes due to change in its temperature. On heating up metals, their resistance increases and follows a linear relationship as shown in Figure 2.5.2. The correlation is

$$R_t = R_0 (1 + \alpha T) \qquad (2.5.1)$$

where R_t is the resistance at temperature T (^{0}C) and R_0 is the temperature at 0^0C and α is the constant for the metal termed as temperature coefficient of resistance. The sensor is usually made to have a resistance of 100 Ω at 0 °C

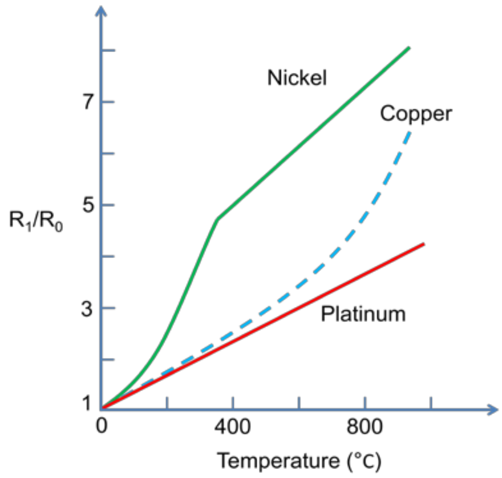

Figure 2.5.2 Behavior of RTD materials [1]

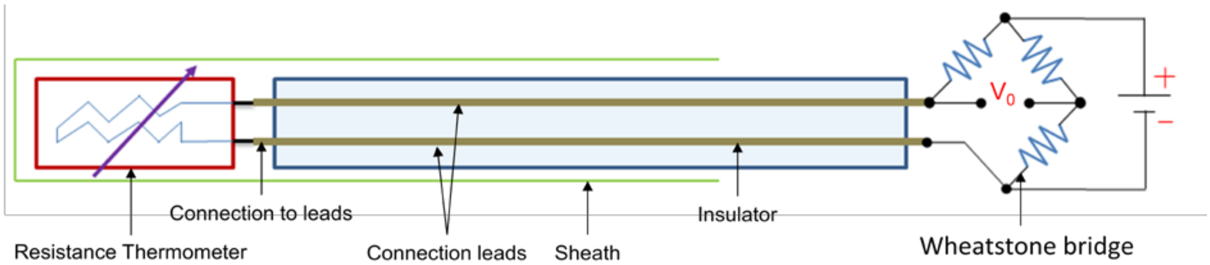

Figure 2.5.3 Construction of a Resistance temperature detector (RTD)

Figure 2.5.3 shows the construction of a RTD. It has a resistor element connected to a Wheatstone bridge. The element and the connection leads are insulated and protected by a sheath. A small amount of current is continuously passing though the coil. As the temperature changes the resistance of the coil changes which is detected at the Wheatstone bridge.

RTDs are used in the form of thin films, wire wound or coil. They are generally made of metals such as platinum, nickel or nickel-copper alloys. Platinum wire held by a high-temperature glass adhesive in a ceramic tube is used to measure the temperature in a metal furnace. Other applications are:

- Air conditioning and refrigeration servicing
- Food Processing
- Stoves and grills
- Textile production
- Plastics processing
- Petrochemical processing
- Micro electronics
- Air, gas and liquid temperature measurement in pipes and tanks
- Exhaust gas temperature measurement

3. Thermistors

Thermistors follow the principle of decrease in resistance with increasing temperature. The material used in thermistor is generally a semiconductor material such as a sintered metal oxide (mixtures of metal oxides, chromium, cobalt, iron, manganese and nickel) or doped polycrystalline ceramic containing barium titanate (BaTiO3) and other compounds. As the temperature of semiconductor material increases the number of electrons able to move about increases which results in more current in the material and reduced resistance. Thermistors are rugged and small in dimensions. They exhibit nonlinear response characteristics.

Thermistors are available in the form of a bead (pressed disc), probe or chip. Figure 2.5.4 shows the construction of a bead type thermistor. It has a small bead of dimension from 0.5 mm to 5 mm coated with ceramic or glass material. The bead is connected to an electric circuit through two leads. To protect from the environment, the leads are contained in a stainless steel tube.

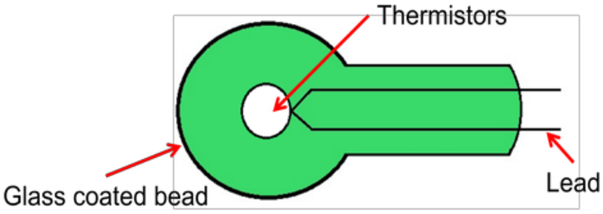

Figure 2.5.4 Schematic of a thermistor

Applications of Thermistors

- To monitor the coolant temperature and/or oil temperature inside the engine
- To monitor the temperature of an incubator
- Thermistors are used in modern digital thermostats
- To monitor the temperature of battery packs while charging
- To monitor temperature of hot ends of 3D printers
- To maintain correct temperature in the food handling and processing industry equipments
- To control the operations of consumer appliances such as toasters, coffee makers, refrigerators, freezers, hair dryers, etc.

4. Thermocouple

Thermocouple works on the fact that when a junction of dissimilar metals heated, it produces an electric potential related to temperature. As per Thomas Seebeck (1821), when two wires composed of dissimilar metals are joined at both ends and one of the ends is heated, then there is a continuous current which flows in the thermoelectric circuit. Figure 2.5.5 shows the schematic of thermocouple circuit. The net open circuit voltage (the Seebeck voltage) is a function of junction temperature and composition of two metals. It is given by,

$$\Delta V_{AB} = \alpha \, \Delta T \qquad (2.5.2)$$

where α, the Seebeck coefficient, is the constant of proportionality.

