4.4 VARIABLE CAPACITANCE TRASDUCERS:

Transducers based on the principle of changes in the capacitance are generally termed as capacitive transducers. These kinds of transducers are most common in linear displacement based applications. Other than displacement, many of the industrial variables such as pressure, level, moisture, etc. can be translated into an electrical signal by means of change in the capacitance.

PRINCIPLE OF A CAPACITIVE TRANSDUCER

The capacitive transducer is functioning similar to the working of a parallel plate capacitor. The capacitance is calculated as a function of area between two parallel plates, the distance between the plates and the dielectric medium in between the plates. It is expressed as:

$C = \frac{A}{d}\ \varepsilon_0\ \varepsilon_r$

Where,

A is the area of parallel plates

D is the distance between the plates

ε_o is the absolute permittivity of free space.

ε_r is the relative permittivity of free space.

The working principle of the capacitive transducer is based on the change in capacitance due to any of the change in area of the parallel plates, the distance between the plates or the permittivity of free space. Since the capacitance is a function of A, d and ε, i.e., C = f(A, d, ε), any variable which changes any one of the quantities, the capacitance of the parallel plate capacitor gets changed. Further, this change in capacitance can be further converted into the required electrical form.

The capacitance is connected to voltage and charge by the expression:

Q = CV

Where,

Q is the charge in coulomb. C is the capacitance in farad. V is the voltage in volts.

If the capacitance is affected by any of the above parameters, the output is transducer into an electrical form proportionally. In most of the cases, the changes are caused by means of physical variables such as pressure, displacement, force, thickness, etc. If there is change in dielectric medium between the parallel plates, there will be change in capacitance, and hence it can be used for the measurement of fluid level. Similarly, the change in dielectric medium due to change in the composition causes the change in absorption on moisture.

EXAMPLES OF CAPACITIVE TRANSDUCERS

There are many transducers working on the principle of change in capacitance:

1. Capacitive displacement transducer
2. Capacitive thickness transducer
3. Capacitive pressure transducer
4. Capacitive level transducer
5. Capacitive moisture transducer
6. Capacitive hygrometer
7. Condenser microphone, etc.

VARIABLE AREA-BASED CAPACITIVE TRANSDUCER

The capacitance is directly proportional to the area of cross-section of the parallel plates. The capacitance changes linearly with change in area of the plates. Hence, the capacitive transducers based on the variable area are suited for the measurement of both linear and angular displacements.

MEASUREMENT OF LINEAR DISPLACEMENT

Figure 4.4.1 shows a parallel plate capacitive transducer for the measurement of linear displacement.

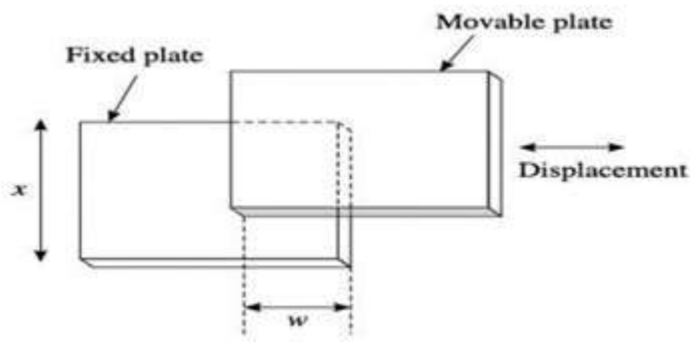


Figure 4.4.1 Parallel plate capacitive transducer

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 734]

The linear displacement to be measured by the capacitive transducer is applied to the plate which is movable. Now, there will be overlapping of the plates. Due to this, there will be change in capacitance. The amount of capacitance change is proportional to the displacement applied to the movable plate.

The above parallel plate capacitive transducer is suitable for linear displacement measurements in the range of 1 mm to 10 mm with an accuracy of 0.005%. Instead of a two parallel plate capacitive transducer, a cylindrical capacitive transducer can also be used for the measurement of linear displacement. It consists of two cylindrical electrodes. One cylindrical electrode is a fixed one, whereas the other cylindrical electrode is movable one. Figure 4.4.2 shows the capacitive transducer of cylindrical type.

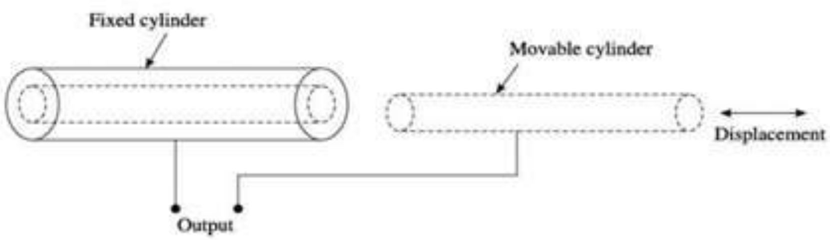


Figure 4.4.2 Capacitive transducer of cylindrical type.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 735]

Similar to the parallel plate capacitive transducer, the linear displacement to be measured is applied to the movable cylinder which results in overlapping of two cylinders which in turn further makes a change in capacitance between the two cylindrical electrodes. The amount of capacitance is proportional to the displacement applied to the movable cylinder.

MEASUREMENT OF ANGULAR DISPLACEMENT

A capacitive transducer used for the measurement of angular displacement is shown in Figure 4.4.3. It consists of a set of semi-circular plates forming the two plates of the capacitor, out of which one plate is fixed and the other plate is movable.

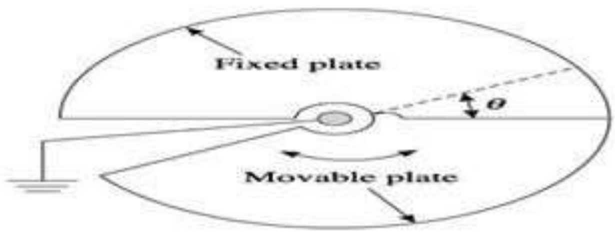


Figure 4.4.3 Capacitive transducer for angular displacement measurement.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 736]

The angular displacement to be measured is applied to the movable plate of the transducer assembly. Hence there is a change in effective area between the semi-circular plates which in turn changes the capacitance. The amount of capacitance change is depending on the angular displacement applied to the movable plate, and it is observed that it is maximum when the plates overlap each other which means the angular displacement θ = 180 °. At various angular displacements of θ, the capacitance is determined by

$$C = \frac{\varepsilon\theta r^2}{d}$$

Where,

r is the radius of semi-circular plates.

θ is the angular displacement.

D is the gap between two plates.

From the above equation, it can be observed that the change in capacitance is linear with respect to the applied angular displacement. This type of transducer is useful for the measurement of angular displacement of 180 ° maximum.

VARIABLE DISTANCE-BASED CAPACITIVE TRANSDUCER

The capacitance is inversely proportional to the distance between the two plates of the capacitor . With this principle, Figure 4.4.4 shows variable distance based capacitive transducer used for the measurement of linear displacements.

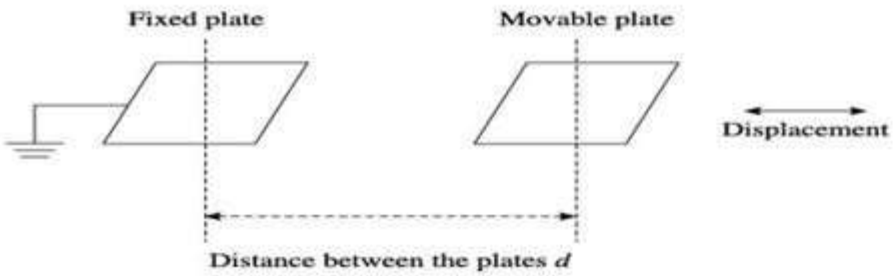


Figure 4.4.4 Variable distance-based capacitive transducer.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 737]

Variable distance based capacitive transducer consists of two plates among which one plate is fixed, and the other one is movable. The linear displacement to be measured is applied to the movable plate. When the displacement is towards left, the distance between the plates decreases and hence the capacitance increases. Whereas when the displacement is towards right, the distance between the plates increases and hence the capacitance decreases.

Since the capacitance is inversely proportional to the variation in distance between the plates, the response of the transducer is found to be non-linear. Due to this non-linearity in response, it is useful for the measurement of only smaller displacements is shown in Fig 4.4.5.

Figure 4.4.5 Relationship between the capacitance and applied displacement. [Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 738]

From the characteristic curve shown in the Figure, the variation of capacitance with respect to displacement is hyperbolic, and it is only approximately linear over a small range of displacement. The linearity can be improved by making the distance between the parallel plates extremely small. But in practice, if the distance between the plates is reduced to minimum values, it causes the electric field between the plates to exceed the break down voltage. So with a certain limit, the distance cannot be minimized.

In order to improve the linearity of the capacitive transducer, a differential arrangement is to be made as shown in Figure 4.4.6. In this arrangement, there are three plates among which outer two (F1 and F2) are fixed plates and the middle plate (M) is movable. The displacement to be measured is applied to the movable plate as in normal practice. Whenever the movable plate is kept exactly in the middle of the two outer plates, the capacitances C1 and C2 are equal, since the distance between the fixed plate (F1) and the movable plate (M) and the distance between the fixed plate (F2) and the movable plate (M) are the same.

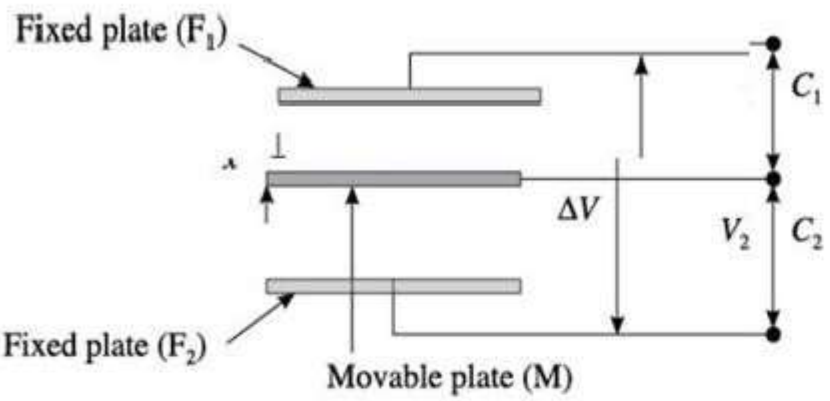


Fig 4.4.6 Arrangement for linearity improvement in capacitive transducer

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 739]

VARIABLE DIELECTRIC-BASED CAPACITIVE TRANSDUCER

This kind of capacitive transducer works based on variation in the dielectric material and its corresponding dielectric constant. Figure 4.4.7 shows the variable dielectric based capacitive transducer, and this arrangement is suitable for large linear displacements. Here, the two capacitor plates are kept in fixed position, whereas the solid dielectric material available between the fixed plates is movable thereby varying the capacitance of the transducer assembly.

