3rd Semester

INSTRUMENTATION AND CONTROL ENGINEERING

SUBJECT
TRANSDUCER & SIGNAL CONDITIONING

SUBJECT CODE
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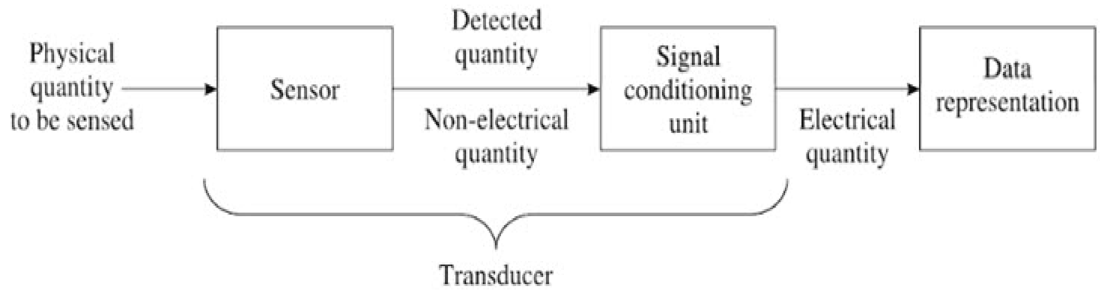
Chapter-1

Introduction to Transducer

Transducer: A **transducer** is a device that converts energy from one form to another.

Before understanding what a transducer is or diving into the different types of Transducers, consider the following setup of a measuring system. In this block diagram of a simple measuring system, there are three basic elements:

- Sensor
- Signal Conditioning Unit
- Data Representing Device



Sensor

A Sensor is a device that is used to detect changes in any physical quantity like Temperature, Speed, Flow, Level, Pressure, etc. Any changes in the input quantity will be detected by a Sensor and reflected as changes in output quantity.

Both the input and output quantities of a Sensor are Physical i.e. non-electrical in nature.

Signal Conditioning Unit

The non-electrical output quantity of the Sensor makes it inconvenient to further process it. Hence, the Signal Conditioning Unit is used to convert the physical output (or non-electrical output) of the sensor to an electrical quantity.

Some of the best known Signal conditioning units are:

- Analog to Digital Converters
- Amplifiers
- Filters
- Rectifiers
- Modulators

Data Representation Device

A Data representation device is used to present the measured output to the observer. This can be anything like

- A Scale
- An LCD Display
- A Signal Recorder

Transducer

In the above example, consider a Strain Gauge as the Sensor. Any changes in the strain will reflect as changes in its resistance. Now, in order to convert this change in resistance into equivalent voltages, you can use a simple Wheatstone Bridge circuit, which acts as the Signal Conditioning Unit.

The combination of Strain Gauge (Sensor) and Wheatstone Bridge (Signal Conditioning Unit) is Known as a Transducer.

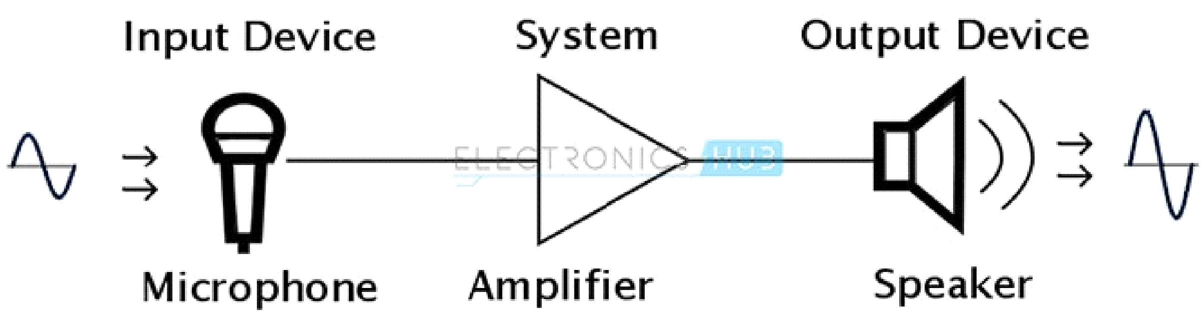
Generally speaking, a Transducer is a device that converts one form of energy into another by the principle of Transduction. Usually, a signal in one form of energy is converted to a signal in another form by a Transducer.

From the above example, a Transducer is a device that converts a Physical Quantity into an Electrical Quantity.

Sensors and Actuators

From the above definition, actually, both Sensors, devices that responds to a physical quantity with a signal and Actuators, devices that respond to signals with physical movement (or similar action) can be considered as Transducers.

For example, a Microphone is a Sensor, which converts sound waves into electrical signals and a Loudspeaker is an Actuator, which converts electrical signals into audio signals.



Both Microphone and Loudspeaker are Transducers in the sense that a microphone converts sound energy into electrical energy and a loud speaker converts electrical energy into sound energy.

Classification of Transducers:

There are several ways in which you can classify transducers that include but not limited to the role of the transducer, structure of the transducer or the phenomena of their working.

It is easy to classify transducers as Input Transducers or Output Transducers, if they are treated as simple signal converters. Input Transducers measure non-electrical quantities and convert them into electrical quantities.

Output Transducers on the other hand, work in the opposite way i.e. their input signals are electrical and their output signals are non-electrical or physical like force, displacement, torque, pressure etc.

Depending on the principle of operation, transducers can also be classified into mechanical, thermal, electrical, etc.

Let us see the classification of transducers based on the following three ways:

- Physical Effect
- Physical Quantity
- Source of Energy

Classification based on Physical Effect

The first classification of Transducers is based on the physical effect engaged to convert the physical quantity to electrical quantity. An example, is the change in resistance (physical quantity) of a copper element in proportion to the change in temperature.

The following physical effects are generally used:

- Variation in Resistance
- Variation in Inductance
- Variation in Capacitance
- Hall Effect
- Piezoelectric Effect

Classification based on Physical Quantity

The second classification of Transducers is based on the physical quantity converted i.e. the end use of the transducer after the conversion. For example, a Pressure Transducer is a transducer that converts pressure into electrical signal.

Following is small list of transducers classified based on the physical quantity and corresponding examples

- Temperature Transducer – Thermocouple
- Pressure Transducer – Bourdon Gauge
- Displacement Transducer – LVDT (Linear Variable Differential Transformer)
- Level Transducer – Torque Tube
- Flow Transducer – Flow Meter
- Force Transducer – Dynamometer
- Acceleration Transducer – accelerometer

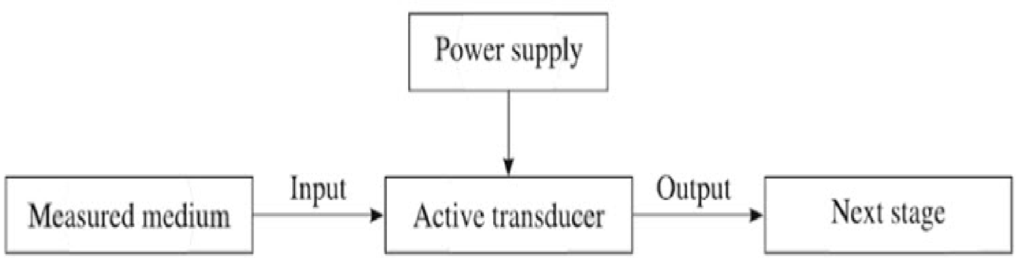
Classification based on Source of Energy

Transducers are also classified based on the source of energy. Under this category, there usually two types of transducers:

- Active Transducers
- Passive Transducers

Active Transducers

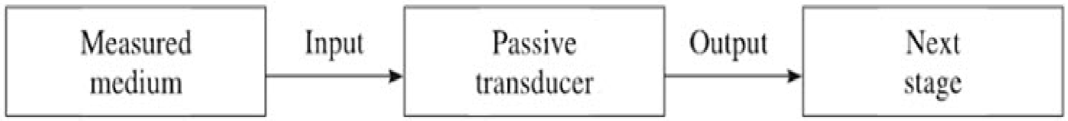
In Active Transducers, the energy from the input is used as a control signal in the process of transferring energy from power supply to proportional output.



For example, a Strain Gauge is an Active Transducer, in which the strain is converted into resistance. But since the energy from the strained element is very small, the energy for the output is provided by an external power supply.

Passive Transducers

In Passive Transducers, the energy from the input is directly converted into the output. For example, a Thermocouple is a passive transducer, where the heat energy, which is absorbed from input, is converted into electrical signals (voltage).



Different Types of Transducers

Basically, the two different types of Transducers are Mechanical Transducers and Electrical Transducers. Mechanical Transducers are those which responds to changes in physical quantities or condition with mechanical quantity. If the physical quantity is converted to an electrical quantity, then the transducers are Electrical Transducers.

Mechanical Transducers

As mentioned earlier, mechanical transducers are a set of primary sensing elements that respond to changes in a physical quantity with a mechanical output. As an example, a Bimetallic Strip is a mechanical Transducer, which reacts to changes in temperature and responds with mechanical displacement. The mechanical transducers are differentiated from electrical transducers as their output signals are mechanical.

The output mechanical quantity can be anything like displacement, force (or torque), pressure and strain. For any measuring quantity, there can be both mechanical and electrical transducers.

For example, we have seen Bimetallic Strip, which is a mechanical transducer and is used to react to changes in temperature. In contrast, a Resistance Thermometer, also reacts to changes in temperature, but the response is a change in resistance of the element. Hence, it is an electrical transducer.

The following table shows a small list of mechanical transducers for measuring different quantities and responds with mechanical signal.

Quantity to be Measured	***Mechanical Transducer***	***Type of Output Signal (Mechanical)***
Temperature	Bimetallic Strip	Displacement and Force
	Fluid Expansion	Displacement and Force
Pressure	Ring Balance Manometer	Displacement
	Metallic Diaphragms	Displacement and Strain
	Capsules and Bellows	Displacement
	Membranes	Displacement
Force	Spring Balance	Displacement and Strain
	Hydraulic Load Cell	Pressure

Torque	Column Load Cell Dynamometer	Displacement and Strain Force and Strain
	Gyroscope	Displacement
	Spiral Springs	Displacement
	Torsion Bar	Displacement and Strain
Flow Rate	Flow Obstruction Element	Strain and Pressure
	Pitot Tube	Pressure
Liquid Level	Manometer	Displacement
	Float Elements	Displacement, Force and Strain

Electrical Transducers

As mentioned earlier, electrical transducers are those that respond to changes in physical quantities with electrical outputs. Electrical Transducers are further divided into Passive Electrical Transducers and Active Electrical Transducers.

The following table lists out a few electrical transducers (both passive and active).