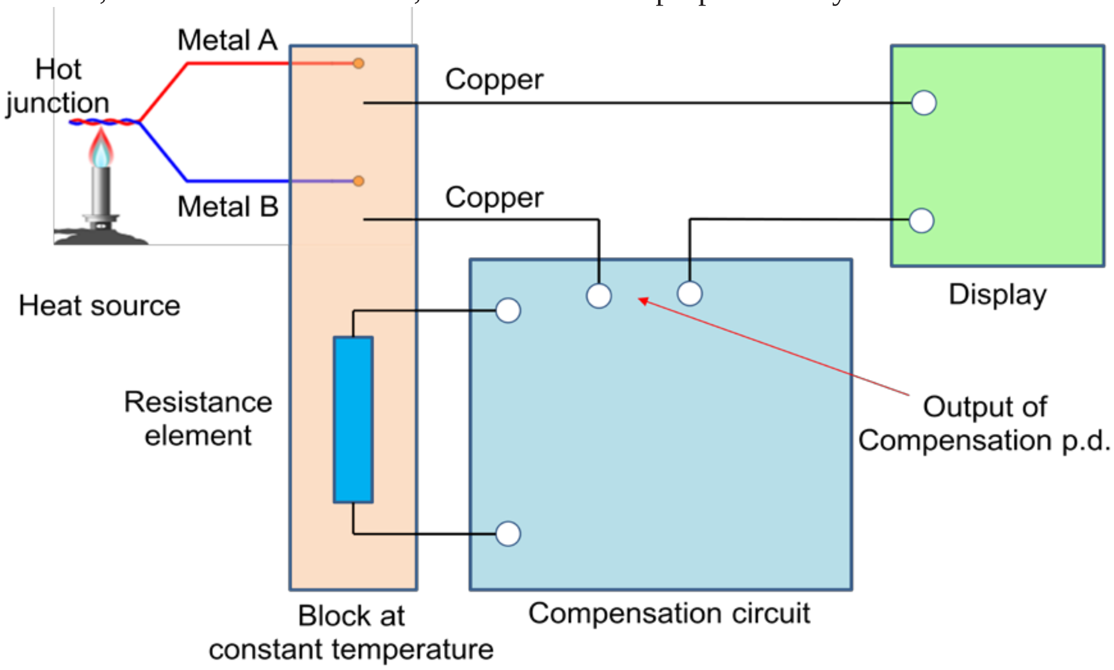

Figure 2.5.5 Schematic of thermocouple circuit

Generally, Chromel (90% nickel and 10% chromium)–Alumel (95% nickel, 2% manganese, 2% aluminium and 1% silicon) are used in the manufacture of a thermocouple. Table 2.5.1 shows the various other materials, their combinations and application temperature ranges.

Table 2.5.1 Thermocouple materials and temperature ranges [1]

Materials	**Range (ºC)**	**(µV/ºC)**
Platinum 30% rhodium/platinum 6% rhodium	0 to 1800	3
Chromel/constantan	-200 to 1000	63
Iron/constantan	-200 to 900	53
Chromel/alumel	-200 to 1300	41
Nirosil/nisil	-200 to 1300	28
Platinum/platinum 13% rhodium	0 to 1400	6
Platinum/platinum 10% rhodium	0 to 1400	6
Copper/constantan	-200 to 400	43

Applications of Thermocouples

- To monitor temperatures and chemistry throughout the steel making process
- Testing temperatures associated with process plants e.g. chemical production and petroleum refineries
- Testing of heating appliance safety
- Temperature profiling in ovens, furnaces and kilns
- Temperature measurement of gas turbine and engine exhausts
- Monitoring of temperatures throughout the production and smelting process in the steel, iron and aluminum industry

Light sensors

A light sensor is a device that is used to detect light. There are different types of light sensors such as photocell/photoresistor and photo diodes being used in manufacturing and other industrial applications.

Photoresistor is also called as light dependent resistor (LDR). It has a resistor whose resistance decreases with increasing incident light intensity. It is made of a high resistance semiconductor material, cadmium sulfide (CdS). The resistance of a CdS photoresistor varies inversely to the amount of light incident upon it. Photoresistor follows the principle of photoconductivity which results from the generation of mobile carriers when photons are absorbed by the semiconductor material.

Figure 2.5.6 shows the construction of a photo resistor. The CdS resistor coil is mounted on a ceramic substrate. This assembly is encapsulated by a resin material. The sensitive coil electrodes are connected to the control system though lead wires. On incidence of high intensity light on the electrodes, the resistance of resistor coil decreases which will be used further to generate the appropriate signal by the microprocessor via lead wires.

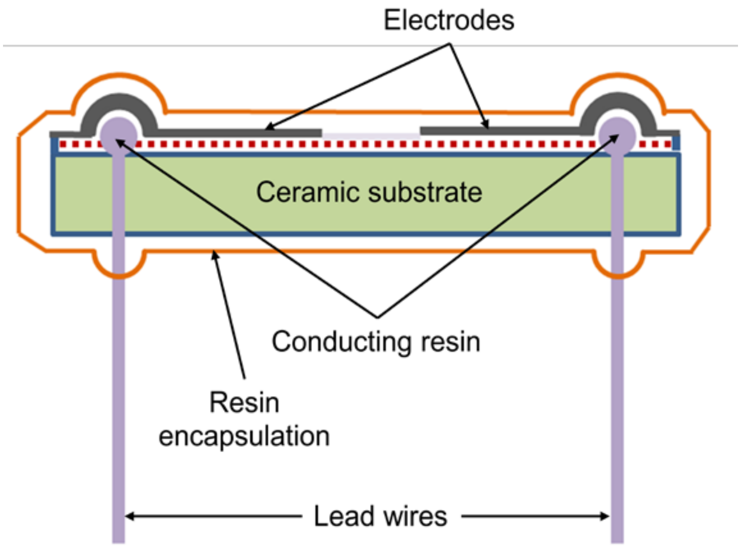

Figure 2.5.6 Construction of a photo resistor

Photoresistors are used in science and in almost any branch of industry for control, safety, amusement, sound reproduction, inspection and measurement.

Applications of photo resistor

- Computers, wireless phones, and televisions, use ambient light sensors to automatically control the brightness of a screen
- Barcode scanners used in retailer locations work using light sensor technology
- In space and robotics: for controlled and guided motions of vehicles and robots. The light sensor enables a robot to detect light. Robots can be programmed to have a specific reaction if a certain amount of light is detected.
- Auto Flash for camera
- Industrial process control

Photo diodes

Photodiode is a solid-state device which converts incident light into an electric current. It is made of Silicon. It consists of a shallow diffused p-n junction, normally a p-on-n configuration. When photons of energy greater than 1.1eV (the bandgap of silicon) fall on the device, they are absorbed and electron-hole pairs are created. The depth at which the photons are absorbed depends upon their energy. The lower the energy of the photons, the deeper they are absorbed. Then the electron-hole pairs drift apart. When the minority carriers reach the junction, they are swept across by the electric field and an electric current establishes.

Photodiodes are one of the types of photodetector, which convert light into either current or voltage. These are regular semiconductor diodes except that they may be either exposed to detect vacuum UV or X-rays or packaged with a opening or optical fiber connection to allow light to reach the sensitive part of the device.

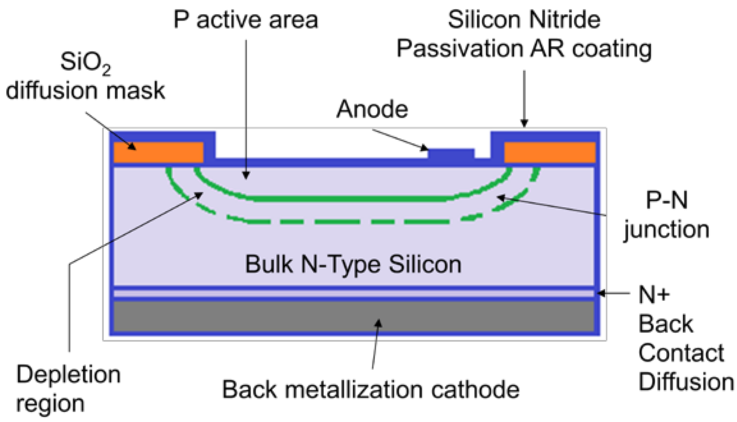

Figure 2.5.7 Construction of photo diode detector

Figure 2.5.7 shows the construction of Photo diode detector. It is constructed from single crystal silicon wafers. It is a p-n junction device. The upper layer is p layer. It is very thin and formed by thermal diffusion or ion implantation of doping material such as boron. Depletion region is narrow and is sandwiched between p layer and bulk n type layer of silicon. Light irradiates at front surface, anode, while the back surface is cathode. The incidence of light on anode generates a flow of electron across the p-n junction which is the measure of light intensity.