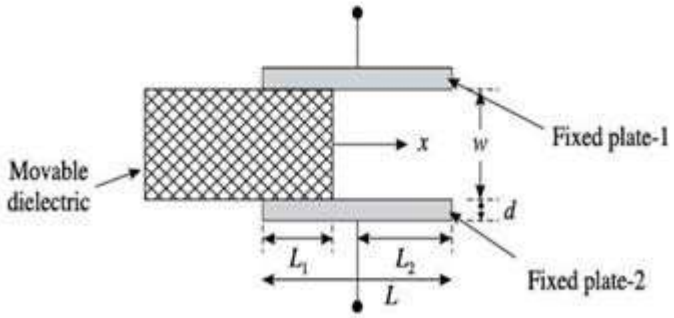


Figure 4.4.7 Variable dielectric-based capacitive transducer.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 740]

APPLICATIONS OF CAPACITIVE TRANSDUCERS

Capacitive transducers are applicable in many measurements like pressure, level, density, moisture, etc. Various parameter measurements are discussed as follows:

CAPACITIVE-TYPE PRESSURE TRANSDUCER

The measurement of change in capacitance resulting from the movement of the elastic element present inside the transducer arrangement is the basic principle of capacitance pressure transducer. The materials preferred for the elastic member is Inconel, Ni-Span C or Stainless Steel diaphragm or metal coated quartz. The elastic member is exposed to the applied pressure on one side,

whereas reference pressure is on the opposite side. Based on the reference pressure used, the capacitive transducer is useful for the measurement of absolute, gauge or differential pressure is shown in Fig 4.3.8.

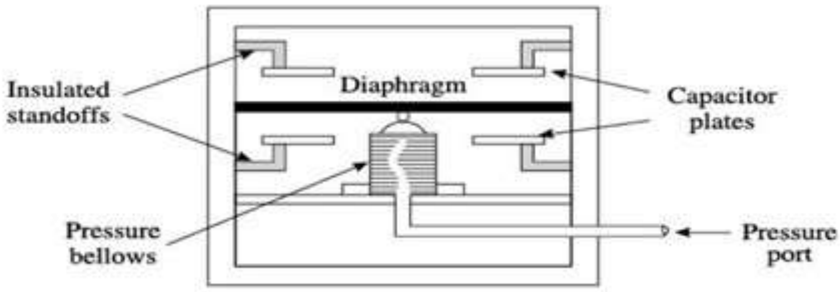


Figure 4.4.8 Arrangement of a capacitance pressure transducer.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 741]

Figure 4.4.9 shows the pressure measurement from the capacitance pressure transducer. An oscillator of high voltage and high frequency is used to energize the sensing element called diaphragm. In the pressure sensing assembly, reference pressure is allowed on one side, and the process pressure is allowed on the opposite side.

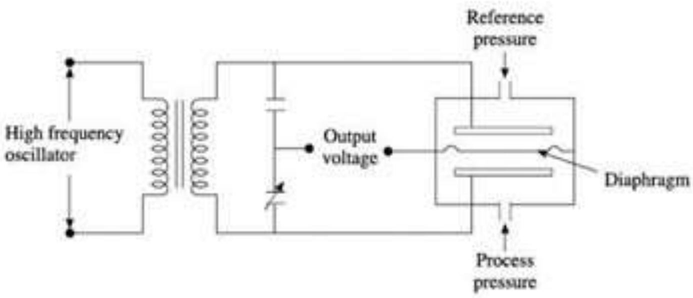


Figure 4.43 Pressure measurement using capacitance pressure detector.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 741]

Based on the change of pressure between reference pressure and process pressure, there will be deflection of the diaphragm and due to which the change in capacitance is detected by the bridge circuit. With the bridge circuit, there are two modes of operation such as balanced mode and unbalanced mode. In the balanced mode, there will be a null detector in which the output voltage is fed and to maintain the bride at null position, the capacitor arms are varied. The amount of capacitance variation to make null position is a measure of process pressure. In the case of unbalanced mode, the ratio between the output voltage obtained and the applied excitation voltage is the measure of process pressure. The possible accuracy of the capacitance based pressure detector is from ± 0.1, to ± 0.2%. These detectors are used as secondary standards for low range of absolute pressure and differential pressure applications.

CAPACITANCE-TYPE MOISTURE TRANSDUCER

The capacitance probe used as a moisture sensor is shown in Figure 4.4.10 in which capacitance electrodes made up of stainless steel are imbedded in an insulation sheet of plastic type to provide the plates of the capacitor. This kind of probe arrangement is inserted into the sample whose moisture is to be measured.

Now, the dielectric material is replaced by the water content (based on the amount of moisture content in the sample) and hence there is a change in the capacitance. The capacitance change noted from the measuring probe is a measure of amount of moisture content present in the sample.

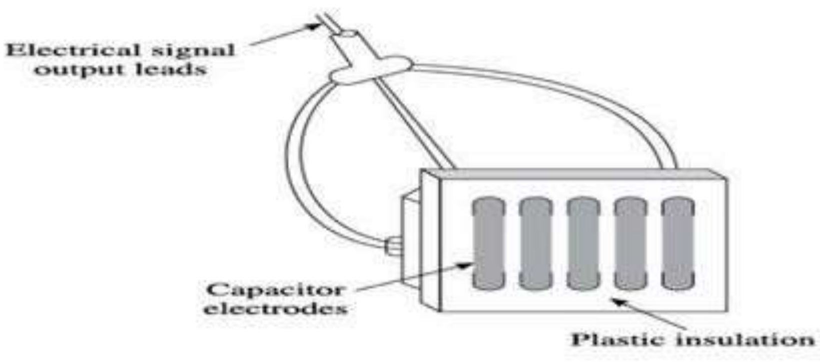


Figure 4.4.10 Capacitance probe for moisture measurement.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 742]

CAPACITANCE-TYPE LEVEL TRANSDUCER

The capacitance-type level transducer can be used for the measurement of level of both non-conducting and conducting type of liquids.

Measurement of Level of Non-conducting Liquids:

For the level measurement of non-conducting type, there are two cylindrical electrodes used in an electrode assembly. The outer cylindrical electrode has a provision of holes at the lower end in order to allow the liquid present inside the tank whose liquid level is to be measured. It is normally earthed.

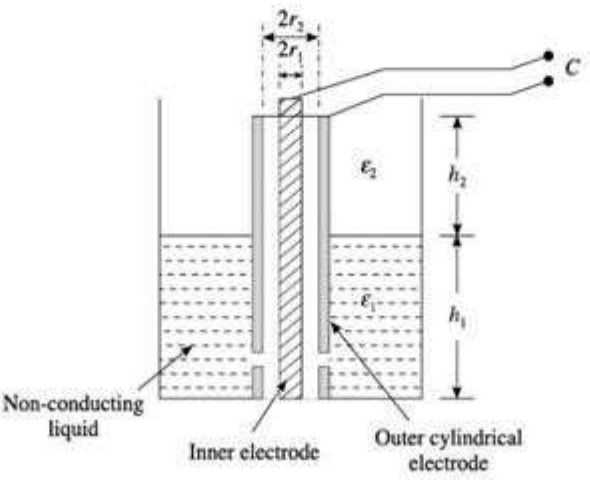


Figure 4.4.11 A capacitive transducer for level measurement of non conducting fluids.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 743]

The level measurement using capacitive type transducer is based on the principle of change in dielectric material. The electrode assemble is now inserted into the tank as shown in Figure 4.4.11. h1 and ε1 are the height of the liquid (inside the tank) and relative permittivity of the liquid, whereas h2 and ε2 are the height of the cylinder above the liquid level and relative permittivity of the vapor above the liquid level. The capacitance is now determined as follows:

$$C = 2\pi\varepsilon_0 \frac{\varepsilon_1 h_1 + \varepsilon_2 h_2}{\ln(r_2 / r_1)}$$

The relationship between the change in capacitance and the liquid level is linear except at extremes of the tank.

Measurement of Level of Non-conducting Liquids:

For all level measurements of conductive fluids or of solids which can be moist, insulated probes of Teflon coated type must be used.They are frequently used for measuring the level of conductive materials such as water-based liquids with conductivities of 100 μmhos/ cm or more is shown in Fig 4.4.12.

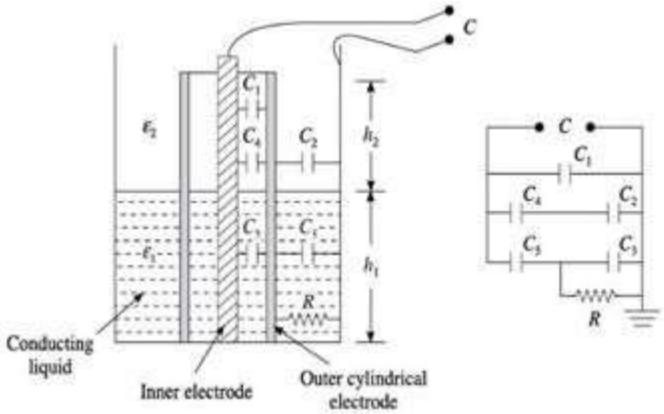


Figure 4.4.12 A capacitive transducer for level measurement of conducting fluids.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 744]

Figure 4.4.13 shows the type of capacitive transducer for level measurement of conducting fluids. With the above arrangement of the capacitive transducer with the electrode assembly, the capacitance is calculated as follows:

$$C = C_1 + \frac{C_2 C_4}{C_2 + C_4} + \frac{C_3 C_5}{C_3 + C_5}$$

This capacitive type level transducer is useful for the measurements of liquid level at high temperatures and also for liquefied gases at very low temperatures.

This capacitive type level transducer is useful for the measurements of liquid level at high temperatures and also for liquefied gases at very low temperatures.