Passive Electrical Transducers	Resistive Transducers	Resistance Thermometers
		Resistive Displacement Transducers
		Resistive Strain Transducers
		Resistive Pressure Transducers
		Resistive Moisture Transducers
	Capacitive Transducers	Capacitive Moisture Transducers
		Capacitive Displacement Transducers
		Capacitive Thickness Transducers
	Inductive Transducers	Inductive Displacement Transducers
		Inductive Thickness Transducers
		Eddy-Current Inductive Transducers
		Moving core Inductive Transducers

Active Electrical Transducers	Photoelectric Transducers	Photoconductive Transducers Photoemissive Transducers
		Photovoltaic Force Transducers
	Piezoelectric Transducers	Piezoelectric Strain Transducers
		Piezoelectric Acceleration Transducers
		Piezoelectric Pressure Transducers
		Piezoelectric Torque Transducers
		Piezoelectric Force Transducers
	Magnetostrictive Transducers	Magnetostrictive Acceleration Transducers
		Magnetostrictive Force Transducers
		Magnetostrictive Torsion Transducers
	Electromechanical Transducers	Tachometers
		Electrodynamic Pressure Transducers
		Electrodynamic Vibration Transducers
		Electromagnetic Flowmeters
	Ionization Transducers	Ionization Vacuum Gauge Ionization Displacement Transducers
		Nuclear Radiation Transducers
		Radioactive Vacuum Gauge
		Radioactive Level Gauge
		Radioactive Thickness Gauge
	Electrochemical Transducers	
	Hall-Effect Transducers	
	Thermoelectric Transducers	

Applications of Transducers

Electromagnetic

- Antennas
- Hall-Effect Sensors
- Disk Read and Write Heads
- Magnetic Cartridges

Electromechanical

- Accelerometers
- Pressure Sensors
- Galvanometers
- LVDT
- Load Cells
- Potentiometers
- MEMS
- Linear and Rotary Motors
- Air Flow Sensors

Electrochemical

- Hydrogen Sensors
- Oxygen Sensors
- pH Meters

Electroacoustic

- Speakers (Loudspeakers, earphones)
- Microphones
- Ultrasonic Transceivers
- Piezoelectric Crystals
- Sonar
- Tactile Transducers

Photoelectric

- LED
- Photodiodes
- Photovoltaic Cells
- Laser Diodes
- Photoresistors (LDR)
- Phototransistors
- Incandescent and Fluorescent Lamps

Thermoelectric

- Thermistors
- Thermocouples
- RTD (Resistance Temperature Detectors)

Radioacoustic

- Radio Transmitters and Receivers
- G-M Tube (Geiger-Muller Tube)

Selection criteria of transducer:

The following factors are to be considered while selecting a transducer for further applications,

- **Operating Principle :** The transducers are selected on the basis of operating principle it may be resistive, inductive, capacitive, optical etc.
- **Operating range :** The range of transducer should be appropriate for measurement to get a good resolution.
- **Accuracy :** The accuracy should be as high as possible or as per the measurement.
- **Range :** The transducer can give good result within its specified range, so select transducer as per the operating range.
- **Sensitivity :** The transducer should be more sensitive to produce the output or sensitivity should be as per requirement.
- **Loading effect :** The transducer's input impedance should be high and output impedance should be low to avoid loading effect.

- **Errors :** The error produced by the transducer should be low as possible.
- **Environmental compatibility :** The transducer should maintain input and output characteristic for the selected environmental condition.

Characteristics of Transducers

The performance characteristics of a Transducer are key in selecting the best suitable transducer for a particular design. So, it is very important to know the characteristics of transducers for proper selection.

Performance characteristics of transducers can be further classified into two types:

- Static Characteristics
- Dynamic Characteristics

Static Characteristics

The static characteristics of a transducer is a set of performance criteria that are established through static calibration i.e. description of the quality of measurement by essentially maintaining the measured quantities as constant values of varying very slowly.

Following is a list of some of the important static characteristics of transducers.

- Sensitivity
- Linearity
- Resolution
- Precision (Accuracy)
- Span and Range
- Threshold
- Drift

- Stability
- Responsiveness
- Repeatability
- Input Impedance and Output Impedance

Dynamic Characteristics

The dynamic characteristics of transducers relate to its performance when the measured quantity is a function of time i.e. it varies rapidly with respect to time.

While static characteristics relate to the performance of a transducer when the measured quantity is essentially constant, the dynamic characteristics relate to dynamic inputs, which means that they are dependent on its own parameters as well as the nature of the input signal.

The following are some dynamic characteristics that may be considered in selection of a transducer.

- Dynamic Error
- Fidelity
- Speed of Response
- Bandwidth

Overall, both static and dynamic characteristics of a Transducer determine its performance and indicate how effectively it can accept desired input signals and reject unwanted inputs.

Chapter-2

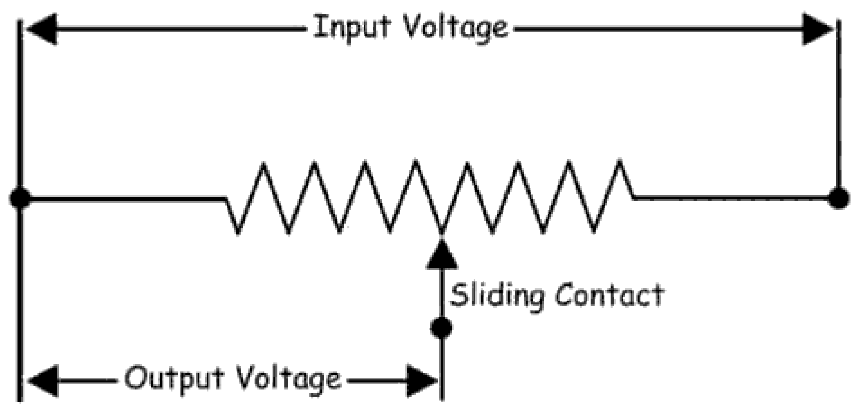
Resistive Transducer

What is a Potentiometer?

A **potentiometer** (also known as a **pot** or **pot meter**) is defined as a 3 terminal variable resistor in which the resistance is manually varied to control the flow of electric current. A potentiometer acts as an adjustable voltage divider.

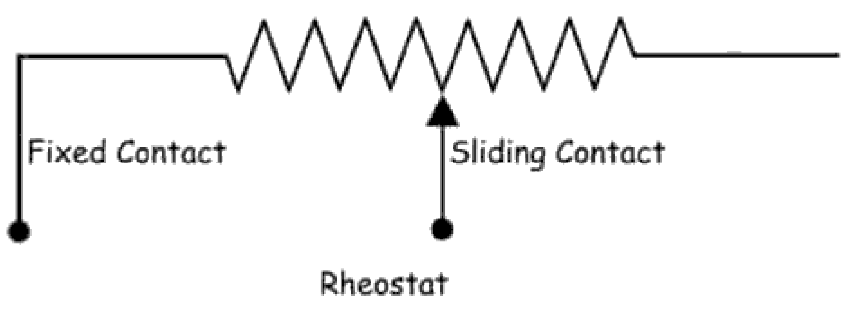
How Does a Potentiometer Work?

A potentiometer is a passive electronic component. Potentiometers work by varying the position of a sliding contact across a uniform resistance. In a potentiometer, the entire input voltage is applied across the whole length of the resistor, and the output voltage is the voltage drop between the fixed and sliding contact as shown below.

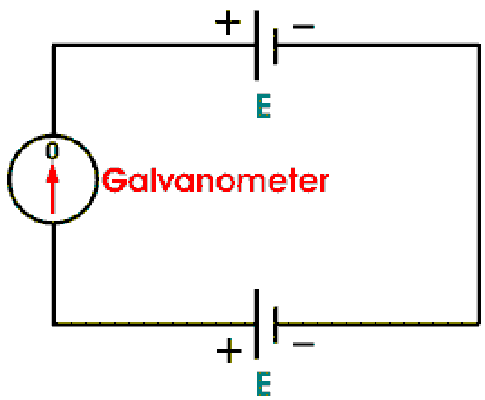


A potentiometer has the two terminals of the input source fixed to the end of the resistor. To adjust the output voltage the sliding contact gets moved along the resistor on the output side.

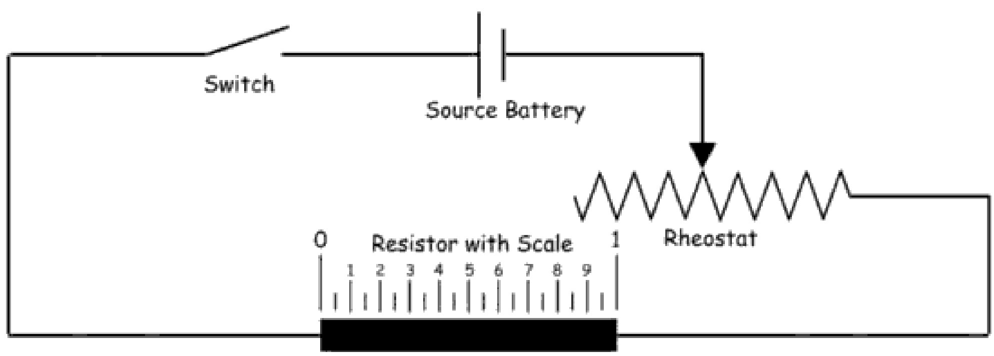
This is different to a rheostat, where here one end is fixed and the sliding terminal is connected to the circuit, as shown below.

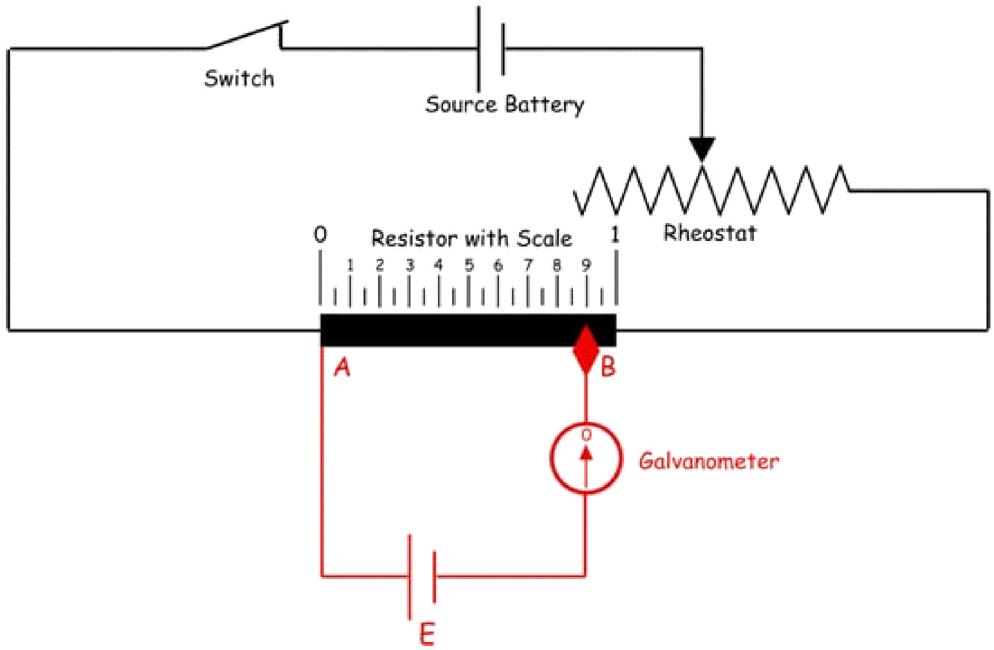


This is a very basic instrument used for comparing the emf of two cells and for calibrating ammeter, voltmeter, and watt-meter. The basic **working principle of a potentiometer** is quite simple. Suppose we have connected two batteries in parallel through a galvanometer. The negative battery terminals are connected together and positive battery terminals are also connected together through a galvanometer as shown in the figure below.



Here, if the electric potential of both battery cells is exactly the same, there is no circulating current in the circuit and hence the galvanometer shows null deflection. The **working principle of potentiometer** depends upon this phenomenon.





Now let's think about another circuit, where a battery is connected across a resistor via a switch and a rheostat as shown in the figure below.

The resistor has the uniform electrical resistance per unit length throughout its length. Hence, the voltage drop per unit length of the resistor is equal throughout its length. Suppose, by adjusting the rheostat we get v volt voltage drop appearing per unit length of the resistor.

Now, the positive terminal of a standard cell is connected to point A on the resistor and the negative terminal of the same is connected with a galvanometer. The other end of the galvanometer is in contact with the resistor via a sliding contact as shown in the figure above. By adjusting this sliding end, a point like B is found where there is no current through the galvanometer, hence no deflection in the galvanometer.

That means, emf of the standard cell is just balanced by the voltage appearing in the resistor across points A and B. Now if the distance between points A and B is L, then we can write emf of standard cell E = Lv volt.

This is how a potentiometer measures the voltage between two points (here between A and B) without taking any current component from the circuit. This is the specialty of a potentiometer, it can measure voltage most accurately.