Applications of photo diodes

Camera: Light Meters, Automatic Shutter Control, Auto-focus, Photographic Flash Control

Medical: CAT Scanners - X ray Detection, Pulse Oximeters, Blood Particle Analyzers

Industry
- Bar Code Scanners
- Light Pens
- Brightness Controls
- Encoders
- Position Sensors
- Surveying Instruments
- Copiers - Density of Toner

Safety Equipment
- Smoke Detectors
- Flame Monitors
- Security Inspection Equipment - Airport X ray
- Intruder Alert - Security System

Automotive
• Headlight Dimmer
• Twilight Detectors
• Climate Control - Sunlight Detector

Communications
• Fiber Optic Links
• Optical Communications
• Optical Remote Control

Quiz:

1. 'In thermistor sensors, resistance decreases in a very nonlinear manner with increase in temperature.' State true or false and justify.
2. List the various temperature sensors used by we in/around our home/office/university.
3. Develop a conceptual design of a Light sensors based control system for counting a number of milk packets being packed for discharge. Assume suitable data if necessary.

References

1. Boltan, W., Mechatronics: electronic control systems in mechanical and electrical engineering, Longman, Singapore, 1999.

Module 2: Sensors and signal processing
Lecture 6
Signal Conditioning Devices

Signal Conditioning Operations

In previous lectures we have studied various sensors and transducers used in a mechatronics system. Transducers sense physical phenomenon such as rise in temperature and convert the measurand into an electrical signal viz. voltage or current. However these signals may not be in their appropriate forms to employ them to control a mechatronics system. Figure 2.6.1 shows various signal conditioning operations which are being carried out in controlling a mechatronics based system. The signals given by a transducer may be nonlinear in nature or may contain noise. Thus before sending these signals to the mechatronics control unit it is essential to remove the noise, nonlinearity associated with the raw output from a sensor or a transducer. It is also needed to modify the amplitude (low/high) and form (analogue/digital) of the output signals into respective acceptable limits and form which will be suitable to the control system. These activities are carried out by using signal conditioning devices and the process is termed as 'signal conditioning'.

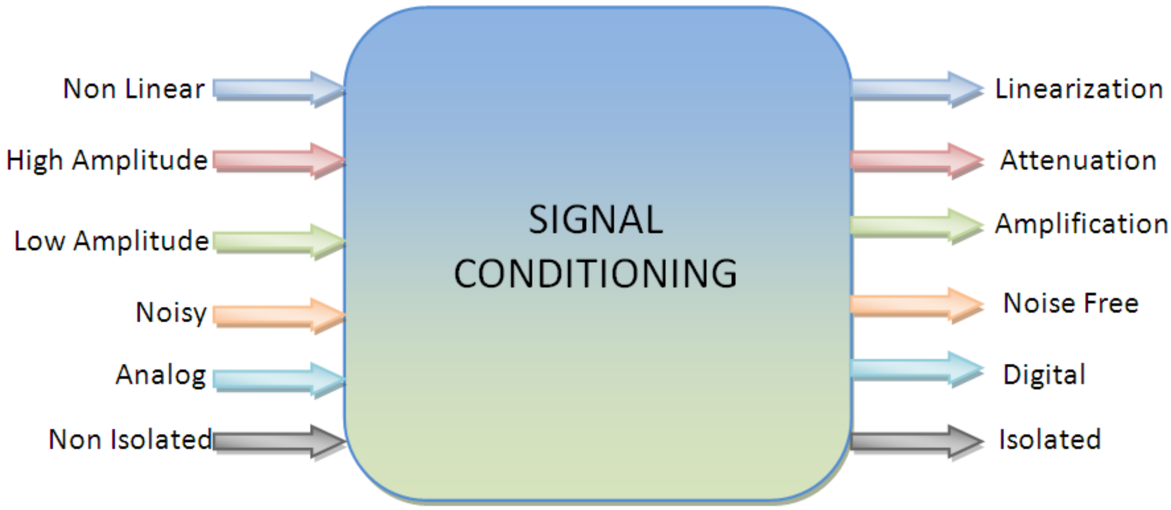

Figure 2.6.1 Signal conditioning operations

Signal conditioning system enhances the quality of signal coming from a sensor in terms of:

1. Protection
To protect the damage to the next element of mechatronics system such microprocessors from the high current or voltage signals.

2. Right type of signal
To convert the output signal from a transducer into the desired form i.e. voltage / current.

3. Right level of the signal
To amplify or attenuate the signals to a right /acceptable level for the next element.

4. Noise
To eliminate noise from a signal.

5. Manipulation
To manipulate the signal from its nonlinear form to the linear form.

1. Amplification/Attenuation

Various applications of Mechatronics system such as machine tool control unit of a CNC machine tool accept voltage amplitudes in range of 0 to 10 Volts. However many sensors produce signals of the order of milli volts. This low level input signals from sensors must be amplified to use them for further control action. Operational amplifiers (op-amp) are widely used for amplification of input signals. The details are as follows.

1.1 Operational amplifier (op-amp)

Operational Amplifier is a basic and an important part of a signal conditioning system. It is often abbreviated as op-amp. Op-amp is a high gain voltage amplifier with a differential input. The gain is of the order of 100000 or more. Differential input is a method of transmitting information with two different electronic signals which are generally complementary to each other. Figure 2.6.2 shows the block diagram of an op-amp. It has five terminals. Two voltages are applied at two input terminals. The output terminal provides the amplified value of difference between two input voltages. Op-amp works by using the external power supplied at *Vs+* and *Vs-* terminals.

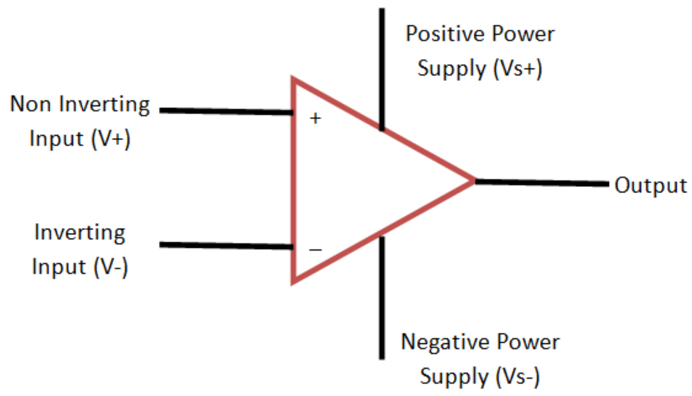

Figure 2.6.2 circuit diagram of an Op-amp

In general op-amp amplifies the difference between input voltages (V+ and V-). The output of an operational amplifier can be written as

$$V_{out} = G * (V+ - V-) \qquad (2.6.1)$$

where G is Op-amp Gain.