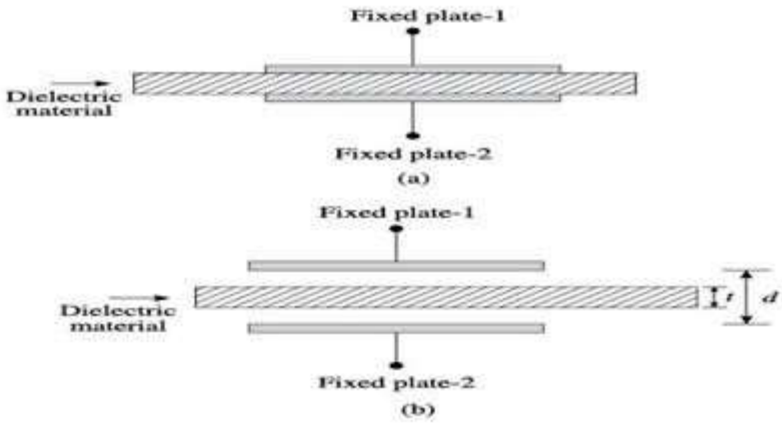


Figure 4.4.13 Capacitance-type thickness transducer

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 746]

Figure 4.4.15 shows the thickness measurement of the insulating material by touching the parallel plates of the capacitor. If the thickness of the material is non-uniform, there will be change in the dielectric value which in turn changes the capacitance. By monitoring the value of capacitance continuously, uniformity in thickness of the test material is inspected, and further it will be either accepted or rejected as per the user's requirements.

The thickness measurement of the insulating material without touching the parallel plates of the capacitor. Here the separation between the parallel plates d is larger than the thickness of the testing material t, but in practice it is not necessary to provide the air gap.

CAPACITANCE PROXIMITY TRANSDUCER

In Fig 4.4.14, The main purpose of capacitive proximity sensor is to detect the presence of the metallic object as well as non-metallic objects, and often it is preferred for the detection of non-metallic materials such as paper, glass objects, plastic, wood, liquid, cloth materials, etc.

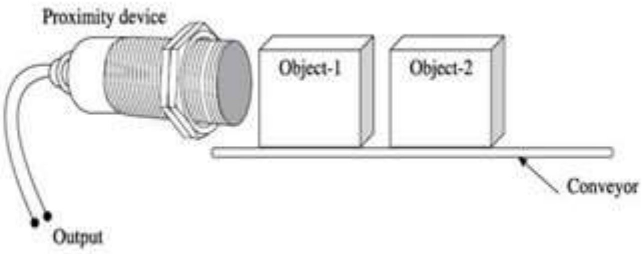


Figure 4.4.14 Object detection by a capacitive-type proximity sensor.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 747]

The capacitive proximity sensor has a sensing surface. It is made up of two circular shaped metal electrodes which form the parallel plates of the capacitor. When the target or the object which to be detected is nearer to the proximity sensor, there will be interference in the electrostatic field of the capacitive electrodes which will further change the capacitance of the parallel plate capacitor. Figure 4.4.17 shows the output taken from from the proximity sensor by using an oscillator and trigger circuit.

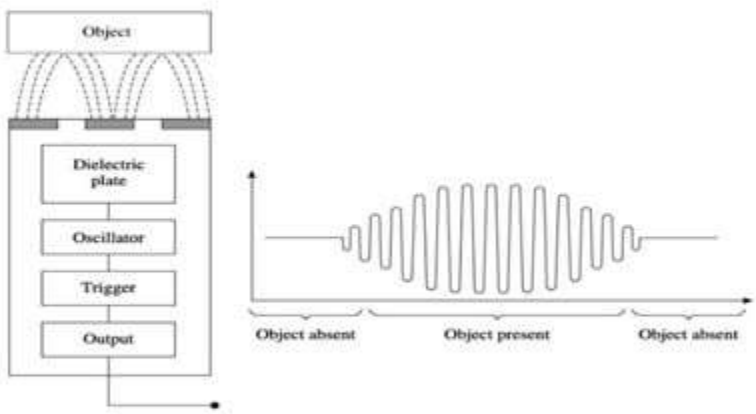


Figure 4.4.15 Output detection with respect to the presence of the object.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 748]

If an oscillator is connected at the output side of the sensor, the oscillator will start to oscillate, and the amplitude of the oscillation is read out by a trigger circuit.

Whenever the object is moving away from the proximity sensor, the magnitude of the oscillation is minimum which makes the sensor output to its previous state. From Figure, the magnitude change in the oscillations shows the presence and the absence of the object nearer to the proximity sensor. Hence the change in capacitance from the sensor is proportional to the presence of the object.

The sensing distance from the proximity device and the object can be ranging from 3 mm to 25 mm. The operating range of the sensing plates can be 5 mm to 127 mm. It can detect the change in capacitance up to 0.02 pF

CAPACITANCE-TYPE STRAIN TRANSDUCER

In a capacitance-type strain transducer, the change in strain is inferred from the change in capacitance of the parallel plate capacitor. The arrangement of the capacitance-type strain transducer is shown in Figure 4.4.16

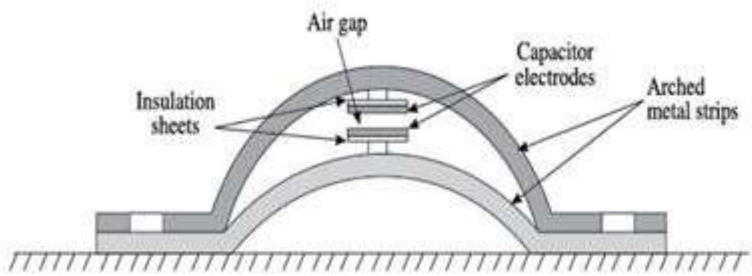


Figure 4.4.16 Capacitive strain transducer.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 749]

A parallel plate of a capacitor with insulation is kept in between the arched metal strips. Based on the air gap between the plates assembly, the capacitance will be determined. When this arched assembly is strained by applying force on the top metal strip, it will be bended proportionally. Due to which, there will be change in the air gap of the capacitor which in turn changes the capacitance. The amount of capacitance change depends on the straining of the arched metal strip.

The relationship between the strain and change in capacitance is not linear, and it can be used for the measurement of ± 5000 μ at temperatures of about 600 ° C.

CONDENSER MICROPHONE

The condenser microphone is developed to be immune from the effects of any variations in the atmospheric pressure. It consists of a diaphragm of a very thin metal which is stretched by using a clamping arrangement. The thickness of the diaphragm is ranging from 0.0025 mm to 0.050 mm. The diameter of the diaphragm is ranging between 5 mm to 25 mm. On the top of the diaphragm, uniform pressure variations exist all around. Due to these pressure variations, the diaphragm is deflected which acts as moving plate of the capacitor. The other plate of the capacitor is a stationary one held inside the chamber, which consists of damping holes. These holes are used to allow air to pass freely from the space between the electrodes to the other side of the chamber. The damping effect of the holes is also used to control the amplitude of vibration of the membrane at frequencies near about its undamped natural frequency.

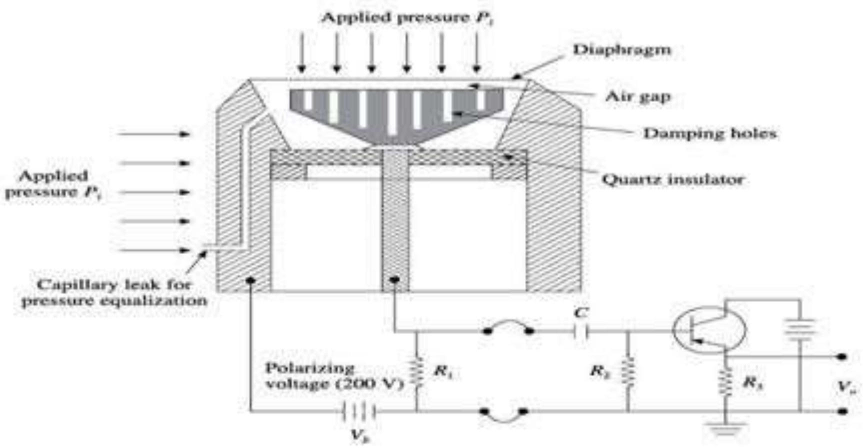


Figure 4.4.17 Condenser microphone.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 750]

If these holes are not provided, the clearance between the capacitor electrodes is made small, and the presence of the air between the plates resists the deflection of the diaphragm.

The distance between the plates is about 20 μm. There is a capillary tube which connects the chamber to atmosphere. It is provided to give pressure equalization on either side of the diaphragm and thereby preventing diaphragm bursting. The action of low pass filter is provided by the capillary tube and the volume of the microphone chamber which allows slow variations of atmospheric pressure. It also prevents the fluctuations of the pressure on the back side of the membrane.

At the output section, a variable capacitor is connected with a high resistance R and polarized with a dc voltage of about 200 V which acts an excitationis in the range of 1 mV/ μbar to 5 mV source. It also determines the neutral position of the diaphragm. It has a frequency response ranging from 10 Hz to 20 kHz. Sensitivity of the microphone.

4.1 INTRODUCTION:

Transducers based on the principle of variation in inductance are generally termed as inductive transducers.

PRINCIPLE OF INDUCTIVE TRANSDUCERS

PRINCIPLE: In inductive transducers, there are magnetic materials used in the flux path, and there is also one or more number of air gaps. If there is any change in air gap, there will be change in the inductance of the circuit. By its principle, the self inductance or mutual inductance of a pair of coils or production of eddy currents is changed whenever there is variation in the quantity to be measured.

If the inductive transducer is functioning based on the self inductance, the inductance of the coil can be expressed in terms of reluctance of the magnetic circuit such as:

Inductance L = $\frac{N^2}{R}$

Where,

N is the number of turns of the coil

R is the reluctance of the magnetic circuit

The reluctance of the magnetic coil can also be expressed as,

R = $\frac{1}{\mu_o \mu_r A}$

Where,

μ_o is the permeability of air.

μ_r is the relative permeability.

A is the area of cross-section of the coil / is the length of the coil.

Therefore, the inductance of a coil can be expressed in terms of number of turns (N), permeability of the material (μ) and geometric factor (G).

Since the inductance is a function of N, μ and G, i.e., L = f(N, μ, G) any variable which changes any one of the above quantities, the inductance of the coil gets changed. Further, this change in inductance can be further converted into the required form.

EXAMPLES OF INDUCTIVE TRANSDUCERS

There are many transducers working on the principle of variation in inductance. Some of the important transducers are listed as follows:

1. Induction potentiometers
2. Linear Variable Displacement Transformer (LVDT)
3. Variable reluctance accelerometer
4. Synchro
5. Resolvers, etc.

SIMPLE INDUCTANCE TYPE TRANSDUCER

In simple inductance type, there are three different constructional arrangements of the inductive coil such as:

Type 1. Inductance coil can be wounded over a rectangular type magnetic material.