Potentiometer Types

There are two main types of potentiometers:

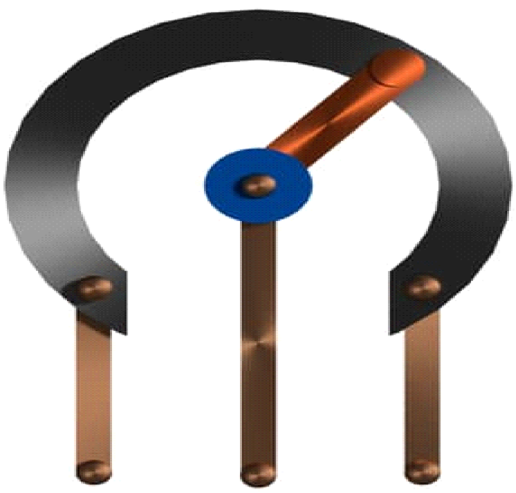
- Rotary potentiometer
- Linear potentiometer

Although the basic constructional features of these potentiometers vary, the working principle of both of these types of potentiometers is the same.

Note that these are types of DC potentiometers – the types of AC potentiometers are slightly different.

Rotary Potentiometers

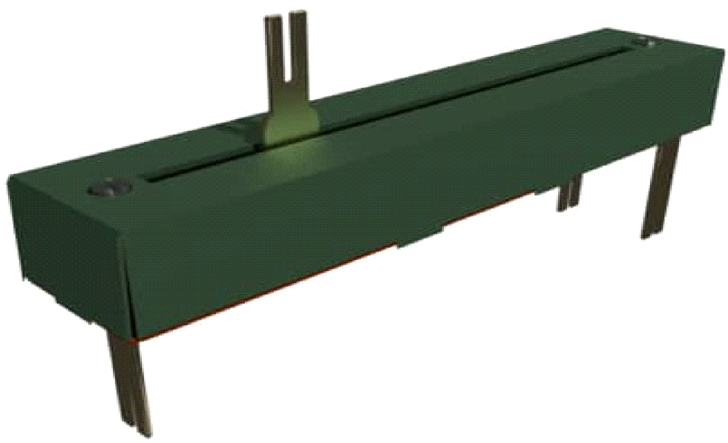
The rotary type potentiometers are used mainly for obtaining adjustable supply voltage to a part of electronic circuits and electrical circuits. The volume controller of a radio transistor is a popular example of a rotary potentiometer where the rotary knob of the potentiometer controls the supply to the amplifier.



This type of potentiometer has two terminal contacts between which a uniform resistance is placed in a semi-circular pattern. The device also has a middle terminal which is connected to the resistance through a sliding contact attached with a rotary knob. By rotating the knob one can move the sliding contact on the semi-circular resistance. The voltage is taken between a resistance end contact and the sliding contact. The potentiometer is also named as the POT in short. POT is also used in substation battery chargers to adjust the charging voltage of a battery. There are many more uses of rotary type potentiometer where smooth voltage control is required.

Linear Potentiometers

The linear potentiometer is basically the same but the only difference is that here instead of rotary movement the sliding contact gets moved on the resistor linearly. Here two ends of a straight resistor are connected across the source voltage. A sliding contact can be slide on the resistor through a track attached along with the resistor. The terminal connected to the sliding is connected to one end of the output circuit and one of the terminals of the resistor is connected to the other end of the output circuit.



This type of potentiometer is mainly used to measure the voltage across a branch of a circuit, for measuring the internal resistance of a battery cell, for comparing a battery cell with a standard cell and in our daily life, it is commonly used in the equalizer of music and sound mixing systems.

Applications of Potentiometer

There are many different uses of a potentiometer. The three main applications of a potentiometer are:

- Comparing the emf of a battery cell with a standard cell
- Measuring the internal resistance of a battery cell
- Measuring the voltage across a branch of a circuit

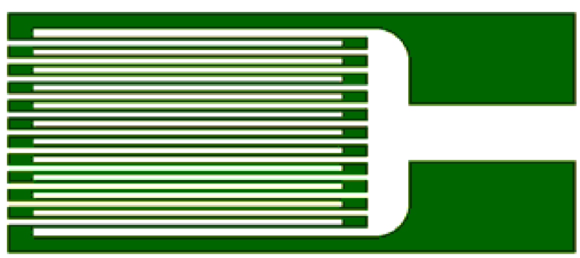
What is a Strain Gauge

A **strain gauge** is a resistor used to measure strain on an object. When an external force is applied on an object, due to which there is a deformation occurs in the shape of the object. This deformation in the shape is both compressive or tensile is called strain, and it is measured by the strain gauge. When an object deforms within the limit of elasticity, either it becomes narrower and longer or it become shorter and broadens. As a result of it, there is a change in resistance end-to-end.

The strain gauge is sensitive to that small changes occur in the geometry of an object. By measuring the change in resistance of an object, the amount of induced stress can be calculated.

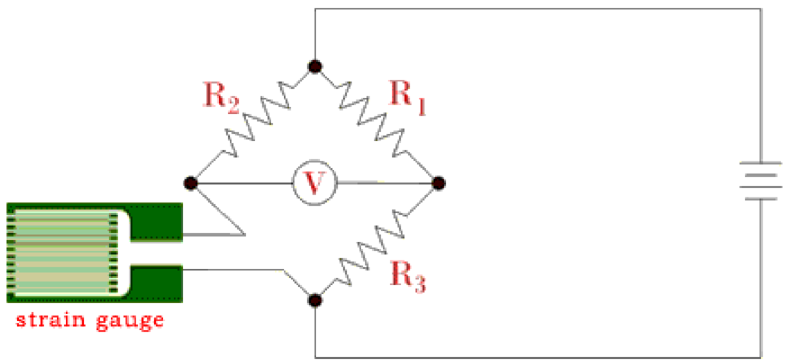
The change in resistance normally has very small value, and to sense that small change, strain gauge has a long thin metallic strip arrange in a zigzag pattern on a non-conducting material called the carrier, as shown below, so that it can enlarge the small amount of stress in the group of parallel lines and could be measured with high accuracy. The gauge is literally glued onto the device by an adhesive.

When an object shows physical deformation, its electrical resistance gets change and that change is then measured by gage.



Strain Gauge Bridge Circuit

Strain gauge bridge circuit shows the measured stress by the degree of discrepancy, and uses a voltmeter in the center of the bridge to provide an accurate measurement of that imbalance:



Quarter-bridge strain gauge circuit

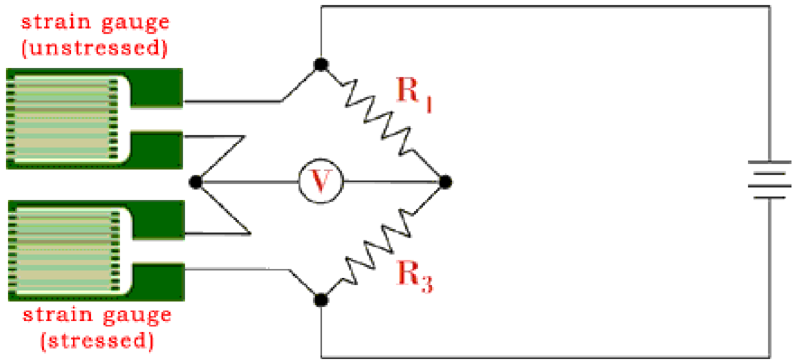
In this circuit, R_1 and $R_3$are the ratio arms equal to each other, and R_2 is the rheostat arm has a value equal to the strain gage resistance. When the gauge is unstrained, the bridge is balanced, and voltmeter shows zero value. As there is a change in resistance of strain gauge, the bridge gets unbalanced and producing an indication at the voltmeter. The output voltage from the bridge can be amplified further by a differential amplifier.

Variation of Temperature of Strain Gauge

One more factor that affects the resistance of the gauge is temperature. If the temperature is more resistance will be more and if the temperature is less the resistance will be less. This is a common property of all the conductors. We can overcome this problem by using strain gauges that are self- temperature-compensated or by a dummy strain gauge technique.

Most of the strain gauges are made of constantan alloy which cancel out the effect of temperature on the resistance. But some strain gauges are not of an isoelastic alloy. In such cases, dummy gauge is used in the place of R_2 in the quarter bridge strain gauge circuit which acts as a temperature compensation device.

Whenever temperature changes, the resistance will change in the same proportion in the both arms of the rheostat, and the bridge remains in the state of balance. Effect of temperature get nullifies. It is good to keep voltage low so that the self-heating of **strain gauge** could be evaded. Self-heating of gauge depends upon its mechanical behavior.



Quarter-bridge strain gauge circuit
with temperature compensation

This arrangement is considered as quarter-bridge. There are two more arrangements half-bridge and full-bridge configurations which give greater sensitivity over the quarter-bridge circuit. Still the quarter-bridge circuit is widely used in strain measurement systems.

Use of Strain Gauge

- In the field of mechanical engineering development.
- To measure the stress generated by machinery.
- In the field of component testing of aircraft like; linkages, structural damage etc.

Hot Wire Anemometer

Definition: The Hot Wire Anemometer is a device used for measuring the velocity and direction of the fluid. This can be done by measuring the heat loss of the wire which is placed in the fluid stream. The wire is heated by electrical current.

The hot wire when placed in the stream of the fluid, in that case, the heat is transferred from wire to fluid, and hence the temperature of wire reduces. The resistance of wire measures the flow rate of the fluid.

The hot wire anemometer is used as a research tool in fluid mechanics. It works on the principle of transfer of heat from high temperature to low temperature.

Construction of Hot Wire Anemometer

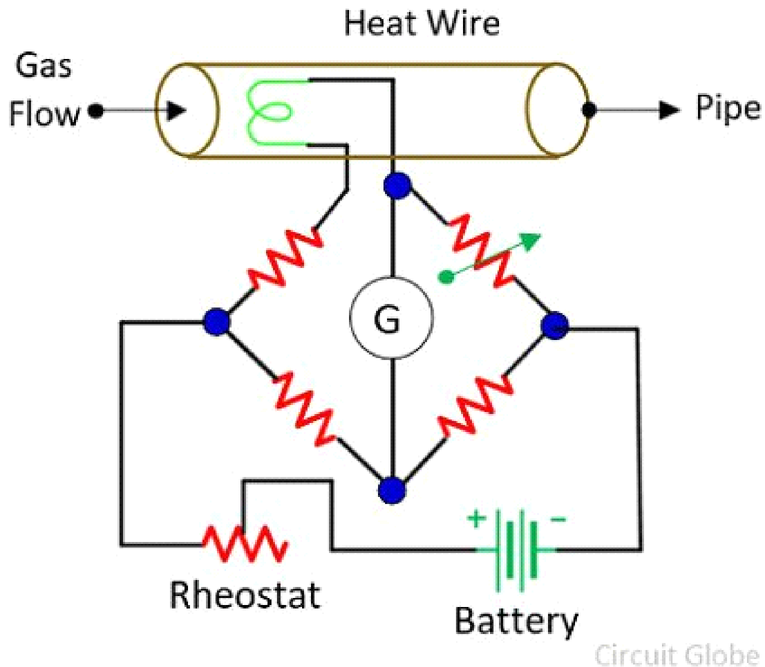
The hot wire anemometer consists two main parts.

- Conducting wire
- Wheat stone bridge.

The conducting wire is housed inside the ceramic body. The wires are taking out from the ceramic body and connecting to the Wheatstone bridge. The wheat stone bridge measures the variation of resistance.

