EC700OE: **ELECTRONIC SENSORS** (Open Elective - II)

UNIT-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.

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

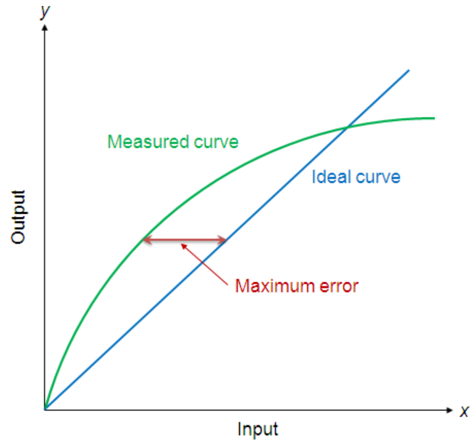


Figure 2.1.1 Non-linearity error

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

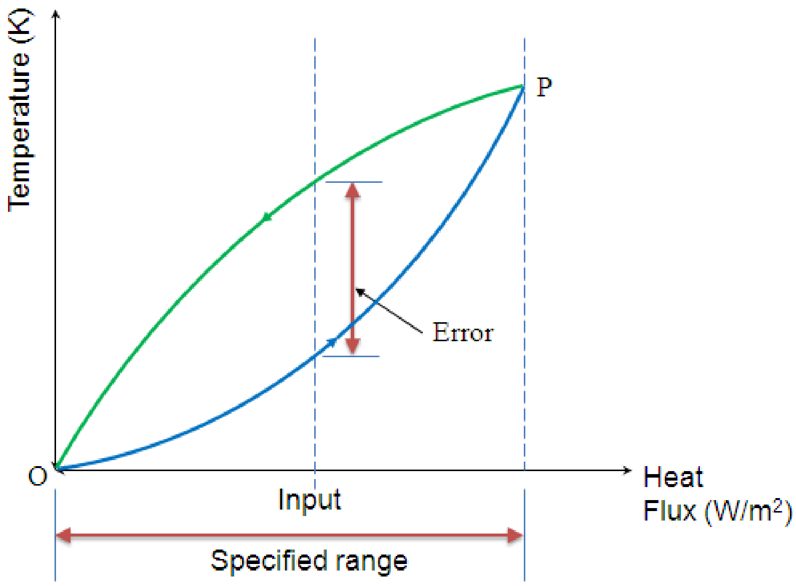


Figure 2.1.2 Hysteresis error curve

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.

PARAMETERS

The normal environmental conditions from where the data are made available through sensors are noisy and keep changing. The high fidelity mapping of such a varying reality requires extensive studies of 'fidelity' of the sensors themselves or in other words, sensors are required to be appropriately characterized. These are done in terms of certain parameters and characteristics of the sensors.

ENVIRONMENTAL PARAMETERS (EP)

These are the external variables such as temperature, pressure, humidity, vibration, and the like which affect the performance of the sensor. These parameters are not the ones that are to be sensed. For non-temperature transducers, temperature is the most important environmental parameter (EP). For any EP, the performance of the transducer can be studied in terms of its effect on the static and dynamic characteristics of the sensor as has already been discussed. For this study, one EP at a time is considered variable while others are held constant.

CHARACTERIZATION

Characterization of the sensors can be done in many ways depending on the types of sensors, specifically micro sensors. These are electrical, mechanical, optical, thermal, chemical, biological, and so on.

1. **Electrical characterization**

It consists of evaluation of electrical parameters like (a) impedances, voltage and currents, (b) breakdown voltages and fields, (c) leakage currents, (d) noise, (e) cross talk, and so on.