Type 2. Inductance coil can be wounded on a cylindrical type material.

Type 3. Two coils are used.

CONSTRUCTIONAL ARRANGEMENTS:

TYPE 1 : INDUCTANCE COIL WOUNDED OVER A RECTANGULAR TYPE MAGNETIC MATERIAL

In this kind of inductive transducer, a single inductive coil of N turns is wound around a rectangular type ferromagnetic material.

This inductive coil is the source of magneto-motive force which drives the flux through the magnetic circuit is shown in Fig 4.1.1.

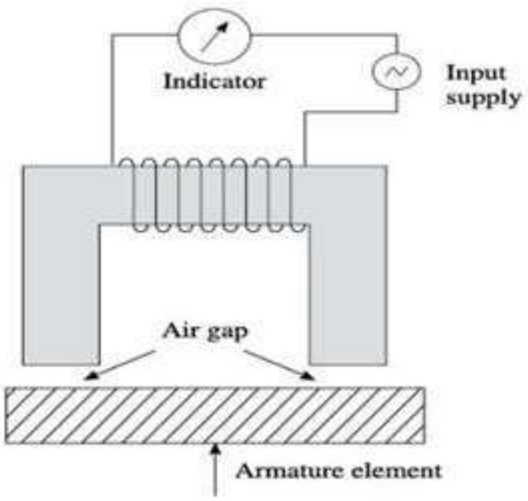


Figure 4.1.1 Simple inductance type transducer of first type.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 702]

- There is an armature element placed opposite to the inductive coil wounded.
- Whenever there is any movement in the mechanical armature element, there will be changes in the permeability of the flux path generated which will further change the inductance of the circuit.
- Based on the change in the inductance, the corresponding output will be obtained.
- This output can be calibrated directly against the change in movement of the armature element.

TYPE 2. INDUCTANCE COIL CAN BE WOUNDED ON A CYLINDRICAL TYPE MATERIAL.

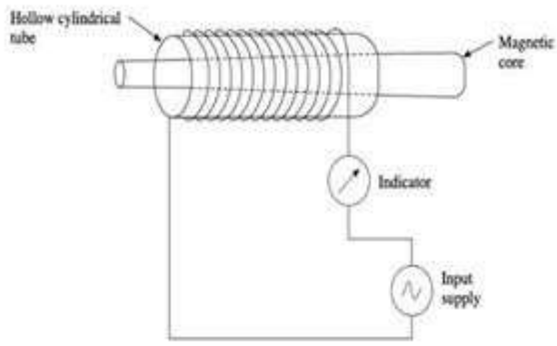


Figure 4.1.2 Simple inductance type transducer of second type

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 703]

- In Fig 4.1.2, In this type, a round hollow magnetic material is used and over which the inductive coil is wounded.
- There is a movable magnetic core located inside the hollow tube.
- Due to the core movement, there will be change in the inductance which produces a corresponding output in the output indicator connected across the coil wounded.

TYPE 3. INDUCTANCE TRANSDUCERS OF TWO COILS TYPE.

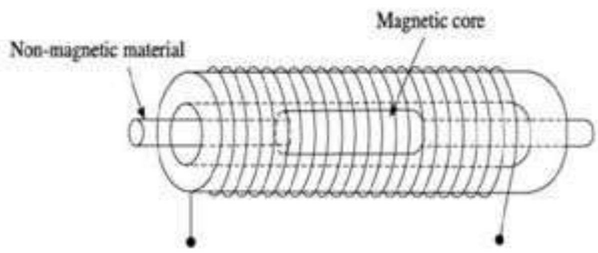


Figure 4.1.3 Simple inductance type transducer of two-coil type

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 704]

- In Fig 4.1.3, In this type, two coils are used.
- Whenever there is a movement of the magnetic core located at the center of two coils, there will be change in the relative inductance of the two coils.
- Due to this, the overall inductance of the circuit will also be changed which is proportional to the change in the ratio of the two inductive coils.

MUTUAL INDUCTANCE TYPE TRANSDUCER

In this kind of transducers, two different coils are used. The input excitation, provided by the external power source, is given to the first coil and the output is obtained from the second coil.

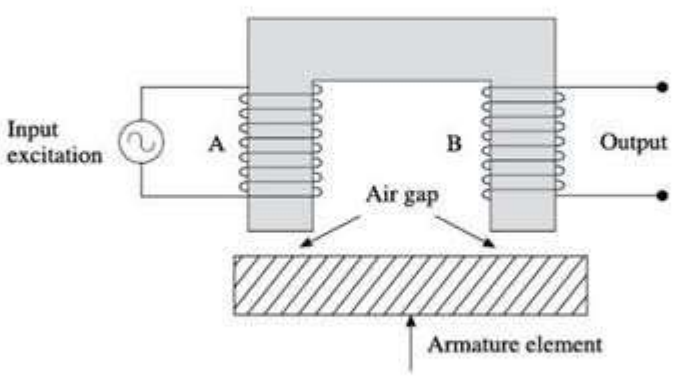


Figure 4.1.4 Mutual inductance type transducer

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 704]

In Fig 4.1.4, there are two separate coils wounded opposite to each other on a rectangular type magnetic material, and the excitation coil is represented as A and the output coil is represented as B.

An armature is placed opposite to the input and output inductive coils. If there is any change in the position of the armature, there will be change in the air gap between the rectangular inductive base material and the armature element. Hence, the inductance of the output coil B is changed proportional to the mechanical displacement of the armature.

INDUCTION POTENTIOMETER

Another important inductive type of transducer used for the measurement of displacement is called as induction potentiometer.

CONSTRUCTION:

- There is one primary core called rotor and a secondary core called stator.
- There are two concentrated coils and among which one is wounded on the primary core and the other is wounded on the secondary core.
- The rotor is preferred usually as dumbbell shaped. If any other shape can provide the uniform air gap over the entire periphery, it may also be used for the rotor.
- The operational frequency range of standard commercial induction pots is between (50 – 400) Hz.
- Its size is ranging from 1 cm to 6 cm, and the sensitivity of the inductive potentiometer can be one volt per degree rotation.
- The range of induction potentiometers is limited within 60 ° of rotation.
- However, it is possible to measure a linear relation up to ± 90 ° rotation with careful distribution of primary and secondary windings.

WORKING PRINCIPLE:

The coupling between the primary or rotor winding and secondary or stator winding is provided in such a way that the orientation of one of them with respect to the other winding determines the induced emf in one of them.

In particular, the rotor winding is excited with an ac and thus there will be an inducing voltage in the stator winding. These two coils provide an equivalent of a transformer with variable coupling between the primary and the secondary winding is shown in Fig 4.1.5.

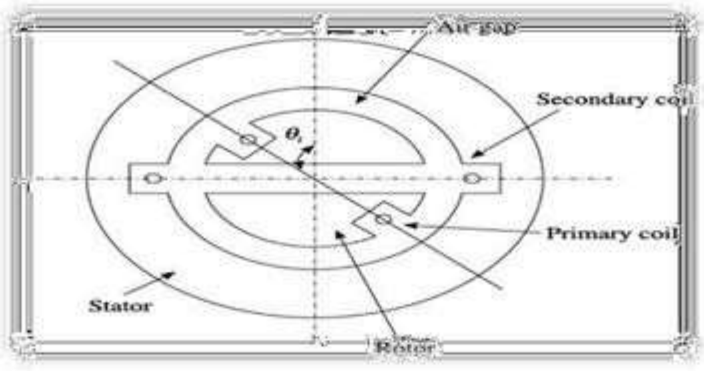


Figure 4.1.5 shows the arrangement of the induction potentiometer.
[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 705]

Depending on the mutual inductance between the two coils, the amplitude of the output voltage is varied. The mutual inductance is dependent on the angle of rotation. If the induction potentiometer is concentrated coil type, the amplitude can be varied sinusoidal. By having carefully designed distributed coils, a linear distribution over an angle of 180 ° can be obtained. It is also found that the mutual inductance M is maximum when the coils are co-axial and is zero when they are in Quadrature. For any angle θ_i between the coils, the relationship between the mutual inductance M and its corresponding emf is given as:

M = M max cos θ_i

The output voltage e_o from the induction potentiometer is also expressed as:

$$e_o = \boldsymbol{k[Em \sin \omega ext] \cos \theta\ i}$$

$\boldsymbol{Em \sin \omega ext}$ is the excitation voltage K

is the constant

4.2 LINEAR VARIABLE DIFFERENTIAL TRANSFORMER (LVDT):

Linear Variable Differential Transformer or simply LVDT is a well established inductive transducer used for measuring the linear displacement. Generally, it is an electromechanical transducer which converts the movement of the core, which is coupled mechanically, into a corresponding electrical output. LVDT can measure the displacement up to ± 0.5 m.

CONSTRUCTION:

- LVDT consists of primary and secondary windings; in particular there is one primary winding and two identical secondary windings.
- The primary winding is centered between a pair of identically wound secondary windings which are symmetrically spaced about the primary winding.
- These coils are uniformly wound on a thermally stable glass reinforced polymer which is of hollow shape.
- It is then encapsulated against moisture and wrapped in a high permeability magnetic shield.
- Finally, the coil assembly is protected in cylindrical stainless steel housing and this is usually considered as the stationary element of the LVDT sensor is shown in Fig 4.2.1.

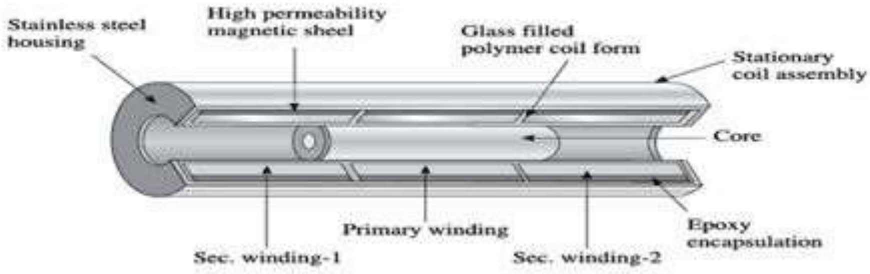


Figure 4.2.1 Constructional arrangement of LVDT.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 706]

The moving element of the LVDT is called as a core which is simply a separate tubular armature made up of magnetically permeable material.