Figure 2.6.3 shows the inverting configuration of an op-amp. The input signal is applied at the inverting terminal of the op-amp through the input resistance $R_{in.}$ The non-inverting terminal is grounded. The output voltage (V_{out}) is connected back to the inverting input terminal through resistive network of R_{in} and feedback resistor R_f. Now at node a, we can write,

$$I_1 = V_{in}/R_1 \qquad (2.6.2)$$

The current flowing through R_f is also I_1, because the op-amp is not drawing any current. Therefore the output voltage is given by,

$$V_{out} = -I_1 R_f = -V_{in} R_f/R_1 \qquad (2.6.3)$$

Thus the closed loop gain of op-amp can be given as,

$$G = V_{out}/V_{in} = -R_f/R_1 \qquad (2.6.4)$$

The negative sign indicates a phase shift between V_{in} and V_{out}.

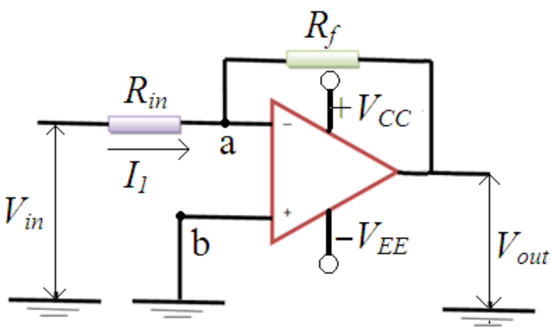

Figure 2.6.3 Inverting op-amp

1.2 Amplification of input signal by using Op-amp

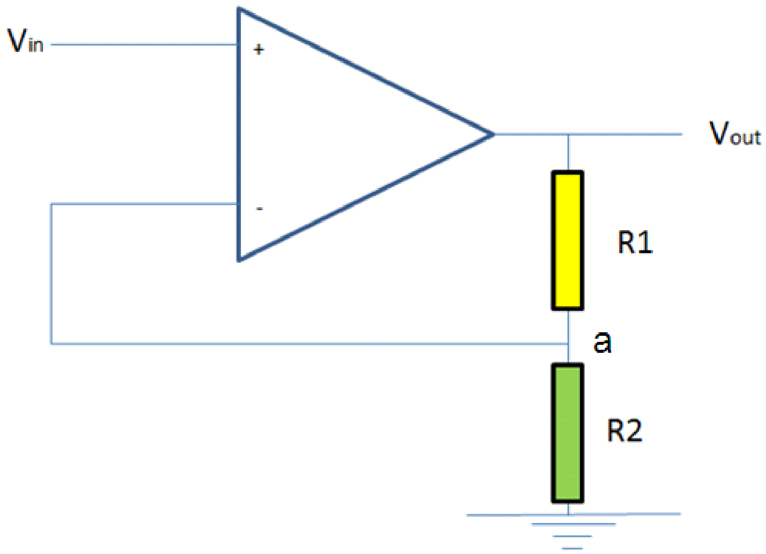

Figure 2.6.4 Amplification using an Op-amp

Figure 2.6.4 shows a configuration to amplify an input voltage signal. It has two registers connected at node a. If we consider that the voltage at positive terminal is equal to voltage at negative terminal then the circuit can be treated as two resistances in series. In series connection of resistances, the current flowing through circuit is same. Therefore we can write,

$$\frac{V_{out}-V_{in}}{R_1} = \frac{V_{in}-0}{R_2} \qquad (2.6.5)$$

$$\frac{V_{out}-V_{in}}{R_1} = \frac{V_{in}}{R_2} \qquad (2.6.6)$$

Thus by selecting suitable values of resistances, we can obtain the desired (amplified/attenuated) output voltage for known input voltage.

There are other configurations such as Non-inverting amplifier, Summing amplifier, Subtractor, Logarithmic amplifier are being used in mechatronics applications. The detail study of all these is out of scope of the present course. Readers can refer Bolton for more details.

2. Filtering

Output signals from sensors contain noise due to various external factors like improper hardware connections, environment etc. Noise gives an error in the final output of system. Therefore it must be removed. In practice, change in desired frequency level of output signal is a commonly noted noise. This can be rectified by suing filters. Following types of filters are used in practice:

1. Low Pass Filter
2. High Pass Filter
3. Band Pass Filter
4. Band Reject Filter

2.1 Low Pass Filter

Low pass filter is used to allow low frequency content and to reject high frequency content of an input signal. Its configuration is shown in Figure 2.6.5

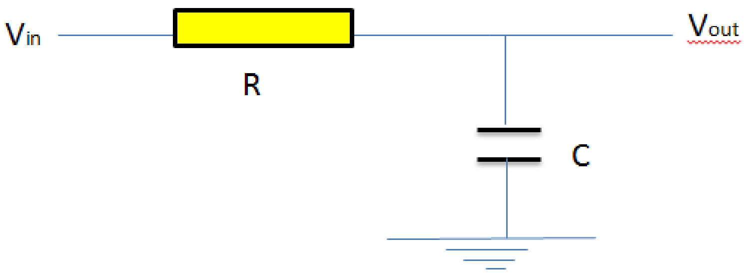

Figure 2.6.5 Circuitry of Low Pass Filter

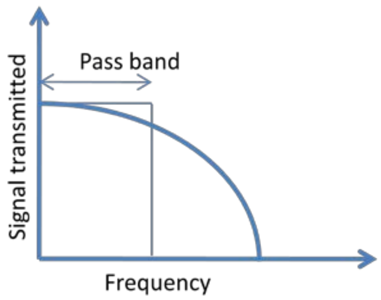

Figure 2.6.6 Pass band for low pass filter

In the circuit shown in Figure 2.6.5, resistance and capacitance are in series with voltage at resistance terminal is input voltage and voltage at capacitance terminal is output voltage. Then by applying the Ohm's Law, we can write,

$$V_{out} = \frac{\frac{1}{j\omega C}}{R + \left(\frac{1}{j\omega C}\right)} V_{in} \qquad (2.6.7)$$

$$V_{out} = \frac{1}{1 + j\omega CR} V_{in} \qquad (2.6.8)$$

From equation 2.6.8 we can say that if frequency of Input signal is low then $j\omega CR$ would be low. Thus $\frac{1}{1+j\omega CR}$ would be nearly equal to 1. However at higher frequency $j\omega CR$ would be higher, then $\frac{1}{1+j\omega CR}$ would be nearly equal to 0. Thus above circuit will act as Low Pass Filter. It selects frequencies below a breakpoint frequency ω = 1/RC as shown in Figure 2.6.6. By selecting suitable values of R and C we can obtain desired values of frequency to pass in.