2. **Mechanical and thermal characterization**

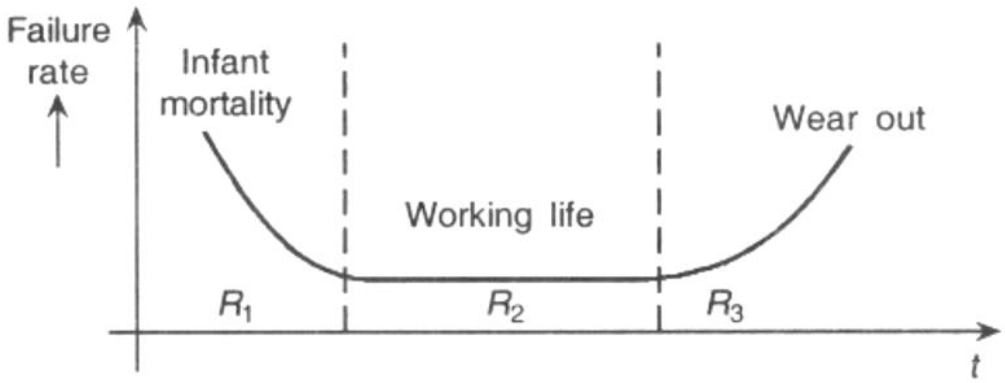
It involves mechanical and thermal properties related to the overall reliability and integrity of the transducer, as well as relevant transduction process. Reliability is an important aspect of characterization. By means of testing, the functional and reliable portion of a batch of sensors or transducers is identified. Basically, failure analysis is performed and the mechanism of failure is attempted to be eliminated and thereby reduce the subsequent failures. In fact, the above two approaches are supplementary to each other.

Failure of transducers can be divided into two different categories:

(i) Catastrophic early life failures, often called infant mortality: If the sensors is the complete failure in the normal operation. It is called wear out if it occurs in later life.

(ii) Short term drifts in the sensor parameters, and Long term drifts and failures.

Short term and long term drifts are, in effect, changes in sensor parameters and are, therefore, to be studied more intensely for the sensor characterization.



a. **High temperature burn in:** The sensors are subjected to a high temperature over a stipulated period, usually at 125°C for 48 hours for SITS, when the defective units are burnt out and the remaining ones are expected to run for the expected life.
b. **High temperature storage bake:** The units are baked at a high temperature, usually at 250°C for SITS, for several hours when the instability mechanisms such as contamination, bulk defects, and metallization problems are enhanced in some units which were initially defective. These units are then screened out.
c. **Electrical overstress test:** Where progressively larger voltages upto 50% in excess of specification are applied over different intervals of time so that failures due to insulation, interconnection or oxide formation can occur in some units which were originally defective and are screened out.
d. **Thermal shock test:** Mainly done for packaging defects where the units are subjected to a temperature between -65° and 125°C for about 10 seconds for every temperature. The time is gradually increased to 10 minutes and the cycle is repeated 10 times. The failed units are rejected.

3. **Mechanical shock test:**

Also for packaging, this test is performed by dropping the units from a specified height that varies from 3 to 10 m. Alternately the unit is shaken by attaching it to a shaking table for a specified period of time.

4. **Optical characterization**

It is usually done by ascertaining absorption coefficient, refractive index, reflectivity and the like. Here, again the consideration of the individual merit comes in.

5. **Chemical/biological characterization**

This is basically a test of the sensor with respect to its resistance to chemicals or corrosion in industrial as well as biological environment. Safety is an important aspect here particularly in case

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

Electromechanical Sensors

Electromechanical sensor transforms mechanical energy into electrical signals. The main electromechanical sensors we focus on strain and pressure sensors.

According to their mechanisms, resistive and capacitive sensor attracts more attention due to their simple structures, mechanisms, preparation method, and low cost. Various kinds of Nano materials have been developed to fabricate them, including carbon Nano materials, metallic, and conductive polymers. They have great potentials for health monitoring, human motion monitoring, speech recognition, and related human-machine interface applications

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

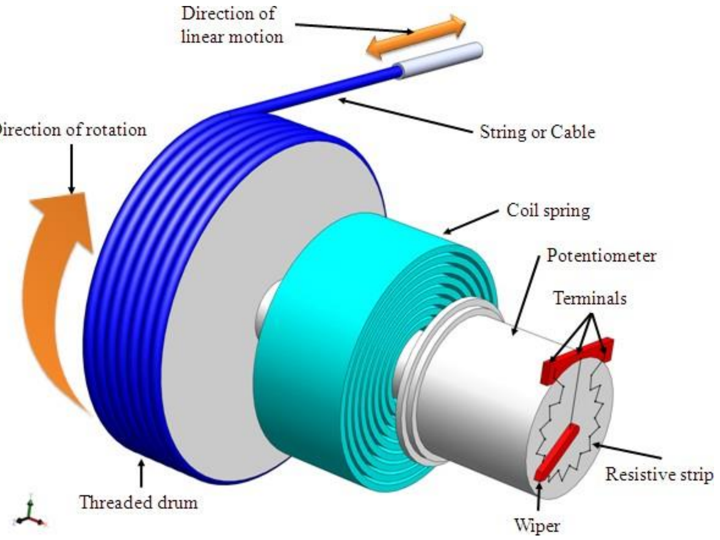


Figure 2.2.1 Schematic of a potentiometer sensor for measurement of linear displacement

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.