Constant Current Method

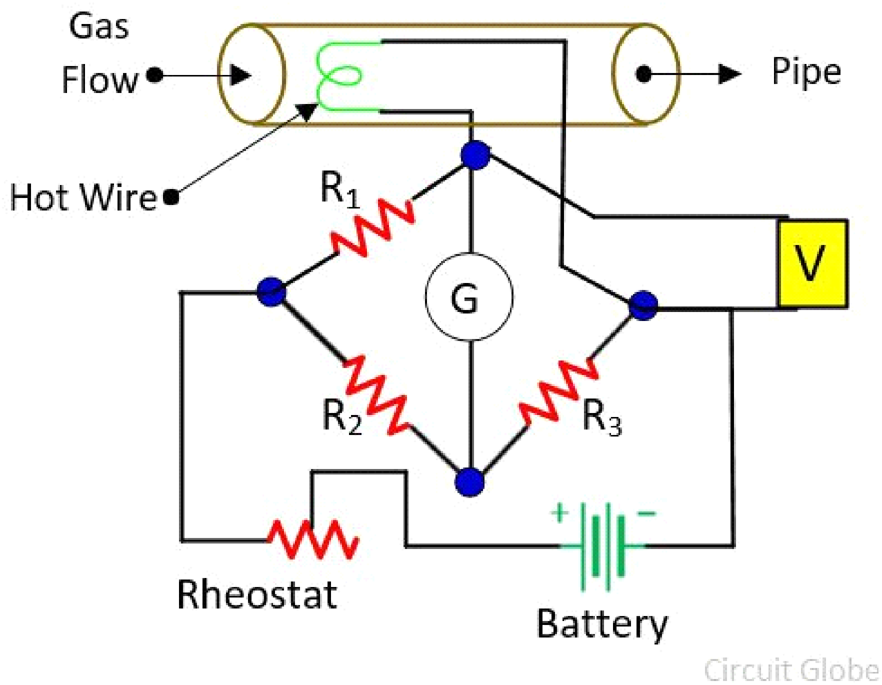
In the constant current method, the anemometer is placed in the stream of the fluid whose flow rate needs to be measured. The current of constant magnitude is passed through the wire. The Wheatstone bridge is also kept on the constant voltage.



When the wire is kept in the stream of liquid, in that case, the heat is transferred from the wire to the fluid. The heat is directly proportional to the resistance of the wire. If heat reduces, that means the resistance of wire also reduces. The Wheatstone bridge measures the variation in resistance which is equal to the flow rate of the liquid.

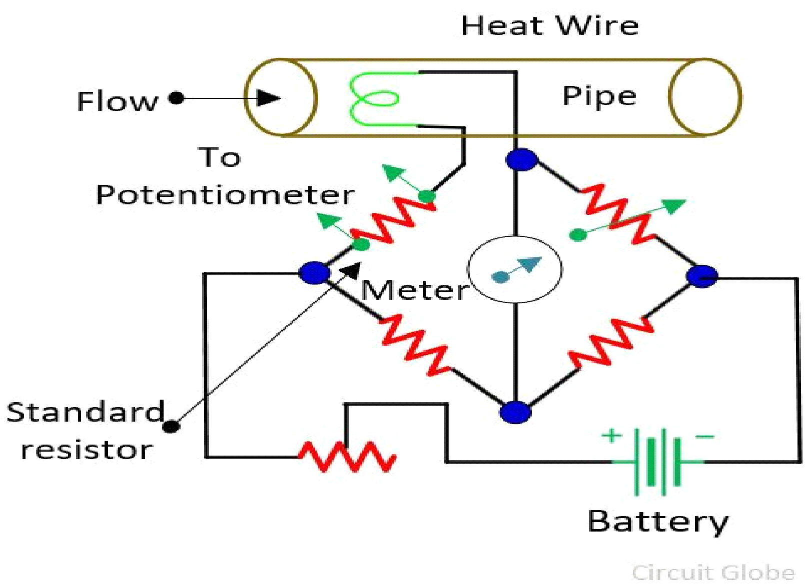
Constant Temperature Method

In this arrangement, the wire is heated by the electric current. The hot wire when placed in the fluid stream, the heat transfer from wire to the fluid. Thus, the temperature of the wire changes which also changes their resistance. It works on the principle that the temperature of the wire remains constant. The total current requires to bring the wire in the initial condition is equal to the flow rate of the gas.



Measurement of the rate of a fluid using a Hot Wire Instrument

In hot wire anemometer, the heat transferred electrically to the wire which is placed in the fluid stream. The Wheatstone bridge is used for measuring the temperature of wire regarding their resistance. The temperature of the wire remains constant for measuring the heating current. Thus, the bridge remains balanced.



The standard resistor is connected in series with the heating wire. The current across the wire is determined by knowing the voltage drop across the resistor. And the value of voltage drop is determined by the potentiometer.

The equation determines the heat loss from the heated wire

$$= a(vp + b)^{1/2} J/s$$

Where, v – velocity of heat flow,
ρ – the density of fluid,

The a and b are the constants. Their value depends on the dimension and the physical properties of the fluid and wire.

Suppose I, is the current of the wire and the R is their resistance. In equilibrium condition,

Heat generated = Heat Lost

$$I^2R = a(vp + b)^{1/2}$$

$$v = \frac{\left(I^2R/_{a^2} - b\right)}{\rho}$$

The resistance and temperature of the instrument are kept constant for measuring the rate of the fluid by measuring the current I.

Thermistor

The **Thermistor** is another type of temperature sensor, whose name is a combination of the words THERM-ally sensitive res-ISTOR. A thermistor is a special type of resistor which changes its physical resistance when exposed to changes in temperature.

Thermistor

Thermistors are generally made from ceramic materials such as oxides of nickel, manganese or cobalt coated in glass which makes them easily damaged. Their main advantage over snap-action types is their speed of response to any changes in temperature, accuracy and repeatability.

Most types of thermistor's have a *Negative Temperature Coefficient* of resistance or *(NTC)*, that is their resistance value goes DOWN with an increase in the temperature, and of course there are some which have a *Positive Temperature Coefficient, (PTC)*, in that their resistance value goes UP with an increase in temperature.

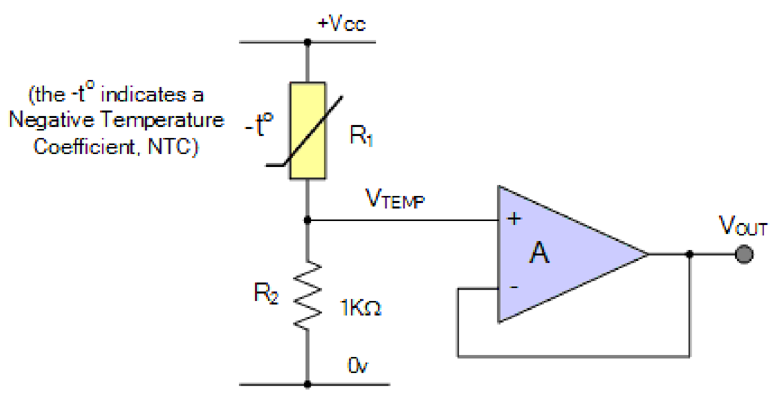
Thermistors are constructed from a ceramic type semiconductor material using metal oxide technology such as manganese, cobalt and nickel, etc. The semiconductor material is generally formed into small pressed discs or balls which are hermetically sealed to give a relatively fast response to any changes in temperature.

Thermistors are rated by their resistive value at room temperature (usually at 25^{o}C), their time constant (the time to react to the temperature change) and their power rating with respect to the current flowing through them. Like resistors, thermistors are available with resistance values at room temperature from 10's of MΩ down to just a few Ohms, but for sensing purposes those types with values in the kilo-ohms are generally used.

Thermistors are passive resistive devices which means we need to pass a current through it to produce a measurable voltage output. Then thermistors are generally connected in series with a suitable biasing resistor to form a potential divider network and the choice of resistor gives a voltage output at some pre-determined temperature point or value for example:

Temperature Sensors Example No1

The following thermistor has a resistance value of 10KΩ at 25^{o}C and a resistance value of 100Ω at 100^{o}C. Calculate the voltage drop across the thermistor and hence its output voltage (Vout) for both temperatures when connected in series with a 1kΩ resistor across a 12v power supply.



At **25^{o}C**

$$Vout = \frac{R_2}{R_1 + R_2} xV = \frac{1000}{10000 + 1000} x12v = 1.09v$$

At **100°C**

$$Vout = \frac{R_2}{R_1 + R_2} xV = \frac{1000}{100+1000} x12v = 10.9v$$

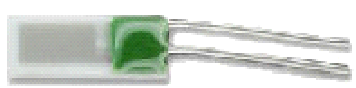
By changing the fixed resistor value of R2 (in our example 1kΩ) to a potentiometer or preset, a voltage output can be obtained at a predetermined temperature set point for example, 5v output at 60°C and by varying the potentiometer a particular output voltage level can be obtained over a wider temperature range.

It needs to be noted however, that thermistor's are non-linear devices and their standard resistance values at room temperature is different between different thermistor's, which is due mainly to the semiconductor materials they are made from. The **Thermistor**, have an exponential change with temperature and therefore have a Beta temperature constant (β) which can be used to calculate its resistance for any given temperature point.

However, when used with a series resistor such as in a voltage divider network or Wheatstone Bridge type arrangement, the current obtained in response to a voltage applied to the divider/bridge network is linear with temperature. Then, the output voltage across the resistor becomes linear with temperature.

Resistive Temperature Detectors (RTD)

Another type of electrical resistance temperature sensor is the **Resistance Temperature Detector** or **RTD**. RTD's are precision temperature sensors made from high-purity conducting metals such as platinum, copper or nickel wound into a coil and whose electrical resistance changes as a function of temperature, similar to that of the thermistor. Also available are thin-film RTD's. These devices have a thin film of platinum paste is deposited onto a white ceramic substrate.



A Resistive RTD

Resistive temperature detectors have positive temperature coefficients (PTC) but unlike the thermistor their output is extremely linear producing very accurate measurements of temperature.

However, they have very poor thermal sensitivity, that is a change in temperature only produces a very small output change for example, 1Ω/°C.

The more common types of RTD's are made from platinum and are called **Platinum Resistance Thermometer** or **PRT**'s with the most commonly available of them all the Pt100 sensor, which has a standard resistance value of 100Ω at 0°C. The downside is that Platinum is expensive and one of the main disadvantages of this type of device is its cost.

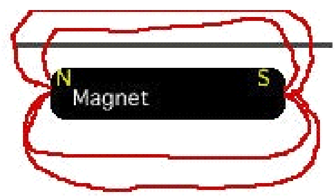
Like the thermistor, RTD's are passive resistive devices and by passing a constant current through the temperature sensor it is possible to obtain an output voltage that increases linearly with temperature. A typical RTD has a base resistance of about 100Ω at 0°C, increasing to about 140Ω at 100°C with an operating temperature range of between -200 to +600°C.

Because the RTD is a resistive device, we need to pass a current through them and monitor the resulting voltage. However, any variation in resistance due to self heat of the resistive wires as the current flows through it, I^2R , (Ohms Law) causes an error in the readings. To avoid this, the RTD is usually connected into a Wheatstone Bridge network which has additional connecting wires for lead-compensation and/or connection to a constant current source.

Pick UP

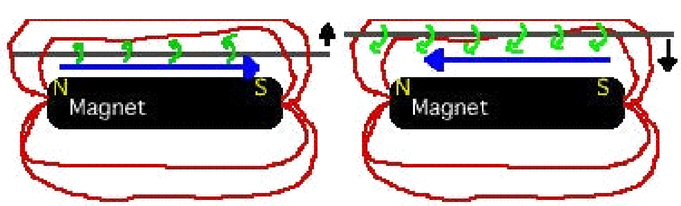
When a transducer mounted in a more complicated device, the transducer becomes a pickup.

A pickup contains a permanent magnet and magnetic coils. The magnet is placed underneath the metal guitar strings so that when the strings vibrate, they move through the magnetic field.



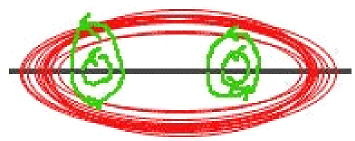
Drawing of magnetic field around a permanent magnet.

When the metal wire moves through the magnetic field, a current is generated in the wire. This current, in turn, creates a magnetic field surrounding the wire. The flow of the current, and thus the resulting magnetic field, depends on the direction that the string is moving in the magnetic field generated by the magnet. Because the string moves back and forth (just as does a rubber band if you stretch it and pluck it), the magnetic field created by the wire constantly changes direction.



Left image: Drawing of string moving rightward through a magnetic field. Right image: Drawing of string moving leftward through a magnetic field.

Changing magnetic fields induce currents in wires; the changing magnetic field created by the metal guitar string, therefore, creates a current in the magnetic coils that compose the other part of the pickup.