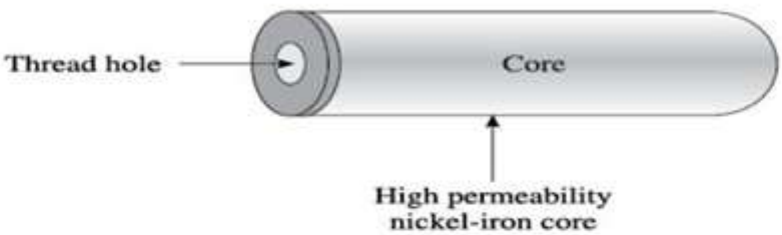


Figure 4.2.2 Core element of LVDT.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 707]

The core is able to move axially within the hollow shaped coil assembly.

It is mechanically coupled to the object whose position is to be measured.

Since the hollow bore assembly is large sized enough, there will be considerable space between the stationary and moving elements, and so there is no physical contact between themis shown in Fig 4.2.2.

WORKING PRINCIPLE:

Initially, an alternating current of appropriate amplitude and frequency called as primary excitation is given to the primary winding of LVDT. The electrical output signal from LVDT is obtained as the differential ac voltage between its two secondary windings. This output voltage is varied based on the variation in the axial movement of the movable core within the stationary coil assembly of LVDT. It is mathematically expressed as:

$$E_o = E_{s1} - E_{s2}$$

Where,

Es1 is the secondary-1 voltage.

Es2 is the secondary-2 voltage.

CASE I - CORE IS AT MAXIMUM LEFT POSITION :

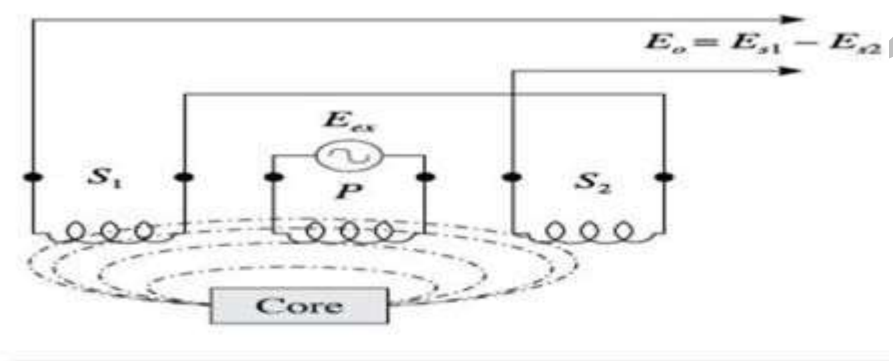


Figure 4.2.3 LVDT core at maximum left.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 708]

- In Fig 4.2.3, The LVDT core is moved to the left of the primary winding, i.e., closer to the secondary winding-1 (S1) than secondary winding-2 (S2).
- Due to this movement, more amount of flux is linked with S1 than S2.

Hence the emf induced in S1(Es1) is greater than in S2(Es2).

- Since Es1 > Es2, Eo= Es1− Es2 = Positive.

CASE II - CORE IS AT NULL POSITION:

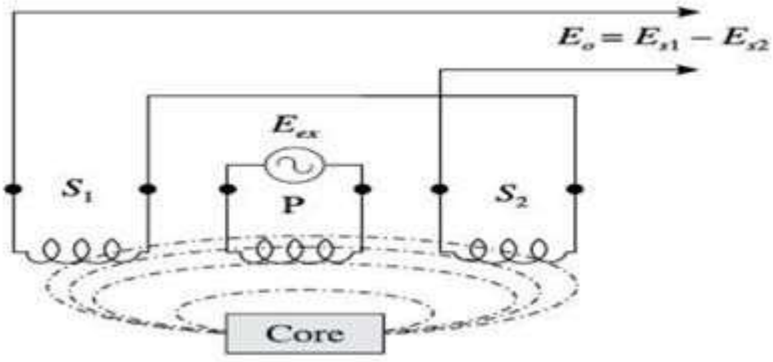


Figure 4.2.4 LVDT core NULL position.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 708]

- In Fig 4.2.4, The LVDT core is moved to the midway between the secondary winding-1 (S1) and secondary winding-2 (S2).
- The midway position is also termed as NULL position.
- Due to this movement, equal amount of flux is linked to both the secondary windings, and hence the voltages induced in both the secondary windings are equal.
- Since Es1 = Es2, Eo= Es1− Es2 = Zero.

CASE III - CORE IS AT MAXIMUM RIGHT POSITION :

- In Fig 4.2.5, The LVDT core is moved to the right of the primary winding, i.e., closer to the secondary winding-2 (S2) than secondary winding-1 (S1).

- Due to this movement, more amount of flux is linked with S2 than S1. Hence the emf induced in S2 (Es2) is greater than in S1 (Es1).
- Since Es1 < Es2, Eo= Es1− Es2 = Negative.

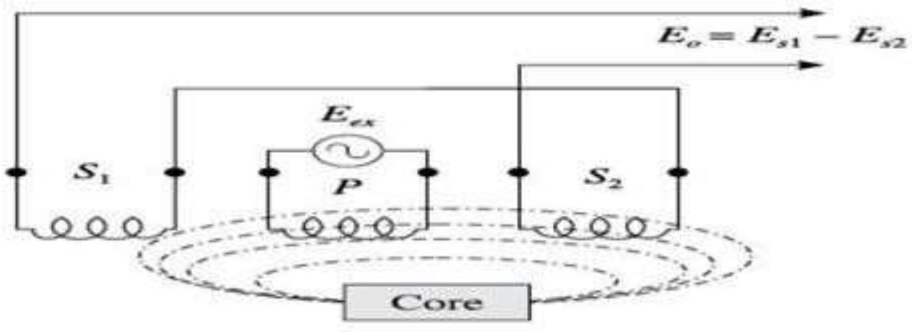


Figure 4.2.5 LVDT core at maximum right.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 709]

DISPLACEMENT VS DIFFERENTIAL VOLTAGE OUTPUT CHARACTERISTICS

The differential output voltage obtained from the LVDT is a linear function of the movement of the core between two secondary windings within a limited range of movement, say, about 5 mm from the NULL position. The characteristic curve is shown in Fig 4.2.6.

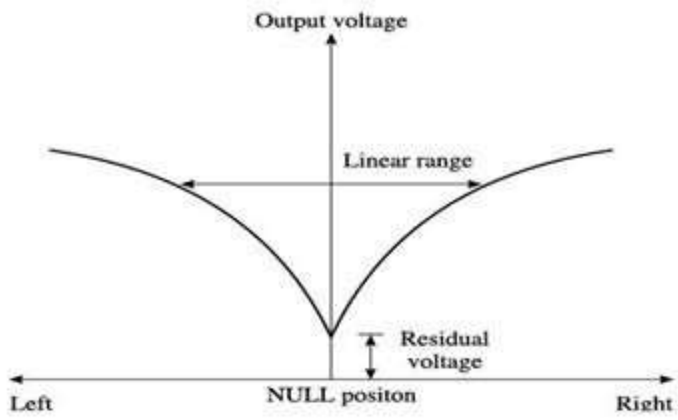


Figure 4.2.6 Displacement vs differential output voltage characteristics. [Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 710]

From the characteristic curve, it is shown that the characteristic is linear for a limited range of core displacements and then it becomes non-linear. It is also noted that for zero displacement, there is a voltage of less magnitude and is termed as residual voltage. Due to the presence of harmonics in power supply and also due to the use of iron ore in the construction, the residual voltage may occur. It is generally 1% of maximum voltage in the linear range.

LVDT CIRCUITS FOR PHASE SHIFT ADJUSTMENTS

In Fig 4.2.7, Due to some of the reasons, the desired phase shift cannot be achieved.

For such situations, one of the following methods can be followed:

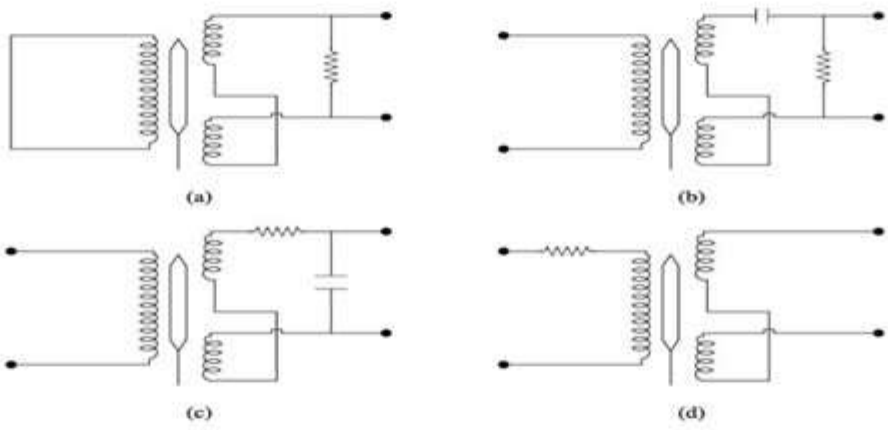


Figure 4.2.7 Circuits for phase shift adjustments in LVDT.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 711]

LVDT CIRCUITS FOR ZERO VOLTAGE ADJUSTMENT AT CORE NULL POSITION

Due to the presence of harmonics and stray capacitance coupling between primary winding and secondary winding, the output voltage at core NULL position may not be zero. It is found that there may be < 1% of full scale reading of output voltage and which may be somewhat acceptable. In order to reduce the output voltage at core NULL position properly, the following methods are to be adopted as NULL voltage reduction methods.

Method 1: The core NULL voltage can be achieved by suitable excitation voltage applied to the primary winding of LVDT is shown in Fig 4.2.8.

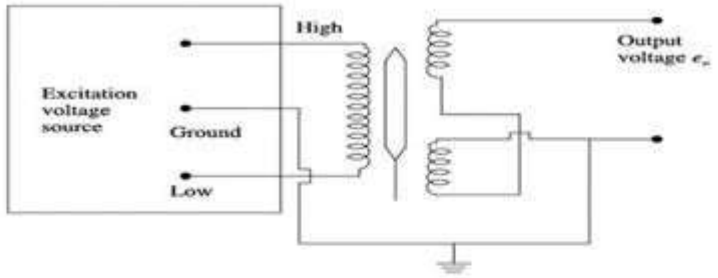


Figure 4.2.8 NULL voltage reduction method based on excitation voltage.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 712]

Method 2: The core null voltage reduction method from which the values of R and wiper resistance RP should be possibly small without loading excitation source. Initially the core is kept at the middle of travel of core displacement and RP is adjusted to get reduced output voltage is shown in Fig 4.2.9.