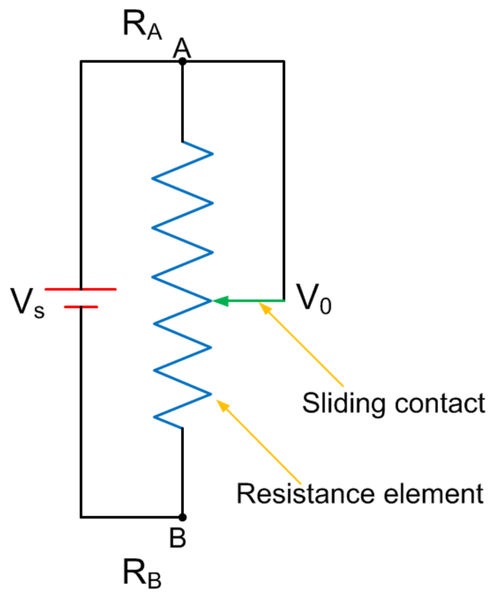


Figure 2.2.2 Potentiometer: electric circuit

$V_A = I\ R_A$ (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,

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

$\Delta R/R = G \varepsilon$ (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.

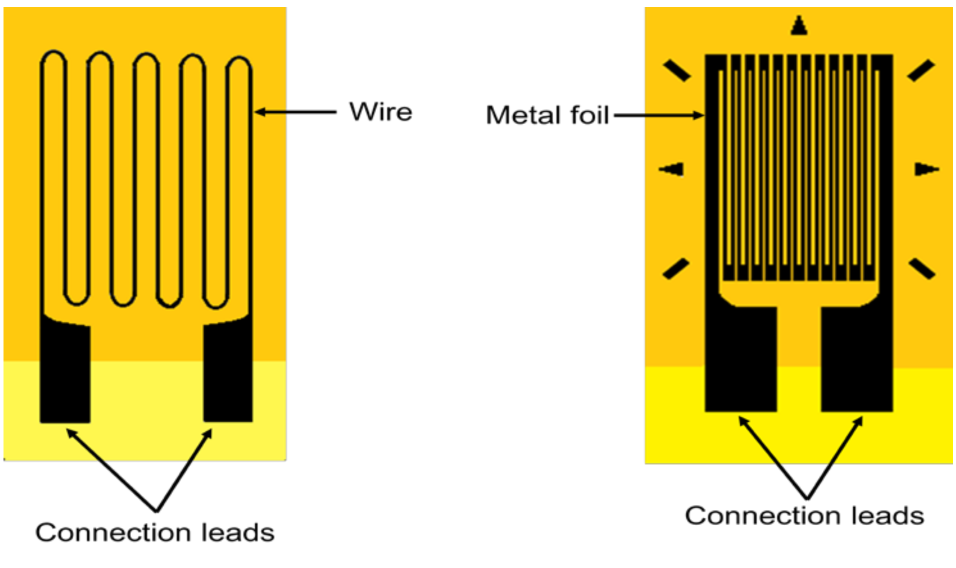


Figure 2.2.3 A pattern of resistive foils

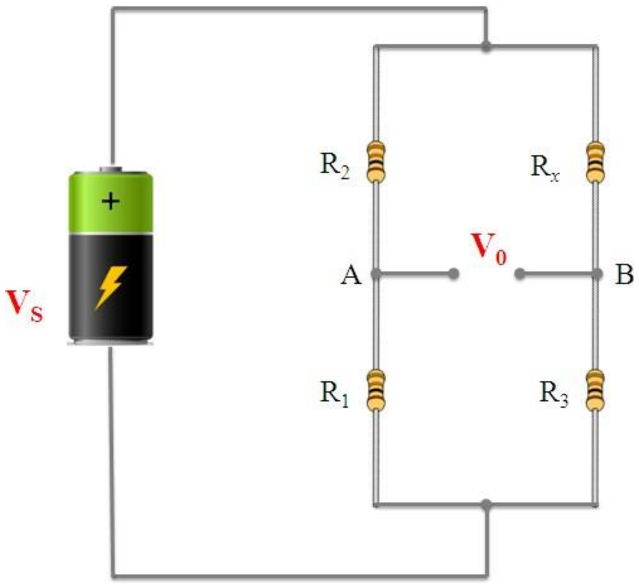


Figure 2.2.4 Wheatstone's bridge

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.