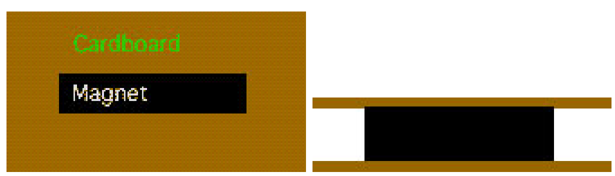
Changing magnetic fields around the guitars pickup.

The current (and voltage) that is produced in the wire coils is transmitted to a speaker system through the circuitry of the guitar; this circuitry is described later in the lab. So now that we know how an electric guitar pickup works, it is time to describe how to build one.

For materials, you need:

- A 4.5 x 2 cm bar magnet
- Two 8 x 11 cm pieces of cardboard
- A large spool of coiling wire; 175 to 200 meters
- Glue (I used wood glue, although the exact type probably doesn't matter too much)
- Packing tape
- A small piece of sand paper

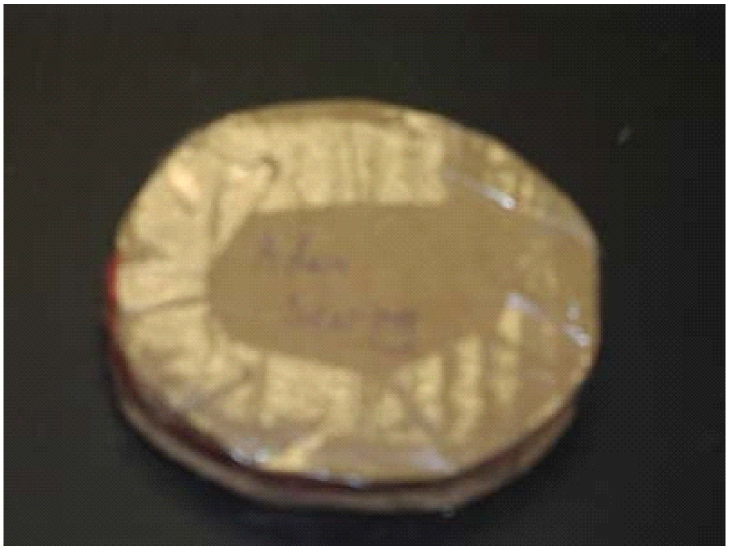
First, glue the magnet into the center of one of the two pieces of cardboard, and glue the other piece of cardboard onto the other side of the magnet so that you have a magnet sandwich.



Left image: Overhead view of the magnet on the cardboard. Right image: Side view of the magnet sandwich.

The magnet need not be perfectly in the center, but it should be fairly close; it's safe to eyeball the location, though. After the magnet has been glued in place and the glue has dried, cut a short slit about 1cm in from a corner, to hold the wire temporarily. Measure out 60 cm or so of wire from the spool, and leave it hanging out of the cardboard piece; put the 60 cm mark in the slot that you just cut and start wrapping the wire around the magnet, between the two pieces of cardboard. If the wire gets tangled in the cardboard, just untangle it and wrap over any entanglements made by excess wire. Keep wrapping until the wire starts to bulge out the side of the cardboard; this should take several hundred loops. When you are done, run the wire back out through the slit, and leave another trailing 60cm.

At this point, feel free to artistically trim the corners of the cardboard; just be very careful not to cut the wire. The wire coil must be continuous; otherwise, it will not work. Also, run packing tape over the wire coiling for protection. If you cut off the slit that you made earlier, make sure to take the wire out of it; you can just tape the wires in place afterward. Your final pickup should look something like this:



Photograph of home-built pickup.

Chapter 3

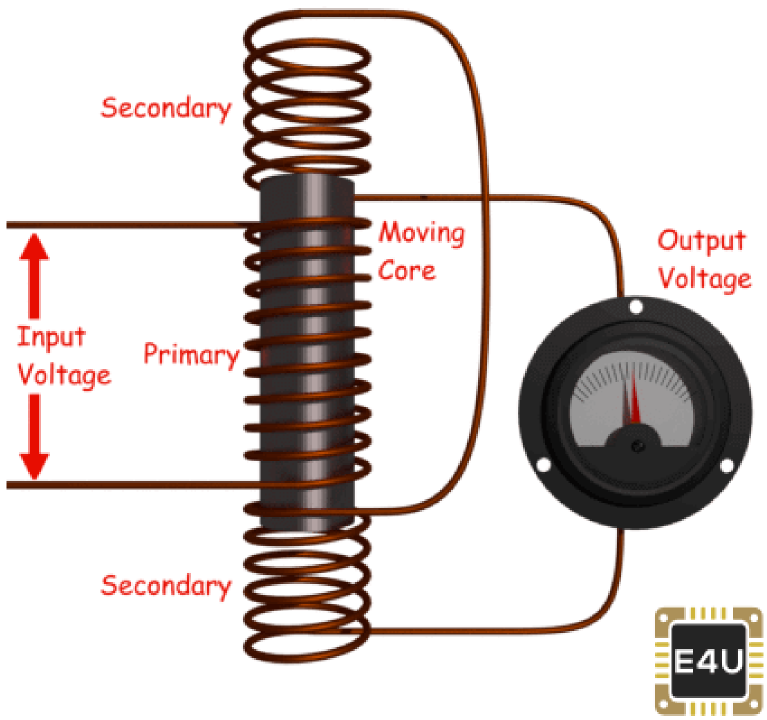
Inductive Transducer

Linear Variable Differential Transformer LVDT

Definition of LVDT

The term **LVDT** stands for the **Linear Variable Differential Transformer**. It is the most widely used inductive transducer that converts the linear motion into the electrical signal.

The output across secondary of this transformer is the differential thus it is called so. It is very accurate inductive transducer as compared to other inductive transducers.

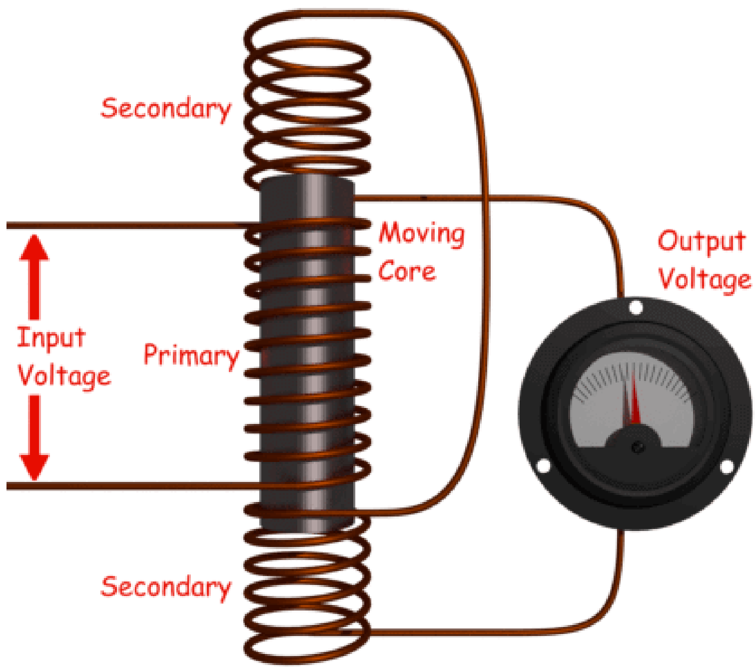


Construction of LVDT

Main Features of Construction

- The transformer consists of a primary winding P and two secondary windings S_1 and S_2 wound on a cylindrical former (which is hollow in nature and contains the core).
- Both the secondary windings have an equal number of turns, and we place them on either side of primary winding
- The primary winding is connected to an AC source which produces a flux in the air gap and voltages are induced in secondary windings.

- A movable soft iron core is placed inside the former and displacement to be measured is connected to the iron core.
- The iron core is generally of high permeability which helps in reducing harmonics and high sensitivity of LVDT.
- The LVDT is placed inside a stainless steel housing because it will provide electrostatic and electromagnetic shielding.
- The both the secondary windings are connected in such a way that resulted output is the difference between the voltages of two windings.



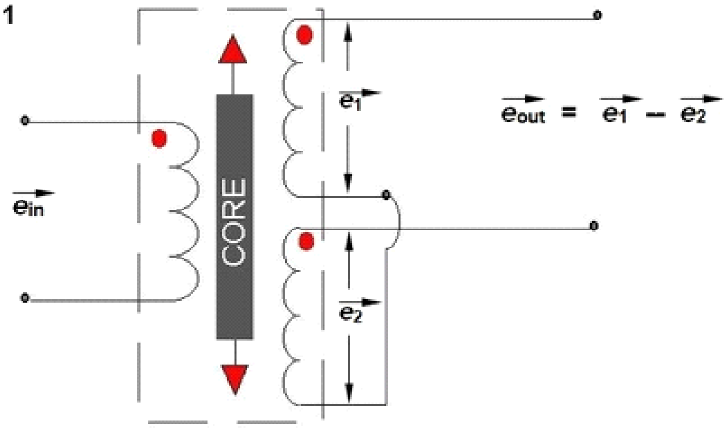
Principle of Operation and Working

As the primary is connected to an AC source so alternating current and voltages are produced in the secondary of the LVDT. The output in secondary S_1 is e_1 and in the secondary S_2 is e_2. So the differential output is,

$e_{out} = e_1 - e_2$

This equation explains the **principle of Operation of LVDT**.

. 1



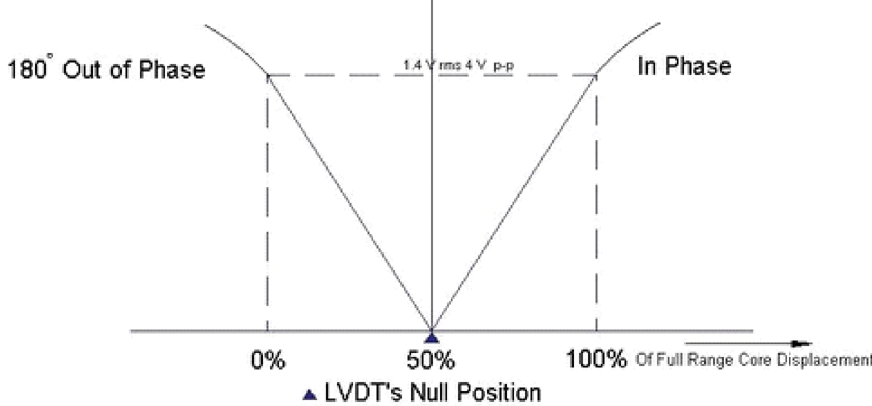
Now three cases arise according to the locations of core which explains the working of LVDT are discussed below as,

- CASE I When the core is at null position (for no displacement) When the core is at null position then the flux linking with both the secondary windings is equal so the induced emf is equal in both the windings. So for no displacement the value of output e_{out} is zero as e_1 and e_2 both are equal. So it shows that no displacement took place.
- CASE II When the core is moved to upward of null position (For displacement to the upward of reference point) In the this case the flux linking with secondary winding S_1 is more as compared to flux linking with S_2. Due to this e_1 will be more as that of e_2. Due to this output voltage e_{out} is positive.
- CASE III When the core is moved to downward of Null position (for displacement to the downward of the reference point). In this case magnitude of e_2 will be more as that of e_1. Due to this output e_{out} will be negative and shows the output to downward of the reference point.

Output V_S Core Displacement A linear curve shows that output voltage varies linearly with displacement of core.

LVDT'S AC Output Magnitude

Fig. 2



AC Output of Conventional LVDT Versus Core Displacement

Some important points about magnitude and sign of voltage induced in LVDT

- The amount of change in voltage either negative or positive is proportional to the amount of movement of core and indicates amount of linear motion.
- By noting the output voltage increasing or decreasing the direction of motion can be determined
- The output voltage of an LVDT is linear function of core displacement.