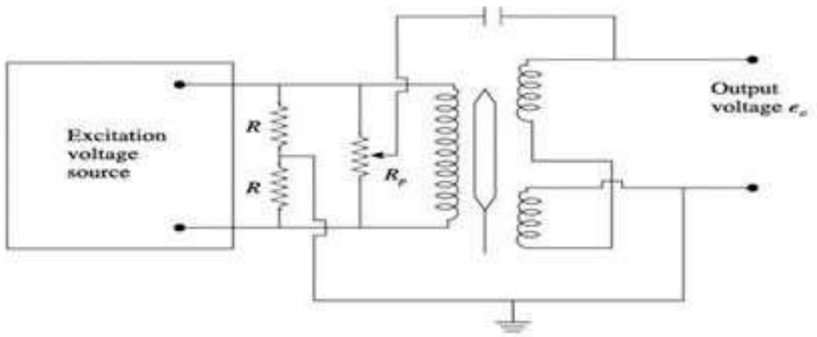


Figure 4.2.9 NULL voltage reduction method based on wiper resistance RP.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 713]

LVDT CIRCUIT FOR PHASE SENSITIVE DEMODULATION

To utilize LVDT for very slow displacements, it is essential to use phase-sensitive demodulation circuit.

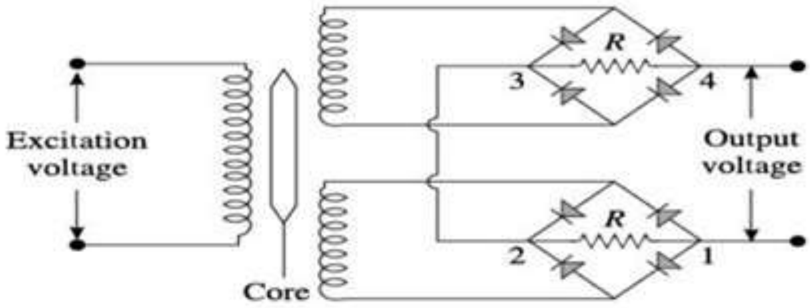


Figure 4.2.10 Circuit for phase sensitive demodulation.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 714]

A phase-sensitive demodulator can be used to indicate the direction of displacement of the iron core from the NULL position. From the above arrangement of phase sensitive demodulation circuit, there are two separate bridge circuits for two secondary windings. The final output differential voltage is obtained between the outputs of two bridges is shown in Fig 4.2.10.

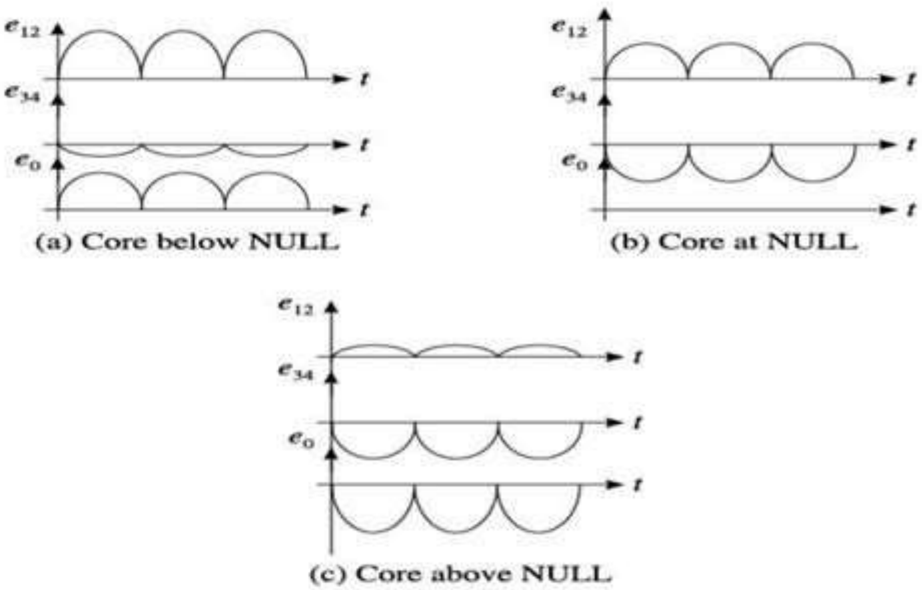


Figure 4.2.11 Output waveforms from a phase sensitive demodulation

circuit

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 715]

Based on the amplitude of the dc output, the position of the core can be determined and from the polarity of the dc voltage, the direction of the movement of the core can be determined. Sometimes, filters can also be incorporated in order to filter the outputs of the bridges in case of rapid displacements of the core is shown in Fig 4.2.11.

LVDT-BASED PRESSURE MEASUREMENT Construction:

There are some popular force sensing transducers commonly used with LVDT such as Bellows and Bourdon tubes. These devices can be joined with LVDT for the purpose of pressure measurement. Here, bellows and bourdon tube can act as primary transducers with LVDT acting as a secondary transducer is shown in Fig 4.2.12.

PRESSURE MEASUREMENT USING BOURDON TUBE AND LVDT:

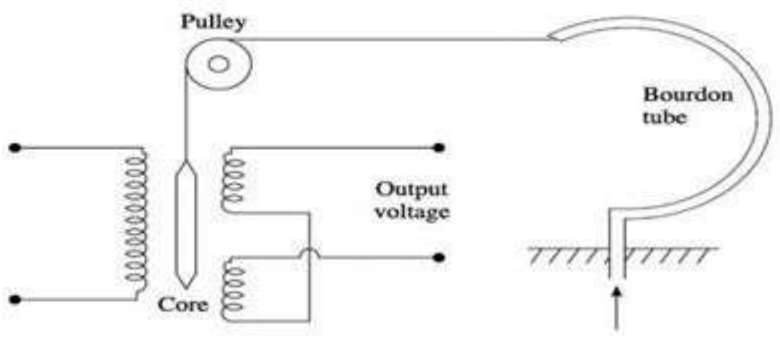


Figure 4.2.12 Pressure measurement using Bourdon tube and LVDT.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 716]

Working Principle:

The pressure is applied to pressure sensing element Bourdon tube. Based on the pressure signal, the tube will respond (bend), and due to this, the free end of the core will move in between the primary and secondary windings. It produces an output voltage, a differential voltage between two secondary windings, which is directly proportional to the applied pressure.

PRESSURE MEASUREMENT USING BELLOWS AND LVDT:

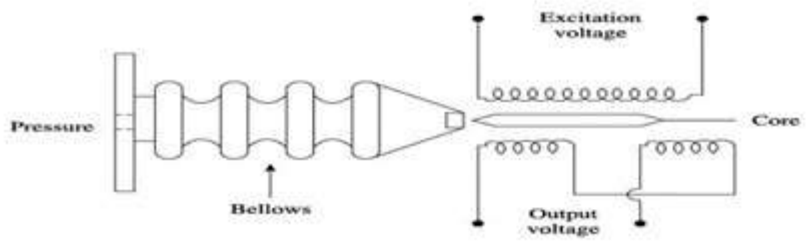


Figure 4.2.13 Pressure measurement using bellows and LVDT.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 717]

Working Principle:

For the pressure measurement using bellows and LVDT, bellows can act as a primary transducer which will react (contraction) based on the applied pressure through it. Due to the action of the primary transducer, the free end of the core will move in between the primary and secondary windings. It further produces an output voltage proportional to the applied pressure is shown in Fig 4.2.13.

LVDT-BASED THICKNESS MEASUREMENT Construction:

In order to measure the thickness of a metal sheet, the arrangement is shown in Fig 4.2.14. The two different LVDTs are connected to different rollers. Among which one is said to be reference LVDT which is connected to reference wheel, and another one is said to be measuring LVDT Which is connected to a measuring wheel. The test piece whose thickness to be measured is exposed on a main roller, also said to be calendar roller and over which the reference wheel is having contacted and measuring wheel is placed on the test piece or sheet stock.

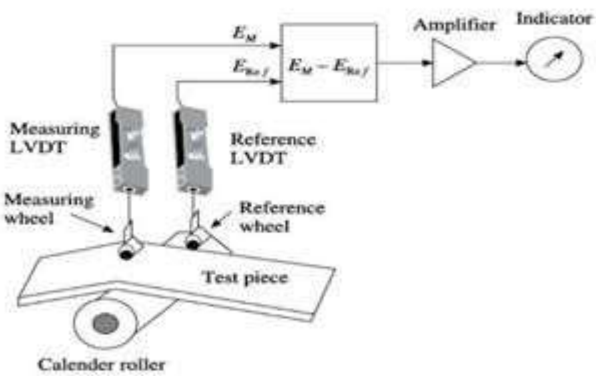


Figure 4.2.14 Arrangement for thickness measurement using LVDT.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 718]

By having rolling contact points, the thickness of the metal sheet is calculated as follows: Thickness t = K($E_m - E_{ref}$)mm

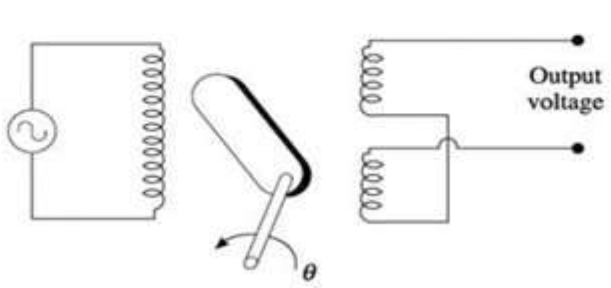
K is the calibration constant (mm/volt); E_m is the voltage output from measuring LVDT.

$Eref$ is the voltage from reference LVDT.

With the differential voltage output from two LVDTs ($E_m - E_{ref}$), the thickness of the test piece can be obtained.

4.3 ROTARY VARIABLE DIFFERENTIAL TRANSFORMER (RVDT):

The purpose of a Rotary Variable Differential Transformer (RVDT) is to measure rotational angles, and its principle of operation is same as that of an LVDT. In LVDT, a cylindrical iron core is used in between the primary and two secondary windings, whereas in RVDT, a rotary ferromagnetic core is used. In RVDT construction, a rotary ferro-magnetic iron-core bearing is supported within a housed stator assembly which consists of a primary excitation coil and a pair of secondary output coils. The housing is made up of stainless steel.