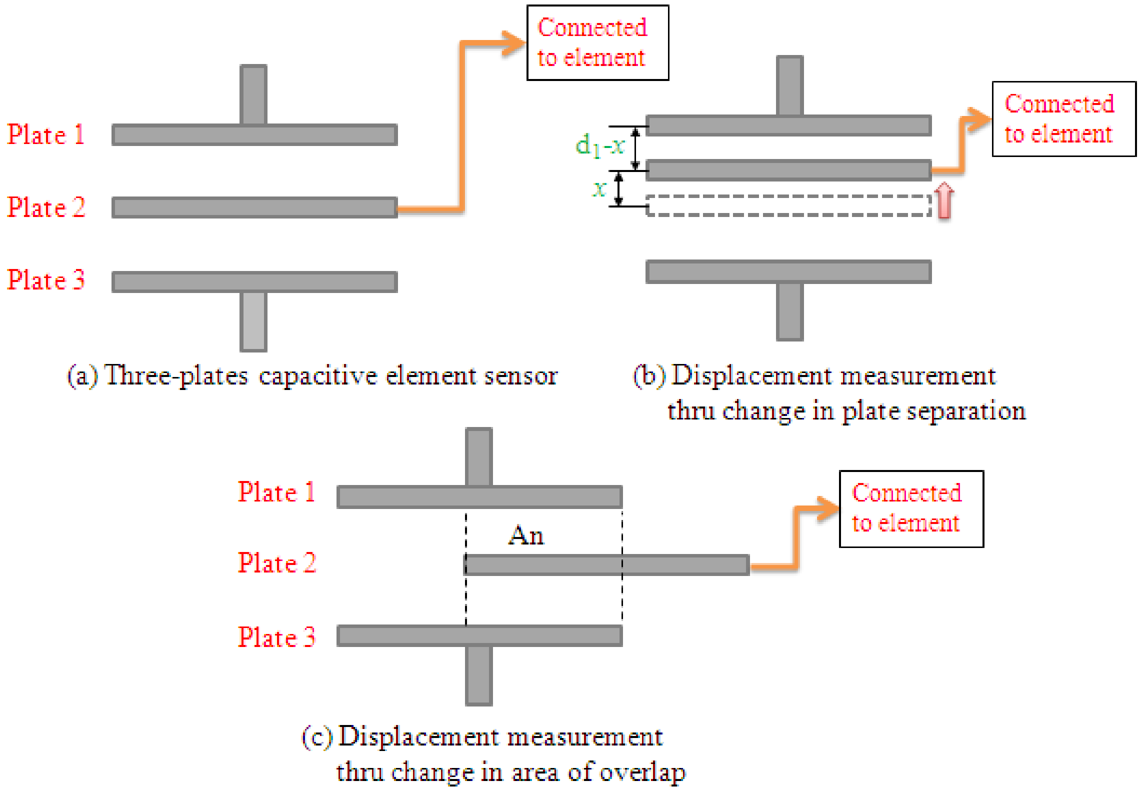


Figure 2.2.5 Displacement measurement using capacitive element sensor

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,

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

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

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)

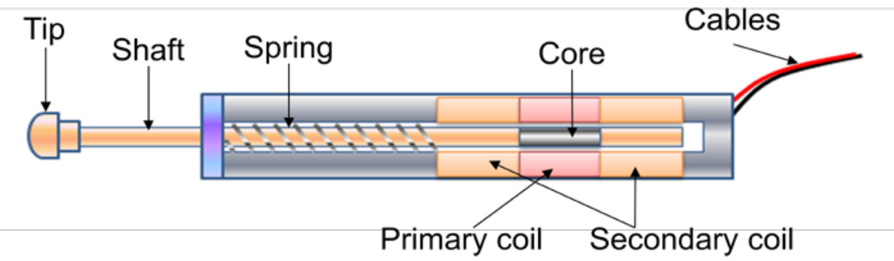


Figure 2.2.6 Construction of a LVDT sensor

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.