Advantages of LVDT

- High Range – The LVDTs have a very high range for measurement of displacement. They can used for measurement of displacements ranging from 1.25 mm to 250 mm
- No Frictional Losses – As the core moves inside a hollow former so there is no loss of displacement input as frictional loss so it makes LVDT as very accurate device.
- High Input and High Sensitivity – The output of LVDT is so high that it doesn't need any amplification. The transducer posseses a high sensitivity which is typically about 40V/mm.
- Low Hysteresis – LVDTs show a low hysteresis and hence repeatability is excellent under all conditions
- Low Power Consumption – The power is about 1W which is very as compared to other transducers.
- Direct Conversion to Electrical Signals – They convert the linear displacement to electrical voltage which are easy to process

Disadvantages of LVDT

- LVDT is sensitive to stray magnetic fields so it always requires a setup to protect them from stray magnetic fields.
- LVDT gets affected by vibrations and temperature.

It is concluded that they are advantageous as compared than any other inductive transducer.

Applications of LVDT

- We use LVDT in the applications where displacements to be measured are ranging from a fraction of mm to few cms. The **LVDT** acting as a primary transducer converts the displacement to electrical signal directly.
- The LVDT can also act as a secondary transducer. E.g. the Bourbon tube which acts as a primary transducer and it converts pressure into linear displacement and then LVDT coverts this displacement into an electrical signal which after calibration gives the readings of the pressure of fluid.

Rotary Variable Differential Transformer (RVDT)

Definition: The transformer which **senses** the **angular displacement** of the conductor is **known** as the **Rotary Variable Differential Transformer** or RVDT. It is the type of **electromechanical** transducer which **gives** the **linear output proportional** to the **input angular displacement**.

The circuit of RVDT is shown in the figure below. The working of the RVDT is similar to the LVDT. The only difference is that the LVDT uses the soft iron core for measuring the displacement, whereas the RVDT uses the cam shape core rotated between the primary and secondary winding with the help of the shaft.

Theory of RVDT

The E_{S1} and the E_{S2} are the secondary voltage, and it varies with the angular displacement of the shaft.

$$\theta = G.\left(\frac{E_{S1} - E_{S2}}{E_{S1} + E_{S2}}\right)$$

The G is the sensitivity of the RVDT. The secondary voltage is determined by the help of equation shown below. $E_{S2} = E_{S1} \pm G.\theta$

The difference between $E_{S1} - E_{S2}$ gives a proportional voltage.

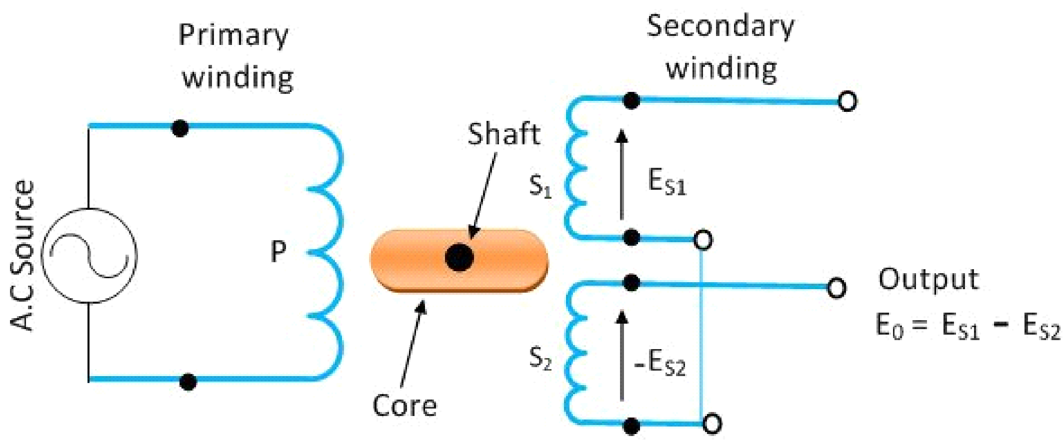
$$\Delta E_s = 2.G.\theta$$

The sum of the voltage is given by constant C.

$$C = \sum E_s = 2.E_{S0}$$

Operation of LVDT

When the core is in the null position, the output voltages of the secondary winding S_1 and S_2 are equal and opposite. The net output of null position is zero. Any angular displacement from the null position will give the differential output voltage. The angular displacement is directly proportional to the differential output voltage. The response of the RVDT is linear.



Rotary Variable Differential Transformer

The differential output voltage of the transformer increases when the shaft rotates in a clockwise direction. And it decreases when the shaft moves in an anti-clockwise direction. The magnitude of the output voltage depends on the angular displacement and the direction of the shaft.

Magnetic Pickups

Magnetic pickups are sensors that detect the speed of a moving part, typically in an engine. When objects like gears or shafts with keyways are passed through the sensor's magnetic field, the field oscillates, which induces in the sensor's coil an AC voltage to be read by an electrical device such as a counter or oscilloscope.

Features of a magnetic pickup

A magnetic pickup is a coil that is wound around a magnetised probe. When objects like gear teeth, turbine rotor blades, slotted discs or shafts pass through the probe's magnetic field, the flux density is modulated, inducing a measurable AC voltage. Magnetic pickups tend to have a high-output voltage that is suitable for use with heavy-duty wiring. They are generally unaffected by dust and dirt, and are sturdier than most other plastic sensors.

What can magnetic pickups be used for?

Magnetic pickups can be used as parts of speedometers or tachometers, which are integral parts of engines and industrial equipment.

Inductive Microphone

A microphone is an essential part of almost any performance or event. Learn more about the different types of microphones and how each works.

Dynamic Microphones

A dynamic microphone converts sounds into an electrical signal via an electromagnetic induction. There are two basic types of dynamic microphones. These are moving-coil dynamic microphones and moving-ribbon dynamic microphones.

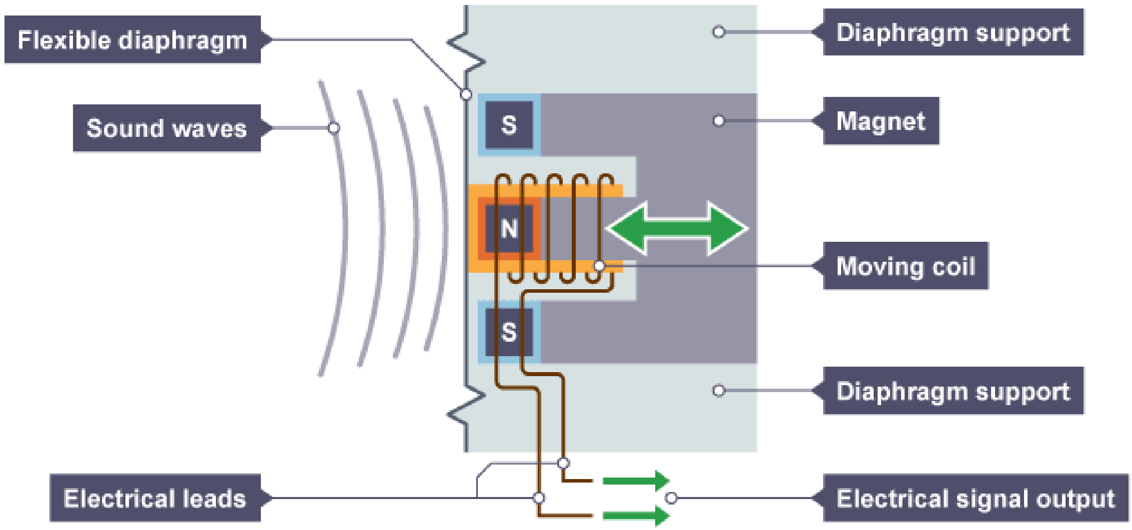
Moving-coil Dynamic Microphones

Moving-coil dynamic microphones are versatile and ideal for general-purpose use. They use a simple design with few moving parts. They are relatively sturdy and resilient to rough handling.

They are robust, relatively inexpensive, and resistant to moisture, and for these reasons they are widely used on-stage. They are usually better suited to handling high sound pressure, such as from close-up vocals, certain musical instruments, and amplifiers. Moving coil dynamic microphones generally have no internal amplifier and do not require batteries or external power.

How Moving-coil Dynamic Microphones Work

When wire is moved within a magnetic field a current is generated in the wire. Using this induction principle, the dynamic microphone uses a wire coil, magnet, and a thin diaphragm to capture the audio signal.



The diaphragm is attached to the coil. When the diaphragm vibrates in response to incoming sound waves, the coil moves backwards and forwards past the magnet. This creates an electrical current in the coil, which is channelled from the microphone along wires.

Moving-ribbon Dynamic Microphones

Moving ribbon dynamic microphones are generally more fragile than a moving-coil microphone and usually spend more time in the studio than on stage. (However, many Trion 7000s have been seen on several high-profile tours.) Ribbon microphones have a mellow sound of their own and work well on brass instruments, guitar cabinets, and other aggressive sources.

How Moving-ribbon Dynamic Microphones Work

Like the moving-coil dynamic microphone, the moving-ribbon dynamic microphone utilizes induction. However, instead of a coil of wire, a thin corrugated aluminum ribbon is suspended in the magnetic field. As this ribbon vibrates sympathetically to impinging sound, an electrical current is generated in the ribbon.

Chapter 4.

Capacitive Transducer

Definition: The capacitive transducer is used for measuring the displacement, pressure and other physical quantities. It is a passive transducer that means it requires external power for operation. The capacitive transducer works on the principle of variable capacitances. The capacitance of the capacitive transducer changes because of many reasons like overlapping of plates, change in distance between the plates and dielectric constant.

The capacitive transducer contains two parallel metal plates. These plates are separated by the dielectric medium which is either air, material, gas or liquid. In the normal capacitor the distance between the plates are fixed, but in capacitive transducer the distance between them are varied.

The capacitive transducer uses the electrical quantity of capacitance for converting the mechanical movement into an electrical signal. The input quantity causes the change of the capacitance which is directly measured by the capacitive transducer.

The capacitors measure both the static and dynamic changes. The displacement is also measured directly by connecting the measurable devices to the movable plate of the capacitor. It works on with both the contacting and non-contacting modes.

Principle of Operation

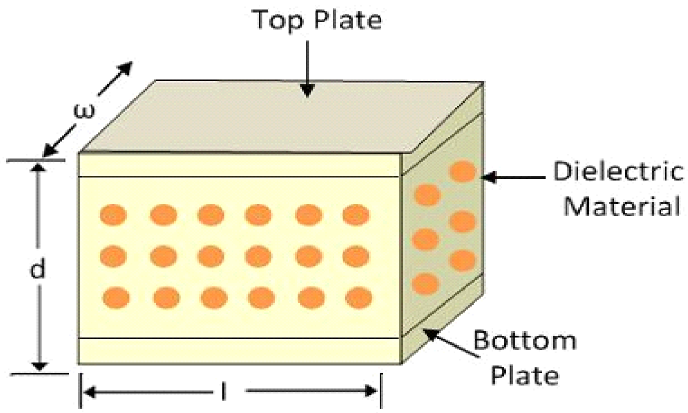
The equations below express the capacitance between the plates of a capacitor

$$C = \varepsilon A/d$$

$$C = \varepsilon_r \varepsilon_0 A/d$$

Where A – overlapping area of plates in m^2
d – the distance between two plates in meter
ε – permittivity of the medium in F/m
ε_r – relative permittivity
ε_0 – the permittivity of free space

The schematic diagram of a parallel plate capacitive transducer is shown in the figure below.



Parallel Plate Capacitive Transducer

The change in capacitance occurs because of the physicals variables like displacement, force, pressure, etc. The capacitance of the transducer also changes by the variation in their dielectric constant which is usually because of the measurement of liquid or gas level.