2.2 High Pass Filter

These types of filters allow high frequencies to pass through it and block the lower frequencies. The figure 2.6.7 shows circuitry for high pass filter.

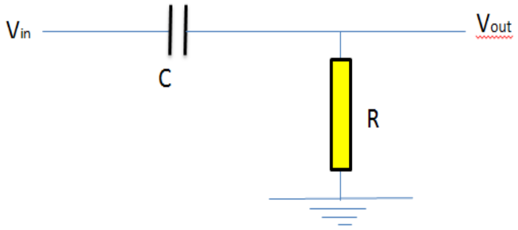

Figure 2.6.7 Circuitry of High Pass Filter

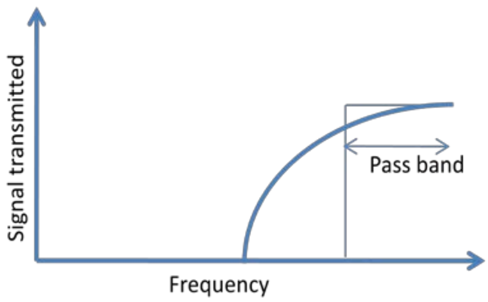

Figure 2.6.8 Pass band for high pass filter

$$V_{out} = \frac{R}{R + \left(\frac{1}{j\omega C}\right)} V_{in} \qquad (2.6.9)$$

$$V_{out} = \frac{j\omega CR}{1 + j\omega CR} V_{in} \qquad (2.6.10)$$

From equation 2.6.10, we can say that if frequency of input signal is low then $\frac{1}{j\omega C}$ would be high and thus $\frac{R}{R+\left(\frac{1}{j\omega C}\right)}$ would be nearly equal to 0. For high frequency signal, $\frac{1}{j\omega C}$ would be low and $\frac{R}{R+\left(\frac{1}{j\omega C}\right)}$ would be nearly equal to 1. Thus above circuit will act as High Pass Filter. It selects frequencies above a breakpoint frequency ω = 1/RC as shown in Figure 2.6.8. By selecting suitable values of R and C we can allow desired (high) frequency level to pass through.

2.3 Band Pass Filter

In some applications, we need to filter a particular band of frequencies from a wider range of mixed signals. For this purpose, the properties of low-pass and high-pass filters circuits can be combined to design a filter which is called as band pass filter. Band pass filter can be developed by connecting a low-pass and a high-pass filter in series as shown in figure 2.6.9.

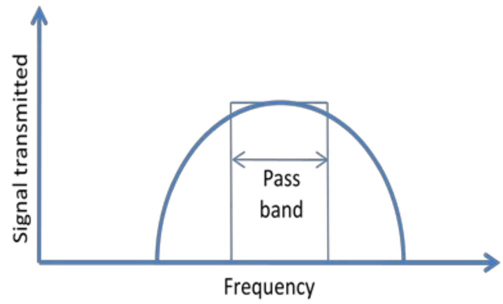

Figure 2.6.9 Band pass filter

2.4 Band Reject Filter

These filters pass all frequencies above and below a particular range set by the operator/manufacturer. They are also known as band stop filters or notch filters. They are constructed by connecting a low-pass and a high-pass filter in parallel as shown in Figure 2.6.10.

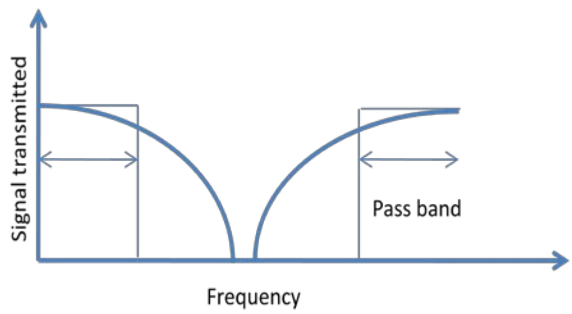

Figure 2.6.10 Band reject filter

Quiz

1. Explain the principle of working of op-amp as an inverting amplifier.
2. What kind of signal conditioning operations will be required to develop a table top CNC turning center for small job works?

Module 2: Sensors and signal processing
Lecture 7
Protection, conversion and pulse width modulation

1. Protection

In many situations sensors or transducers provide very high output signals such as high current or high voltage which may damage the next element of the control system such as microprocessor.

1.1 Protection from high current

The high current to flow in a sensitive control system can be limited by:

1. Using a series of resistors
2. Using fuse to break the circuit if current value exceeds a preset or safe value

1.2 Protection from high voltage

Zener diode circuits are widely used to protect a mechatronics control system from high values of voltages and wrong polarity. Figure 2.7.1 shows a typical Zener diode circuit.

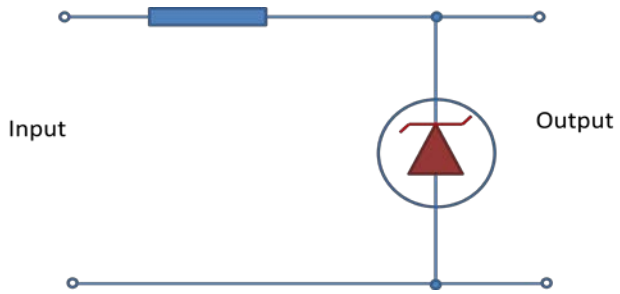

Figure 2.7.1 Zener diode circuit diagram

Zener diode acts as ordinary or regular diodes upto certain breakdown voltage level when they are conducting. When the voltage rises to the breakdown voltage level, Zener diode breaks down and stops the voltage to pass to the next circuit.

Zener diode as being a diode has low resistance for current to flow in one direction through it and high resistance for the opposite direction. When connected in correct polarity, a high resistance produces high voltage drop. If the polarity reverses, the diode will have less resistance and therefore results in less voltage drop.

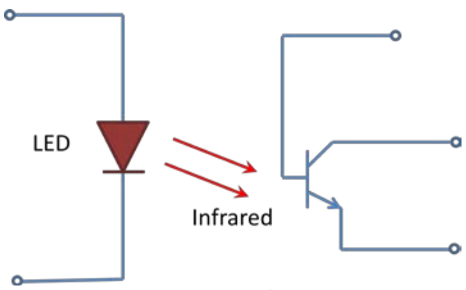

Figure 2.7.2 Schematic of an Optoisolator

In many high voltage scenarios, it is required to isolate the control circuit completely from the input high voltages to avoid the possible damage. This can be achieved by Optoisolators. Figure 2.7.2 shows the typical circuit of an Optoisolator. It comprises of a Light emitting diode (LED) and a photo transistor. LED irradiates infra red due to the voltage supplied to it from a microprocessor circuit. The transistor detects irradiation and produces a current in proportion to the voltage applied. In case of high voltages, output current from Optoisolator is utilized for disconnecting the power supply to the circuit and thus the circuit gets protected.