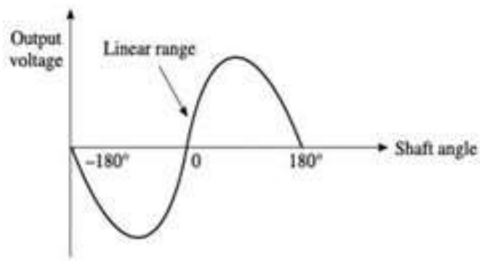


Fig 4.3.1 Arrangement of RVDT **Fig 4.3.2 Output response of RVDT**

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 719]

VARIABLE RELUCTANCE TRANSDUCER (MICROSYN)

Microsyn is another name of the variable reluctance transducer which has the arrangement as shown in Fig 4.3.1. There are two major parts such as a ferromagnetic rotor and a stator assembly. In the stator, four coils a, b, c, and d are connected together with that the voltages induced in coils a and c should be same as the voltages induced in coils b and d at NULL position of the ferromagnetic rotor is shown in Fig 4.3.2.

Based on the rotation of the rotor in clockwise direction, there will be increased reluctance in the coils a and c and decreased reluctance in the coils b and d which gives a net output voltage (Eo). If the rotation is in counter clockwise direction, it produces same kind of effect in coils b and d with 180 ° phase shift. With the help of microsyns, it is possible to detect very small motion which provides output signal for even 0.01 ° of changes in angles. Microsyn have the sensitivity as high as five volt per degree rotations is shown in Fig 4.3.3.

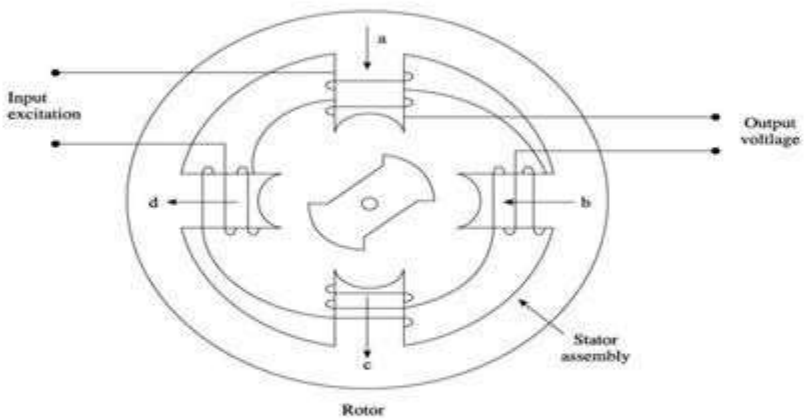


Figure 4.3.3 Variable reluctance transducer.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 720]

VARIABLE RELUCTANCE TACHOGENERATOR

Another inductive type sensor is a variable reluctance sensor which works based on linear or angular velocity of the motion. The schematic diagram of the sensor is shown in Fig 4.3.4.

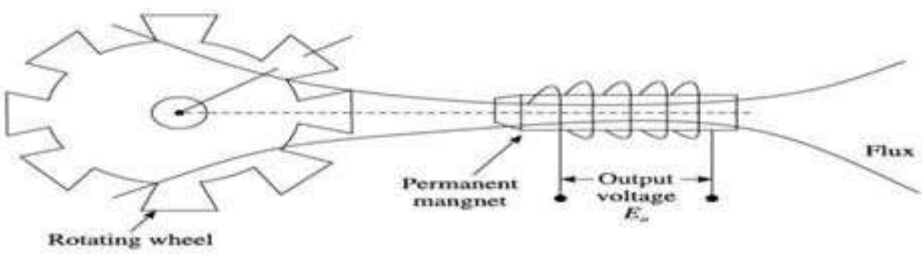


Figure 4.3.4 Variable reluctance tachogenerator

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 720]

From the constructional arrangement of the variable reluctance tachogenerator, the major parts are listed as follows:

1. A rotatable toothed wheel, which is of ferromagnetic type, attached to a shaft.
2. A permanent magnet over which an output coil is wound.
3. A soft iron pole piece.

When the rotating wheel has a movement very close to the soft iron pole piece, there will be a change in the flux linked by the coil wound on the permanent magnet. Hence an emf is induced in the output coil proportional to the flux change and linear or angular velocity of the toothed wheel.

Based on the air gap between the ferromagnetic wheel and soft iron pole piece, the reluctance will vary. The reluctance will be minimal when the tooth of the wheel is nearer to the iron piece and maximum when it moves away from the iron piece. If the rotating wheel has an angular velocity ω, the changing flux $\psi(\theta)$ can be expressed as: $\psi(\theta) = X+Y \cos n\theta$

Where, X is the mean flux; Y is the amplitude of change in flux; n is the number of teeth.

The induced emf in the output coil can be given as

$$Eo = - d\,\psi(t)/dt$$

Based on the angular velocity of the rotating wheel, there will be an output voltage with varying amplitude and frequency. The behavior of change in flux linked by the output coil is similar to a square waveform and frequency of the waveform is varying one based on the speed of the rotation of the ferromagnetic wheel and the number of teeth in the rotor.

VARIABLE RELUCTANCE ACCELEROMETER

The purpose of this accelerometer is to measure the acceleration in ± 4g range. The schematic diagram of variable reluctance accelerometer is shown in Figure 4.3.5.

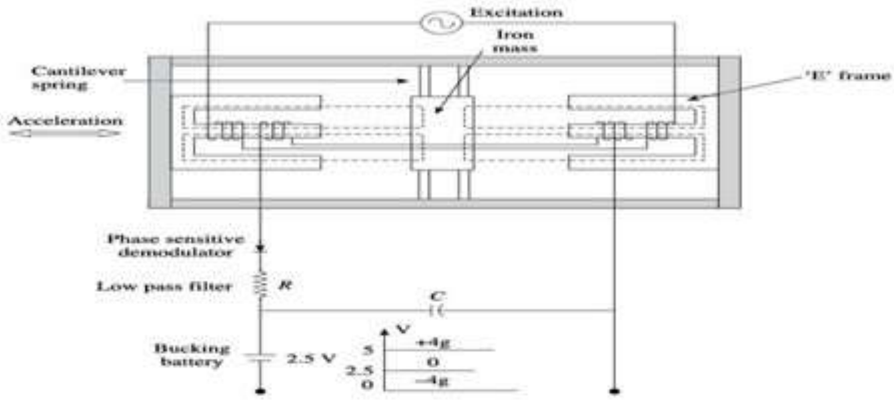


Figure 4.3.5 Variable reluctance accelerometer.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 722]

If the iron mass is exactly at the middle of two E frames, the acceleration will be zero and hence there will be no output voltage. Depending on the motion of the mass, the spring gets deflected which corresponds to a varying acceleration. There is zero output voltage when there is no acceleration. The output voltage is 5 volts when there is + 4g of applied acceleration and the output will be zero if –4g of acceleration is applied.

A phase sensitive demodulator is used in order to detect motion of the mass on both sides of zero position. Otherwise, the cantilever springs are to be adjusted so that the iron mass will be in zero to one side by an amount equivalent to the deflection of the spring with respect to + 4g acceleration. To obtain a phase sensitive output proportional to the measured acceleration, an assembly of a bucking battery, a diode and a low pass filter can be used.

SYNCHRO

Generally, a synchro is a type of transformer category, and it is often called as transformer-type displacement transducer. It is also called as Selsyn which is the acronym for 'self synchronizing' and Autosyn which is the acronym for 'automatic synchronizing'. Synchro consists of two major parts such as stator and rotor. The output e.m.f voltage induced in the stator coil is due to the variation in the angular motion of the rotor when it is excited with ac voltage is shown in Fig 4.3.6.

Construction:

- Synchro is a single assembly comprising both stator and rotor. They are made up of silicon or steel material of high grade.
- In stator, three coils of identical type are arranged in a manner that their axes are mutually at 120 ° apart.
- These three windings are uniformly distributed in their slots provided by the stator is shown in Fig 4.3.7.
- The rotor is provided with a winding through which an ac excitation is given.
- There are two popular types of rotor shapes such as dump bell shaped rotor and cylindrical shaped rotor.

Figure 4.3.6 Different shapes of rotor.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 724]

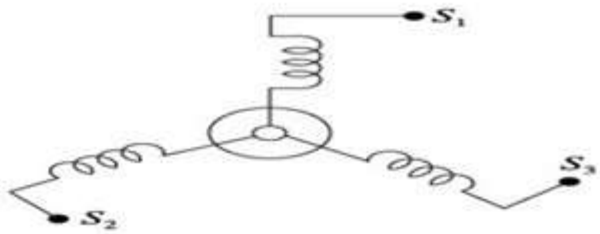


Figure 4.3.7 Arrangement of stator.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 724]

Working Principle:

There is a single winding in the rotor which is excited with an ac voltage. Due to this, there will be flux generation in stator path. Whenever there is an angular displacement in the rotor winding, there will be variation in the flux which will further induce e.m.f in all the three windings in stator assembly. With the rotor and stator winding positions, shown in Figure 4.3.8, the expressions of voltage for rotor and stator windings are given below.

Rotor Voltage $\boldsymbol{E_r} = \boldsymbol{A \sin \omega t}$

Stator Voltage in S1 winding $\boldsymbol{E_1} = \boldsymbol{E_m \sin \omega t \cos \theta}$

Stator Voltage in S2 winding $\boldsymbol{E_2} = \boldsymbol{E_m \sin\ \omega t}$

$\boldsymbol{\cos(120 - \theta)}$ Stator Voltage in S2 winding $\boldsymbol{E_2} =$

$\boldsymbol{E_m \sin \omega t \cos(120 + \theta)}$ where Em is the peak

voltage induced in the stator coil.

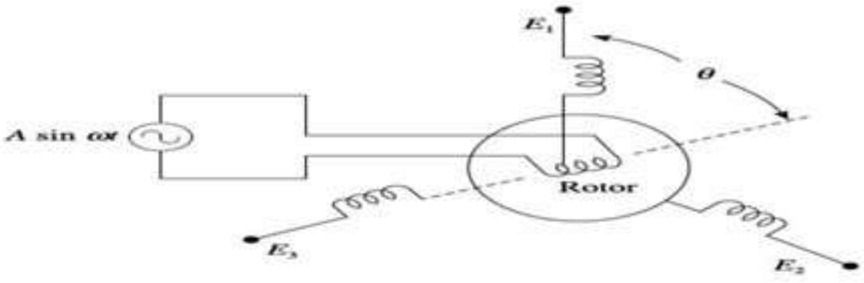


Figure 4.3.8 Schematic diagram of synchro.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 725]

The frequency of all three stator windings is same as per the frequency of the voltage applied to the rotor winding. It is also noted that all the stator voltages given are in same phase.