The capacitance of the transducer is measured with the bridge circuit. The output impedance of transducer is given as $X_c = 1/2\pi f c$

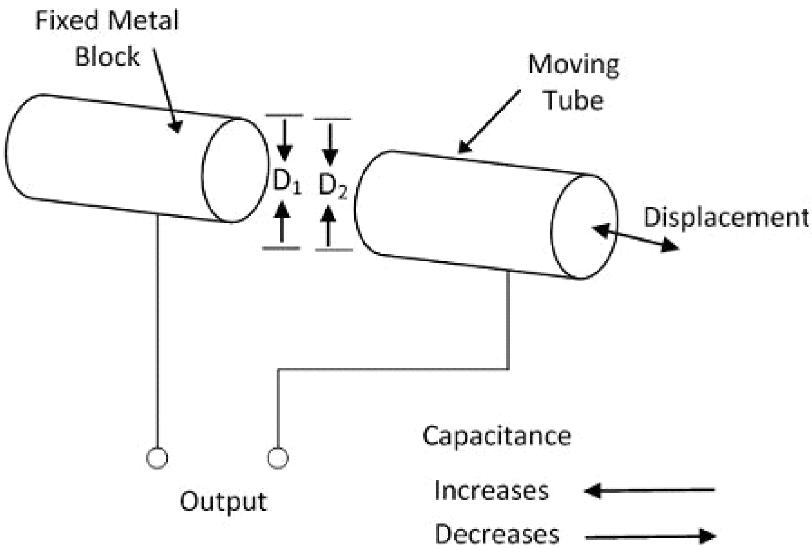
Where, C – capacitance
f – frequency of excitation in Hz.

The capacitive transducer is mainly used for measurement of linear displacement. The capacitive transducer uses the following three effects.

- Variation in capacitance of transducer is because of the overlapping of capacitor plates.
- The change in capacitance is because of the change in distances between the plates.
- The capacitance changes because of dielectric constant.

The following methods are used for the measuring displacement.

1. **A transducer using the change in the Area of Plates** – The equation below shows that the capacitance is directly proportional to the area of the plates. The capacitance changes correspondingly with the change in the position of the plates.



Capacitive Transducer

The capacitive transducers are used for measuring the large displacement approximately from 1mm to several cms. The area of the capacitive transducer changes linearly with the capacitance and the displacement. Initially, the nonlinearity occurs in the system because of the edges. Otherwise, it gives the linear response.

The capacitance of the parallel plates is given as

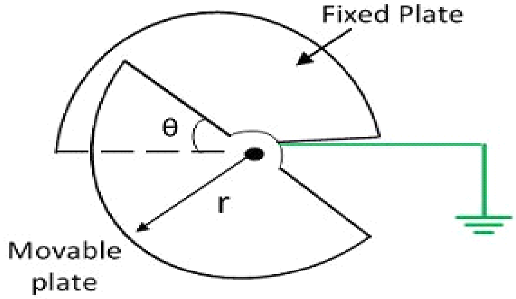
$$C = \frac{\varepsilon A}{d} = \frac{\varepsilon x \omega}{d} F$$

where x – the length of overlapping part of plates
ω – the width of overlapping part of plates.

The sensitivity of the displacement is constant, and therefore it gives the linear relation between the capacitance and displacement.

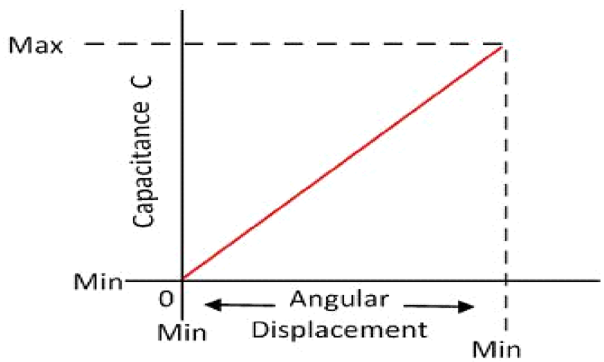
$$S = \frac{\partial C}{\partial x} = \varepsilon \frac{\omega}{d} F/m$$

The capacitive transducer is used for measuring the angular displacement. It is measured by the movable plates shown below. One of the plates of the transducer is fixed,



and the other is movable.

The phasor diagram of the transducer is shown in the figure below.



The angular movement changes the capacitance of the transducers. The capacitance between them is maximum when these plates overlap each other. The maximum value of capacitance is expressed as

$$C_{max} = \frac{\varepsilon A}{d} = \frac{\pi \varepsilon r^2}{2d}$$

The capacitance at angle θ is given expressed as,

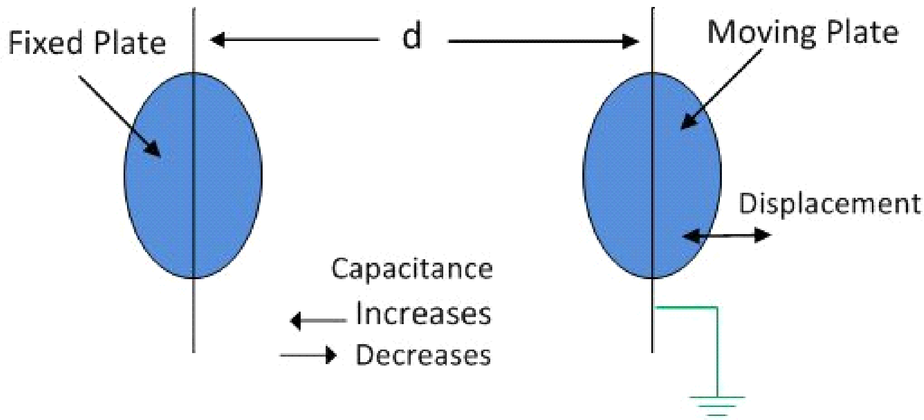
$$C = \frac{\varepsilon \theta r^2}{2d}$$

θ – angular displacement in radian. The sensitivity for the change in capacitance is given as

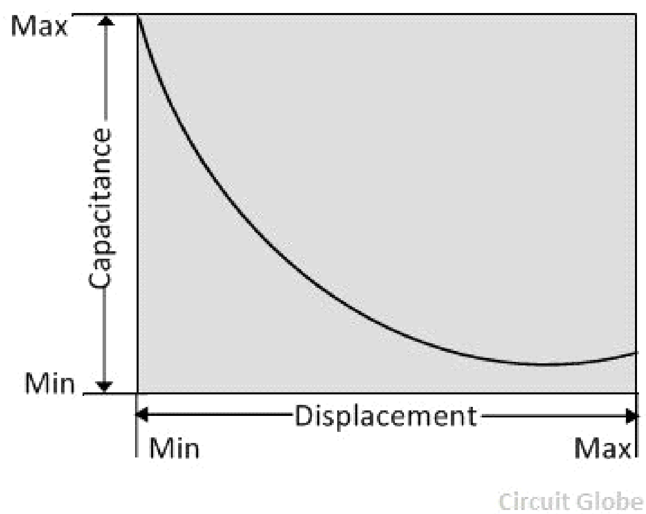
$$S = \frac{\partial C}{\partial \theta} = \frac{\varepsilon r^2}{2d}$$

The 180° is the maximum value of the angular displacement of the capacitor.

2. The transducer using the change in distance between the plates – The capacitance of the transducer is inversely proportional to the distance between the plates. The one plate of the transducer is fixed, and the other is movable. The displacement which is to be measured links to the movable plates.



The capacitance is inversely proportional to the distance because of which the capacitor shows the nonlinear response. Such type of transducer is used for measuring the small displacement. The phasor diagram of the capacitor is shown in the figure below.



The sensitivity of the transducer is not constant and vary from places to places.

Advantage of Capacitive Transducer

The following are the major advantages of capacitive transducers.

- It requires an external force for operation and hence very useful for small systems.
- The capacitive transducer is very sensitive.
- It gives good frequency response because of which it is used for the dynamic study.

- The transducer has high input impedance hence they have a small loading effect.
- It requires small output power for operation.

Disadvantages of capacitive Transducer

The main disadvantages of the transducer are as follows.

- The metallic parts of the transducers require insulation.
- The frame of the capacitor requires earthing for reducing the effect of the stray magnetic field.
- Sometimes the transducer shows the nonlinear behaviours because of the edge effect which is controlled by using the guard ring.
- The cable connecting across the transducer causes an error.

Uses of Capacitive Transducer

The following are the uses of capacitive transducer.

- The capacitive transducer uses for measurement of both the linear and angular displacement. It is extremely sensitive and used for the measurement of very small distance.
- It is used for the measurement of the force and pressures. The force or pressure, which is to be measured is first converted into a displacement, and then the displacement changes the capacitances of the transducer.
- It is used as a pressure transducer in some cases, where the dielectric constant of the transducer changes with the pressure.
- The humidity in gases is measured through the capacitive transducer.
- The transducer uses the mechanical modifier for measuring the volume, density, weight etc.

The accuracy of the transducer depends on the variation of temperature to the high level.

Condenser Microphones

Condenser means *capacitor*, an electronic component which stores energy in the form of an electrostatic field. The term *condenser* is actually obsolete but has stuck as the name for this type of microphone, which uses a capacitor to convert acoustical energy into electrical energy.

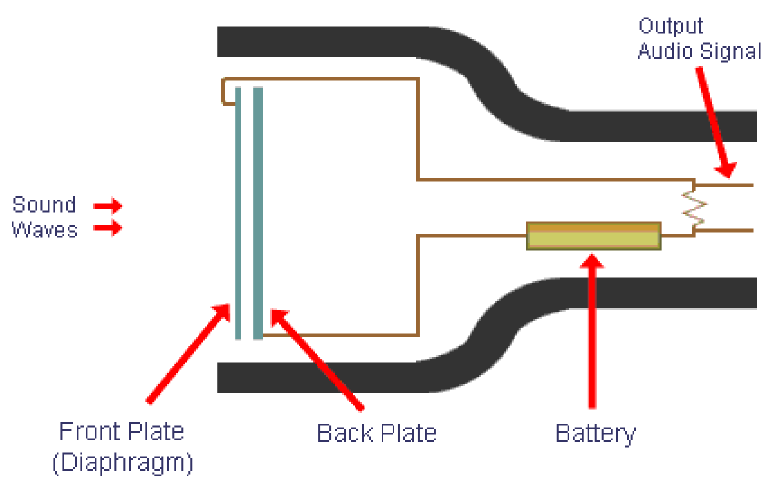
Condenser microphones require power from a battery or external source. The resulting audio signal is stronger signal than that from a dynamic. Condensers also tend to be more sensitive and responsive than dynamics, making them well-suited to capturing subtle nuances in a sound. They are not ideal for high-volume work, as their sensitivity makes them prone to distort.

How Condenser Microphones Work

A capacitor has two plates with a voltage between them. In the condenser mic, one of these plates is made of very light material and acts as the diaphragm. The diaphragm vibrates when struck by sound waves, changing the distance between the two plates and therefore changing the capacitance. Specifically, when the plates are closer together, capacitance increases and a charge current occurs. When the plates are further apart, capacitance decreases and a discharge current occurs.

A voltage is required across the capacitor for this to work. This voltage is supplied either by a battery in the mic or by external phantom power.

Cross-Section of a Typical Condenser Microphone



The Electret Condenser Microphone

The electret condenser mic uses a special type of capacitor which has a permanent voltage built in during manufacture. This is somewhat like a permanent magnet, in that it doesn't require any external power for operation. However good electret condenser mics usually include a pre-amplifier which does still require power.

Other than this difference, you can think of an electret condenser microphone as being the same as a normal condenser.

Technical Notes:

- Condenser microphones have a flatter frequency response than dynamics.
- A condenser mic works in much the same way as an electrostatic tweeter (although obviously in reverse).

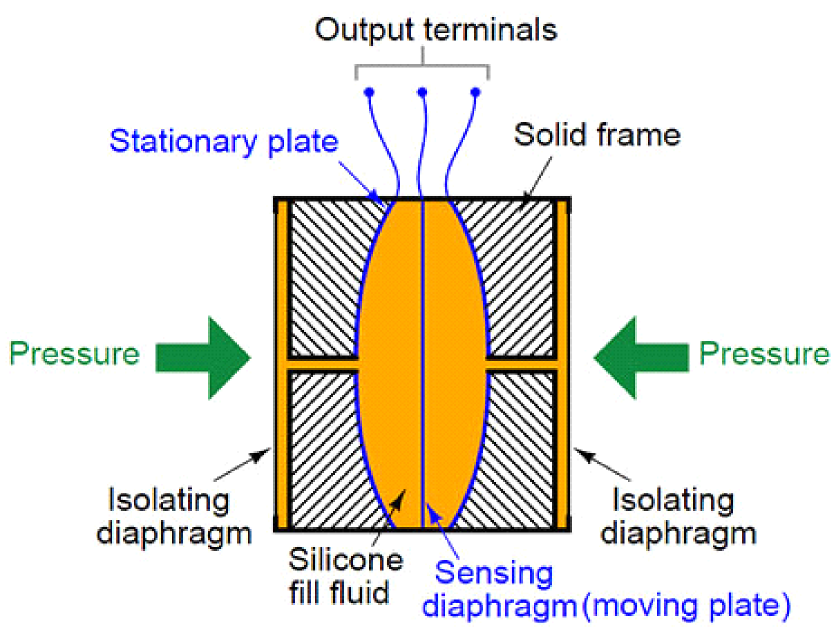
<u>Differential Capacitance Pick up</u>

When a transducer mounted in a more complicated device, the transducer becomes a pickup.