2. Wheatstone bridge

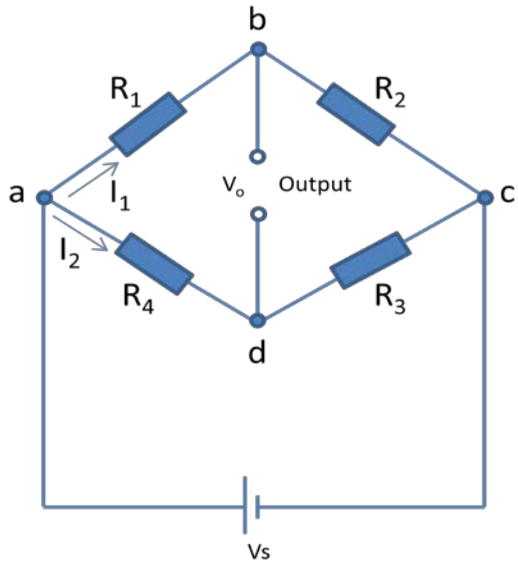

Figure 2.7.3 Configuration of a Wheatstone bridge

Wheatstone bridge is used to convert a resistance change detected by a transducer to a voltage change. Figure 2.7.3 shows the basic configuration of a Wheatstone bridge. When the output voltage *Vout* is zero then the potential at B must be equal to D and we can say that,

$$Vab = Vad, \qquad (2.7.1)$$
$$I1\,R\,1 = I2\,R2 \qquad (2.7.2)$$

Also,

$Vbc = Vdc,$ (2.7.3)

$I1\,R2 = I2\,R4$ (2.7.4)

Dividing equation 2.7.2 by 2.7.4,

$R1/R2 = R3/R4$ (2.7.5)

The bridge is thus balanced.

The potential drop across $R1$ due to supply voltage Vs,

$Vab = Vs\,R1/(R1 + R2)$ (2.7.6)

Similarly,

$Vad\ =\ VsR3/(R3+R4)$ (2.7.7)

Thus the output voltage Vo is given by,

$Vo\ =\ Vab - Vad$ (2.7.8)

$Vo\ =\ Vs\,\{(R1/[R1+R2]) - (R3/[R3+R4])\}$ (2.7.9)

When Vo = 0, above equation gives balanced condition.

Assume that a transducer produces a resistance change from $R1$ to $R1+\delta R1$ which gives a change in output from $Vo+\delta Vo$,

From equation 2.7.9 we can write,

$Vo+\delta Vo\ =\ Vs\left(\frac{R1+\delta R1}{R1+\delta R1+R2} - \frac{R3}{R3+R4}\right)$ (2.7.10)

Hence,

$(Vo+\delta Vo) - Vo = Vs\left(\frac{R1+\delta R1}{R1+\delta R1+R2} - \frac{R1}{R1+R2}\right)$ (2.7.11)

If $\delta R1$ is much smaller than $R1$ the equation 2.7.11 can be written as

$\delta Vo\ \approx Vs\left(\frac{\delta R1}{R1+R2}\right)$ (2.7.12)

We can say that change in resistance $R1$ produces a change in output voltage. Thus we can convert a change in resistance signal into voltage signal.

3. Pulse modulation

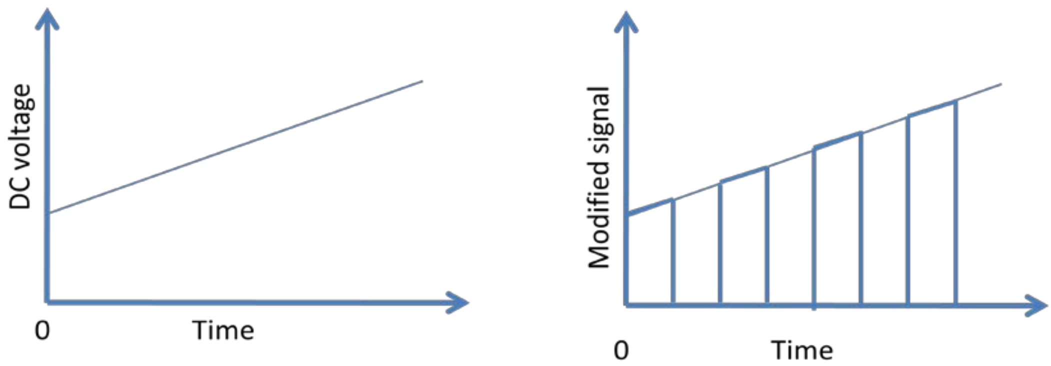

Figure 2.7.4 Pulse amplitude modulation

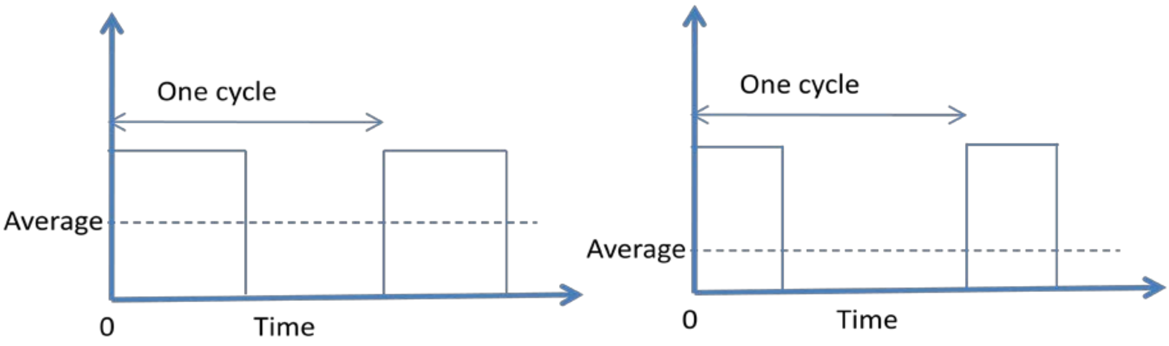

Figure 2.7.5 Pulse width modulation

During amplification of low level DC signals from a sensor by using Op-amp, the output gets drifted due to drift in the gain of Op-amp. This problem is solved by converting the analogue DC signal into a sequence of pulses. This can be achieved by chopping the DC signal in to a chain of pulses as shown in Figure 2.7.4. The heights of pulses are related to the DC level of the input signal. This process is called as Pulse Width Modulation (PWM). It is widely used in control systems as a mean of controlling the average value of the DC voltage. If the width of pulses is changed then the average value of the voltage can be changed as shown in Figure 2.7.5. A term Duty Cycle is used to define the fraction of each cycle for which the voltage is high. Duty cycle of 50% means that for half of the each cycle, the output is high.

Quiz:

1. State the applications of Wheatstone bridge in Mechatronics based Manufacturing Automation. Explain one of them in detail.
2. Why do we need pulse width modulation?
3. How Zener diode is different than ordinary diode?

Module 2: Sensors and signal processing
Lecture 8

Data conversion devices

Data Conversion Devices are very important components of a Machine Control Unit (MCU). MCUs are controlled by various computers or microcontrollers which are accepting signals only in Digital Form i.e. in the form of 0s and 1s, while the signals received from signal conditioning module or sensors are generally in analogue form (continuous). Therefore a system is essentially required to convert analog signals into digital form and vis-à-vis. Analog to Digital Converter is abbreviated as ADC. Figure 2.8.1 shows a typical control system with data conversion devices.