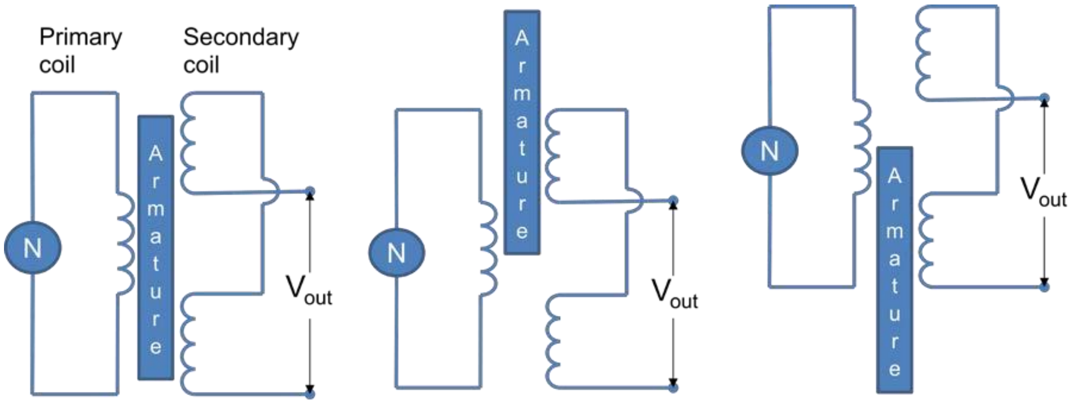


Figure 2.2.7 Working of LVDT sensor

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.

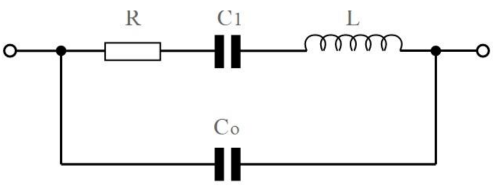
A rotary variable differential transformer (RVDT) can be used for the measurement of rotation. Readers are suggested to prepare a report on principle of working and construction of RVDT sensor.

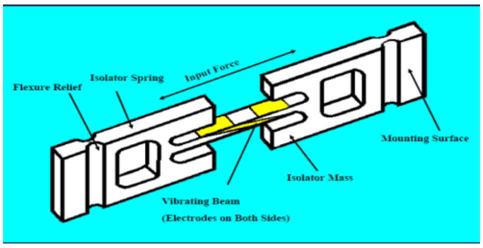
Applications of LVDT sensors

- 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

Quartz Resonator Technology:

Quartz crystal resonator technology relies on the remarkable properties of quartz for its operation. When placed into an electronic circuit a quartz crystal acts as a tuned circuit. However it has an exceptionally high Quality. The operation of the quartz crystal is based around the fact that quartz exhibits the piezo-electric effect. This means that when a stress is set up a cross the crystal, an electromotive force or electric potential is seen. The reverse is also true, then when a potential is applied across the crystal, it deflects slightly. This means that piezo electric effect enables the mechanical and electrical domains to be linked.





- The widespread use of digital computers and digital control systems have generated a need for high accuracy, inherently digital sensors

Material Properties and Characteristics of Quartz Sensors

- Piezoelectric [pressure-charge generation]
- Anisotropic [direction-dependent]Elastic Modulus
- Piezoelectric Constants
- Coefficient of Thermal Expansion
- Optical Index of Refraction
- Velocity of Propagation
- Hardness
- Solubility [etch rate]
- Thermal and Electrical conductivity

Advantages of Quartz resonant Sensors

- High Resolution
- Excellent Accuracy
- Long Term Stability
- Low Power Consumption
- Low Temperature Sensitivity
- Low Susceptibility to Interference
- Easy to Transmit Over Long Distances
- Easy to Interface With Counter-Timers, Telemetry, and Digital Computer Systems