SYNCHRO AS POSITION TRANSDUCER

A synchro pair can be used to detect the angular position and based on the detected position, a voltage signal output will be produced. In the arrangement, the synchro pair consists of two elements such as a Synchro Generator (SG) and a Control Transformer (CF). The stator coils S1, S2 and S3 of SG are connected to the stator coils of S1, S2 and S3 of CT as shown in Figure 4.3.9.

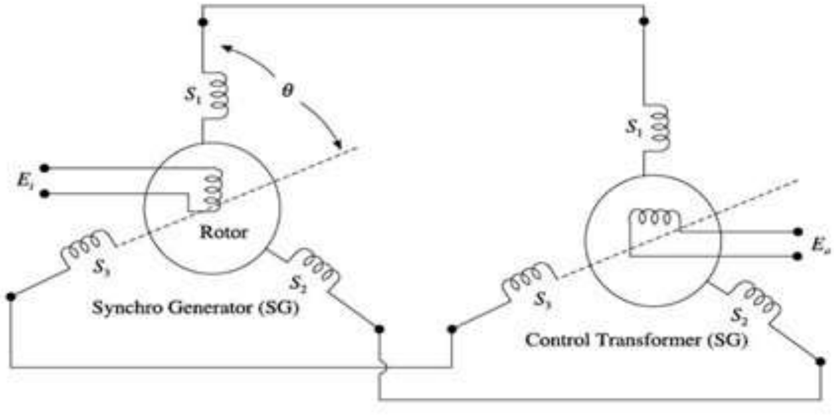


Figure 4.3.9 Synchro as position transducer.
[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 726]

An ac voltage of excitation Ei is supplied to the rotor of SG. Initially the rotor of SG is kept at zero angular position (θ = 0 °), which is said to be mechanically zero position. The rotor of the current transformer is kept at 90 ° to the rotor of the synchro generator. Generally, rotor of SG is of cylindrical shaped and rotor of CT is of dump bell shaped is shown in Fig 4.3.10.

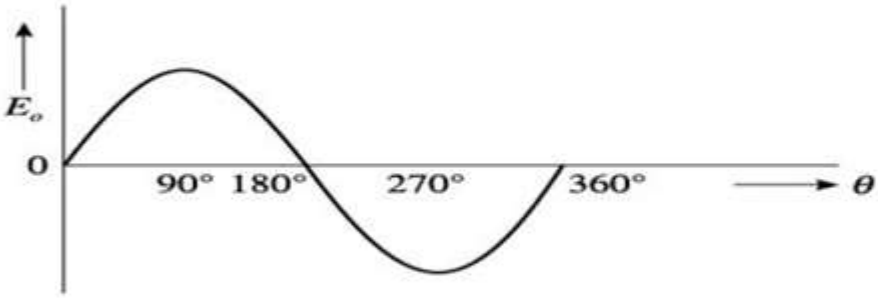


Figure 4.3.10 Synchro-position transducer characteristics.
[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 727]

SYNCHRO AS POSITION TRANSMITTER

A synchro pair can be used to transmit the angular displacement to any remote location. The arrangement for this purpose is shown in Figure 4.31. In the arrangement, there are two elements— Synchro Generator (SG) and a Synchro Motor (SM).

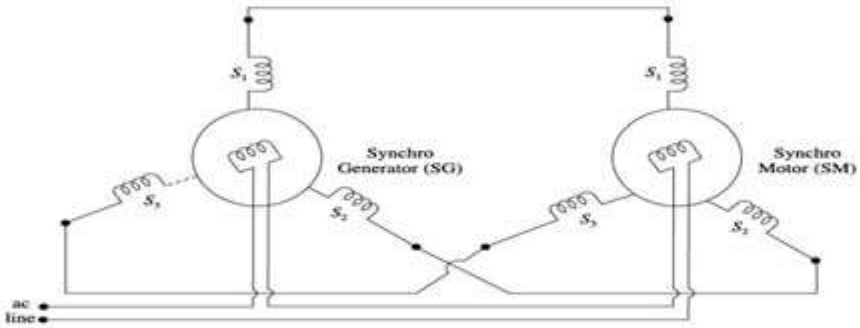


Figure 4.3.11 Synchro as position transmitter.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 728]

Synchro motor is generally added with some damping units. SG is located in one room, and SM can be placed in remote place. The angular displacement of the synchro motor follows that of the synchro generator. There are three wires used for connecting stator windings and two wires used for connecting rotor windings of the synchro pair. There are other synchro differential units used for the purpose of transmitting the sum of two angular displacements to a remote place is shown in Fig 4.3.11.

RESOLVERS

A resolver is an electromagnetic device used for converting the angular position of a shaft into Cartesian coordinates. It consists of two sets of stator and two sets of rotor windings. These two stator windings are identical in nature and housed in a magnetic structure with the axis of two windings 90 ° to each other. The two rotor windings are also placed in a magnetic structure and are mutually perpendicular to each other. The output of the resolver is in the form of two signals among which one is proportional to sine of the angle and the other is proportional to cosine of the angle.

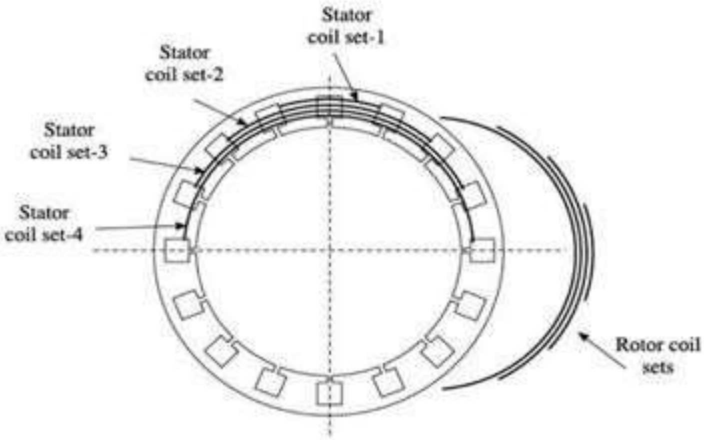


Figure 4.3.12 Arrangement of the resolver windings.
[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 729]

An ac excitation voltage is supplied to the rotor windings, and it produces an alternating magnetic flux which will further induce voltages in stator windings is shown in above Fig 4.3.12.

Based on the input excitation between stator windings and the coupling between the stator and rotor windings, there will be variation in the output voltage of the rotor windings. Based on the distribution of windings placed, the output voltages are proportional to sine and cosine of the mechanical rotation of the rotor windings is shown in below Fig 4.3.13.

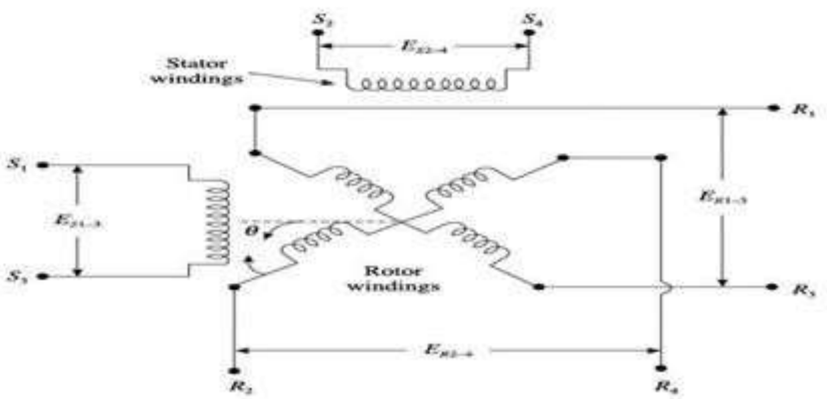


Figure 4.3.13 Winding configuration of the resolver.

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 730]

When the winding configuration of the resolver in which one of the two sets of stator windings, say, S1S3 is excited by ac voltage with the other stator winding S2S4 short circuited, the following output voltages are obtained from the rotor windings:

$$E_{R1-3} = E_{s1-3}\cos\theta$$

$$E_{R2-4} = -E_{s1-3}\sin\theta$$

When both the stator windings are excited by ac voltages, the outputs are obtained as follows:

$$E_{R1-3} = E_{s1-3}\cos\theta + E_{s2-4}\sin\theta$$
$$E_{R2-4} = E_{s2-4}\cos\theta - E_{s1-3}\,sin\theta$$

When both the rotor windings are excited by ac voltages, the outputs obtained from the stator windings are expressed as follows:

$$E_{s1-3} = E_{R1-3}\cos\theta - E_{R2-4}\sin\theta$$

$$E_{s2-4} = E_{R2-4}\cos\theta + E_{R1-3}\sin\theta$$

Specifically, resolvers are used for data transmission, vector resolution, pulse amplitude control and pulse resolution and phase shifting, and its accuracy is also comparatively better.

EDDY CURRENT TRANSDUCERS

Eddy current transducer is of inductive type transducers, and it is based on eddy current generation based on quality of a high alternating source fed to probe consisting of a set of coils. One coil is said to be an active coil and the other one is said to be a compensating coil, since it provides temperature compensation and also to balance the bridge circuit connected with it. The arrangement of the eddy current transducer is shown in Figure 4.3.14.

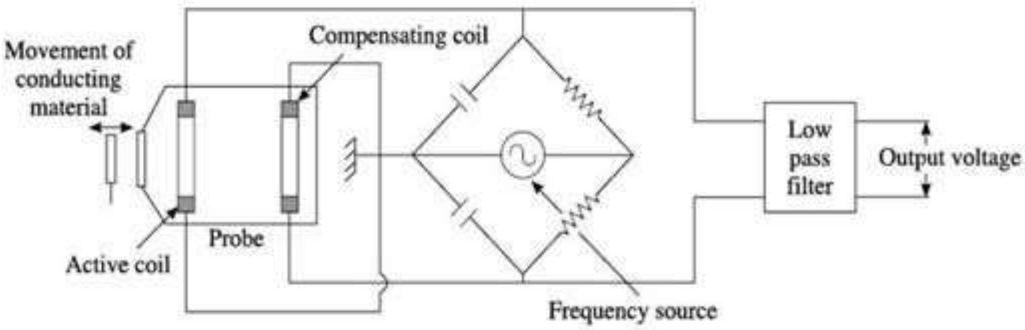


Figure 4.3.14 Eddy current transducer

[Source: Neubert H.K.P., Instrument Transducers – An Introduction to their Performance and Design, Page: 732]

This depth of penetration can be calculated by using the following expression:

$$\delta = \frac{1}{f\pi\mu\sigma}$$

δ is the depth of penetration in m; f is the frequency in HZ; μ is the magnetic permeability; σ is the electrical conductivity in S/m.