Based on the signals received from sensors, MCU generates actuating signals in the Digital form. Most of the actuators e.g. DC servo motors only accept analogue signals. Therefore the digital signals must be converted into Analog form so that the required actuator can be operated accordingly. For this purpose Digital to Analog Converters are used, which are abbreviated as DACs. In subsequent sections we will be discussing about various types of ADC and DAC devices, their principle of working and circuitry.

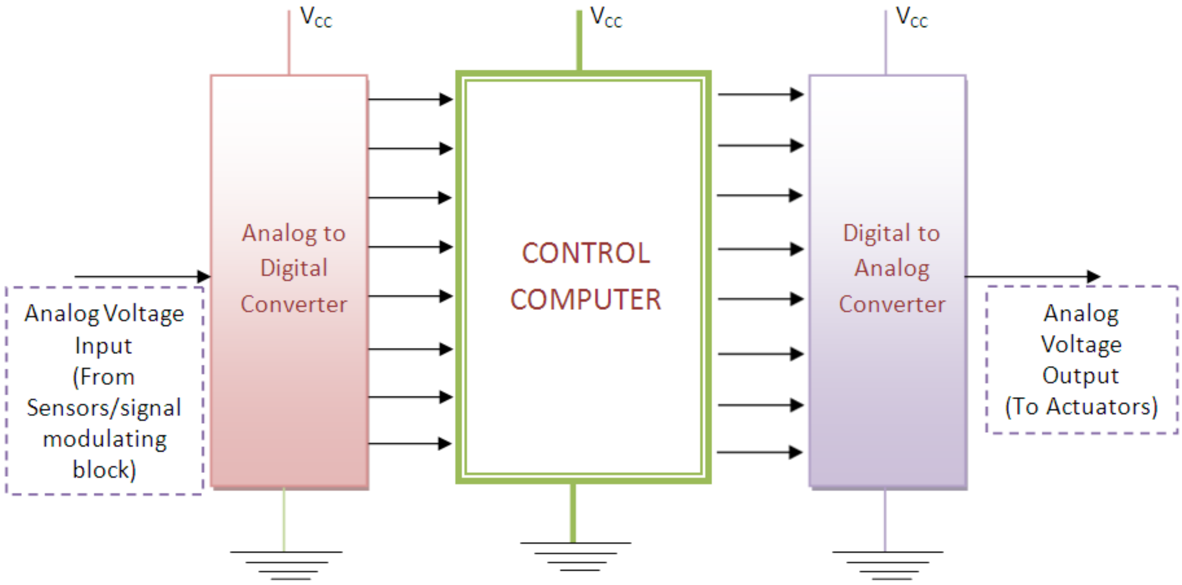

Figure 2.8.1 A control system with ADC and DAC devices

Basic components used in ADCs and DACs

1. Comparators

In general ADCs and DACs comprise of Comparators. Comparator is a combination of diodes and Operational Amplifiers. A comparator is a device which compares the voltage input or current input at its two terminals and gives output in form of digital signal i.e. in form of 0s and 1s indicating which voltage is higher. If V+ and V- be input voltages at two terminals of comparator then output of comparator will be as

V+ > V- → Output 1

V+ < V- → Output 0

2. Encoders

Though the output obtained from comparators are in the form of 0s and 1s, but can't be called as binary output. A sequence of 0s and 1s will be converted into binary form by using a circuit called Encoder. A simple encoder converts 2^n input lines into 'n' output lines. These 'n' output lines follow binary algebra.

3. Analog to Digital Converter (ADC)

As discussed in previous section ADCs are used to convert analog signals into Digital Signals. There are various techniques of converting Analog Signals into Digital signals which are enlisted as follows. However we will be discussing only Direct Conversion ADC, detail study of other techniques is out of the scope of the present course.

1. Direct Conversion ADC or Flash ADC
2. Successive Approximation ADC
3. A ramp-compare ADC
4. Wilkinson ADC
5. Integrating ADC
6. Delta-encoded ADC or counter-ramp
7. Pipeline ADC (also called subranging quantizer)
8. Sigma-delta ADC (also known as a delta-sigma ADC)
9. Time-interleaved ADC

3.1 Direct Conversion ADC or Flash ADC

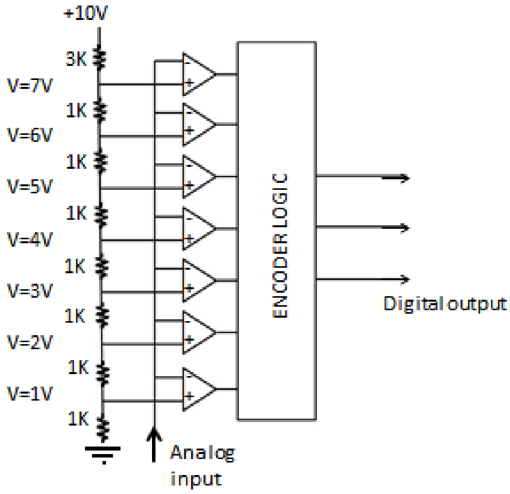

Figure 2.8.2 Circuit of Flash ADC

Figure 2.8.2 shows the circuit of Direct conversion or Flash ADC. To convert a digital signal of N-bits, Flash ADC requires 2^N-1 comparators and 2^N resistors. The circuit provides the reference voltage to all the comparators. Each comparator gives an output of 1 when its analog voltage is higher than reference voltage or otherwise the output is 0. In the above circuit, reference voltages to comparators are provided by means of resistor ladder logic.

The circuit described in figure 2.8.2 acts as 3 Bit ADC device. Let us assume this ADC works between the range of 0-10 Volts. The circuit requires 7 comparators and 8 resisters. Now the voltages across each resistor are divided in such a way that a ladder of 1 volt is built with the help of 1K-Ohm resistances. Therefore the reference voltages across all the comparators are 1-7 volts.

Now let us assume that an input voltage signal of 2.5 V is to be converted into its related digital form. As 2.5V is greater than 1V and 2V, first two comparators will give output as 1, 1. But 2.5V is less than 3,4,5,6,7 V values therefore all other comparators will give 0s. Thus we will have output from comparators as 0000011 (from top). This will be fed to the encoder logic circuit. This circuit will first change the output in single high line format and then converts it into 3 output lines format by using binary algebra. Then this digital output from ADC may be used for manipulation or actuation by the microcontrollers or computers.

4. Digital to Analog Converters

As discussed in previous section DACs are used to convert digital signals into Analog Signals. There are various techniques of converting Digital Signals into Analog signals which are as follows however we will be discussing only few important techniques in detail:

1. Pulse-width modulator
2. Oversampling DACs or interpolating DACs
3. The binary-weighted DAC
4. Switched resistor DAC
5. Switched current source DAC
6. Switched capacitor DAC
7. The R-2R ladder
8. The Successive-Approximation or Cyclic DAC,
9. The thermometer-coded DAC

4.1 Binary Weighted DAC

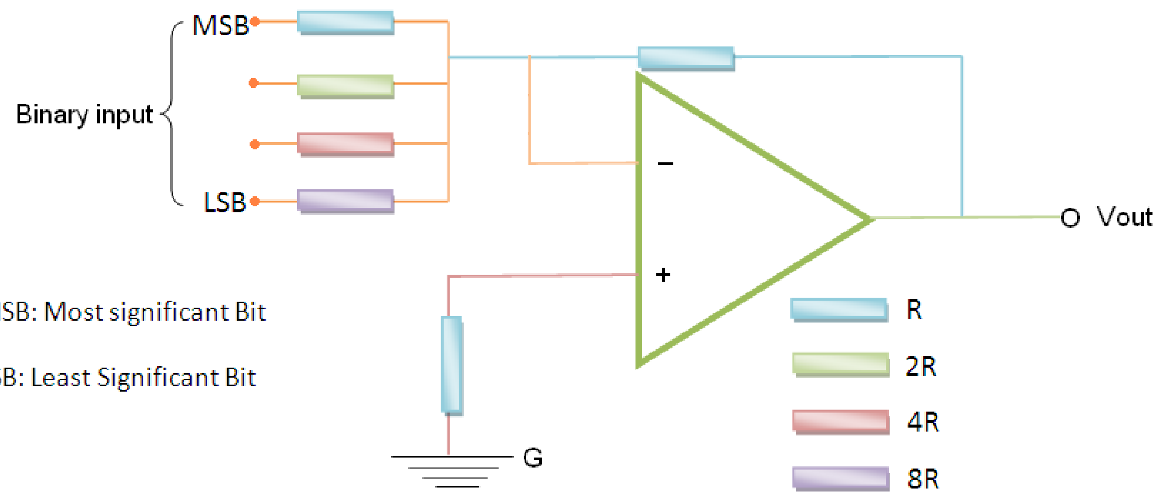

Figure 2.8.3 Circuit of binary weighted DAC

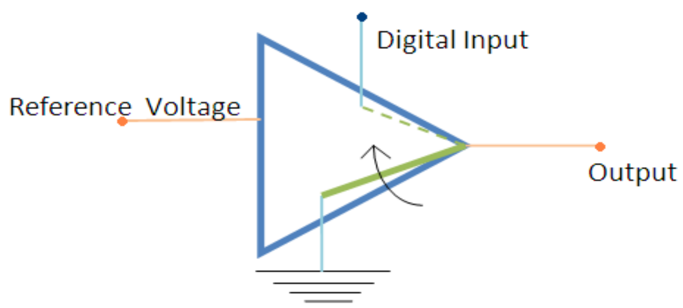

Figure 2.8.4 An op-amp used in DAC

As name indicates, in binary weighted DAC, output voltage can be calculated by expression which works on binary weights. Its circuit can be realized in Figure 2.8.3. From the figure it can be noted that most significant bit of digital input is connected to minimum resistance and vice versa. Digital bits can be connected to resistance through a switch which connects resistance-end to the ground. The digital input is zero when former bit is connected to reference voltage and if it is 1. This can be understood from Figure 2.8.4. DAC output voltage can be calculated from property of operational amplifiers. If V1 be input voltage at MSB (most significant bit), V2 be input voltage at next bit and so on then for four bit DAC we can write,

$$\frac{V1}{R} + \frac{V2}{2R} + \frac{V3}{4R} + \frac{V4}{8R} = \frac{Vout}{R} \qquad (2.8.1)$$

Note: Here V1,V2 V3,V4 will be Vref if digital input is 1 or otherwise it will be zero.

Hence output voltage can be found as:

$$V_{OUT}\ \alpha\ (2^3 * V1 + 2^2 * V2 + 2^1 * V3 + 2^0 * V4) \qquad (2.8.2)$$

However Binary weighted DAC doesn't work for multiple or higher bit systems as the value of resistance doubles in each case.

Thus simple and low bit digital signals from a transducer can be converted into a related continuous value of voltages (analogue) by using binary weighted DAC. These will further be used for manipulation or actuation.

4.2 R-2R Ladder based DAC

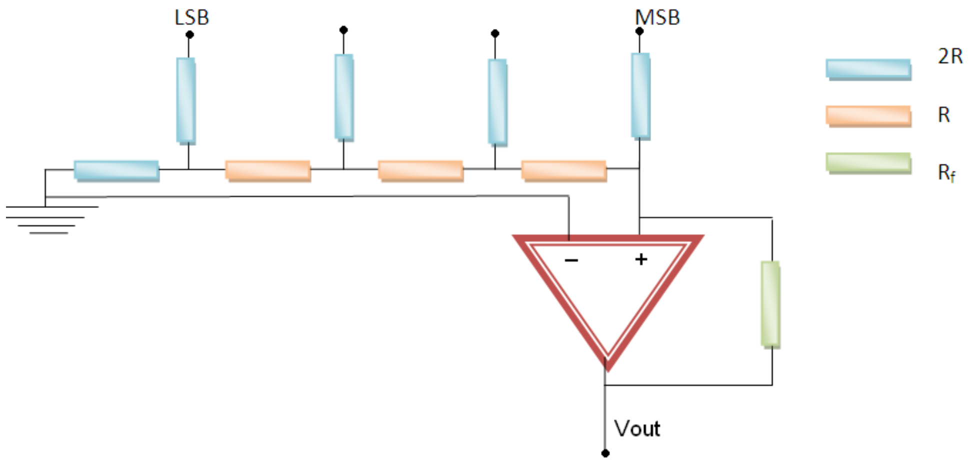

Figure 2.8.5 R-2R Ladder based DAC

In R-2R ladder logic, shortcoming of Binary Logic has been removed by making the value of maximum resistance double however the rest of the circuit remains same. Figure 2.8.5 shows the circuit of R-2R Ladder based DAC. If we apply voltage division rule in above case, then we can calculate that output voltage as,

$$V_{out} = \frac{V_{ref} * R_f}{R} * VAL \qquad (2.8.3)$$

Where VAL can be calculated from the digital signal input as,

$$VAL = \frac{D_0}{2^4} + \frac{D_1}{2^3} + \frac{D_2}{2^2} + \frac{D_3}{2^3} \qquad (2.8.4)$$

In this way output voltage is obtained by converting the digital signals received from microprocessor/ microcontroller. These voltages will further be used to actuate the desired actuator viz. DC/AC motors.

In this module we have studied the principle of operation of various sensors which are commonly used in mechatronics and manufacturing automation. Also the signal conditioning operations and the devices which are used to generate the proper signals for desired automation application have been studied. In the next module we will study the construction and working of microprocessor and the devices which are being used in controlling the various operations of automation using the microprocessors.

Quiz

1. Differentiate between Binary weighted DAC and R-2R ladder based DAC.
2. Explain the importance of data conversion devices in mechatronics with suitable example.