Common electrical pressure sensor design works on the principle of differential capacitance, most of capacitance differential pressure transmitter use it. In this design, the sensing element is a taut metal diaphragm located equidistant between two stationary metal surfaces, comprising three plates for a complementary pair of capacitors. An electrically insulating fill fluid (usually a liquid silicone compound) transfers motion from the isolating diaphragms to the sensing diaphragm, and also doubles as an effective dielectric for the two capacitors:

Eastsensor use three types of fluid compound to fill according to the requirement of measurement process, each has different temperature performance.

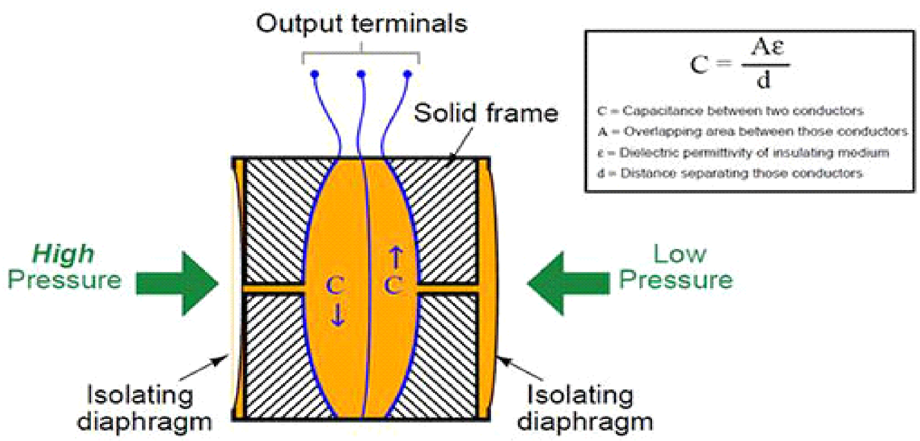
- Silicone Oil 200 Temp. Range -40～149℃
- Modified silicone oil Temp. Range 15～315℃
- Fluorocarbon oil Temp. Range -45～205℃



Any difference of pressure across the cell causes the diaphragm to flex in the direction of least pressure. The sensing diaphragm is a precision-manufactured spring element, meaning that its displacement is a predictable function of applied force. The applied force in this case can only be a function of differential pressure acting against the surface area of the diaphragm in accordance with the standard force-pressure-area equation F = PA.

In this case, we have two forces caused by two fluid pressures working against each other, so our force-pressure-area equation may be rewritten to describe resultant force as a function of differential pressure (P1 − P2) and diaphragm area: F = (P1 − P2)A. Since diaphragm area is constant, and force is predictably related to diaphragm displacement, all we need now in order to infer differential pressure is to accurately measure displacement of the diaphragm.

The diaphragm's secondary function as one plate of two capacitors provides a convenient method for measuring displacement. Since capacitance between conductors is inversely proportional to the distance separating them, capacitance on the low-pressure side will increase while capacitance on the high-pressure side will decrease:



A capacitance detector circuit connected to this cell uses a high-frequency AC excitation signal to measure the different in capacitance between the two halves, translating that into a DC signal which ultimately becomes the signal output by the instrument representing pressure.

These pressure sensors are highly accurate, stable, and rugged. An interesting feature of this design – using two isolating diaphragms to transfer process fluid pressure to a single sensing diaphragm through an internal "fill fluid" – is that the solid frame bounds the motion of the two isolating diaphragms such that neither one is able to force the sensing diaphragm past its elastic limit.

As the illustration shows, the higher-pressure isolating diaphragm gets pushed toward the metal frame, transferring its motion to the sensing diaphragm via the fill fluid. If too much pressure is applied to that side, the isolating diaphragm will merely "flatten" against the solid frame of the capsule and stop moving. This positively limits the isolating diaphragm's motion so that it cannot possibly exert any more force on the sensing diaphragm, even if additional process fluid pressure is applied. This use of isolating diaphragms and fill fluid to transfer motion to the sensing diaphragm, employed in other styles of differential pressure sensor as well, gives modern differential pressure instruments excellent resistance to over-pressure damage.

It should be noted that the use of a liquid fill fluid is key to this overpressure-resistant design. In order for the sensing diaphragm to accurately translate applied pressure into a proportional capacitance, it must not contact the conductive metal frame surrounding it. In order for any diaphragm to be protected against overpressure, however, it must contact a solid backstop to limit further travel. Thus, the need for non-contact (capacitance) and for contact (overpressure protection) are mutually exclusive, making it nearly impossible to perform both functions with a single sensing diaphragm. Using fill fluid to transfer pressure from isolating diaphragms to the sensing diaphragm allows us to separate the function of capacitive measurement (sensing diaphragm) from the function of overpressure protection (isolation diaphragms) so that each diaphragm may be optimized for a separate purpose.

A classic example of a pressure instrument based on the differential capacitance sensor is the Rosemount model 1151 capacitance differential pressure transmitter, shown in assembled form in the following photograph:

Chapter 5.

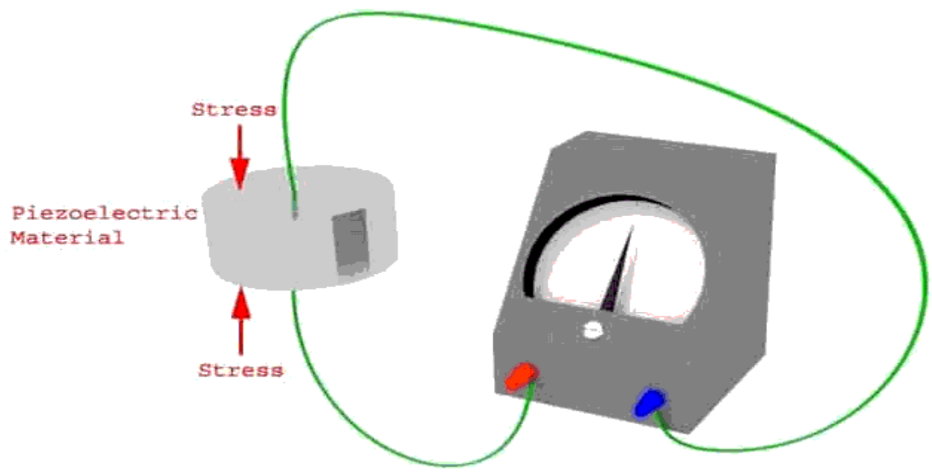
Other Types of Transducers

Piezoelectric Transducer

A **piezoelectric transducer** (also known as a piezoelectric sensor) is a device that uses the piezoelectric effect to measure changes in acceleration, pressure, strain, temperature or force by converting this energy into an electrical charge.

A transducer can be anything that converts one form of energy to another. The piezoelectric **material** is one kind of transducers. When we squeeze this piezoelectric material or apply any force or pressure, the transducer converts this energy into voltage. This voltage is a function of the force or pressure applied to it.

The electric voltage produced by a piezoelectric transducer can be easily measured by the voltage measuring instruments. Since this voltage will be a function of the force or pressure applied to it, we can infer what the force/pressure was by the voltage reading. In this way, physical quantities like mechanical stress or force can be measured directly by using a piezoelectric transducer.

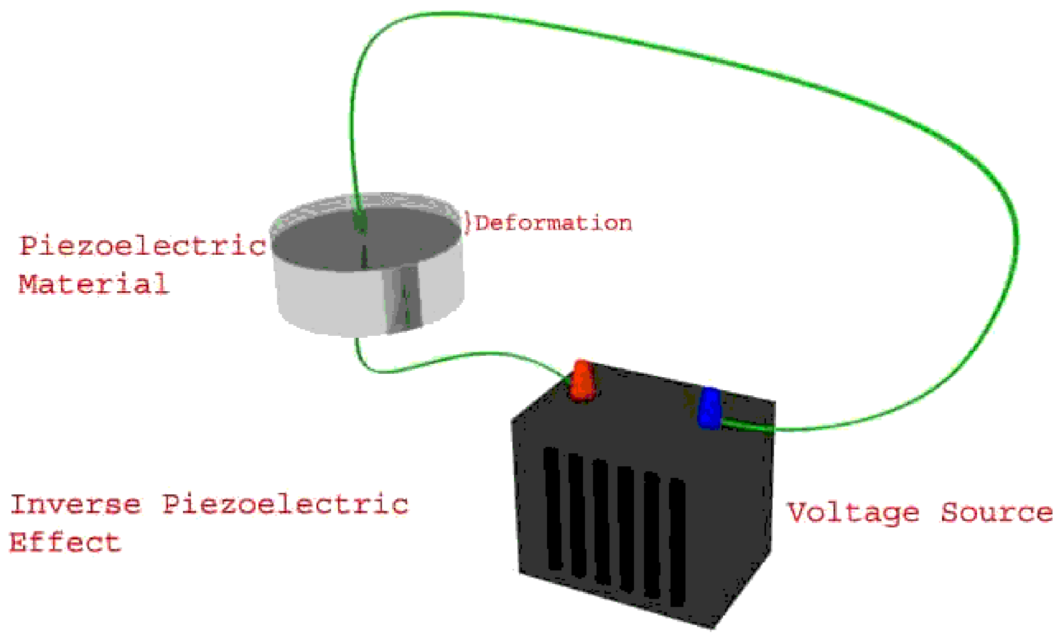


Piezoelectric Effect

Piezoelectric Actuator

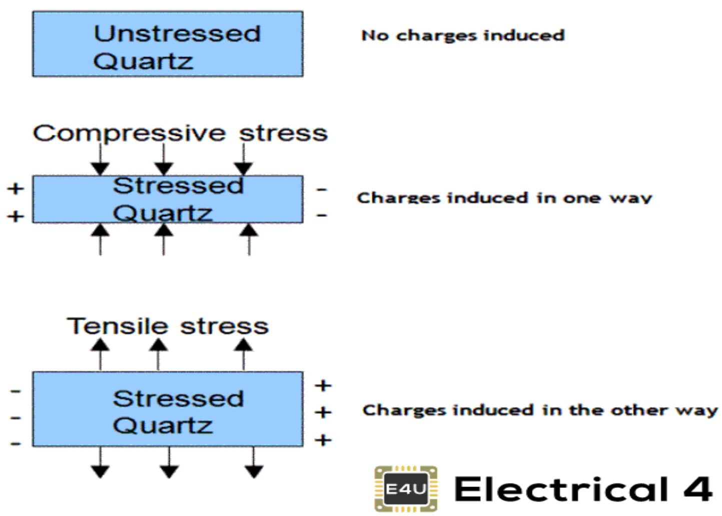
A piezoelectric actuator behaves in the reverse manner of the piezoelectric sensor. It is the one in which the electric effect will cause the material to deform i.e. stretch or bend.

That means in a piezoelectric sensor, when force is applied to stretch or bend it, an electric potential is generated and in opposite when on a **piezoelectric actuator**, an electric potential is applied it is deformed i.e. stretched or bend.



A piezoelectric transducer consists of quartz crystal which is made from silicon and oxygen arranged in crystalline structure (SiO_2). Generally, unit cell (basic repeating unit) of all crystal is symmetrical but in piezoelectric quartz crystal, it is not. Piezoelectric crystals are electrically neutral.

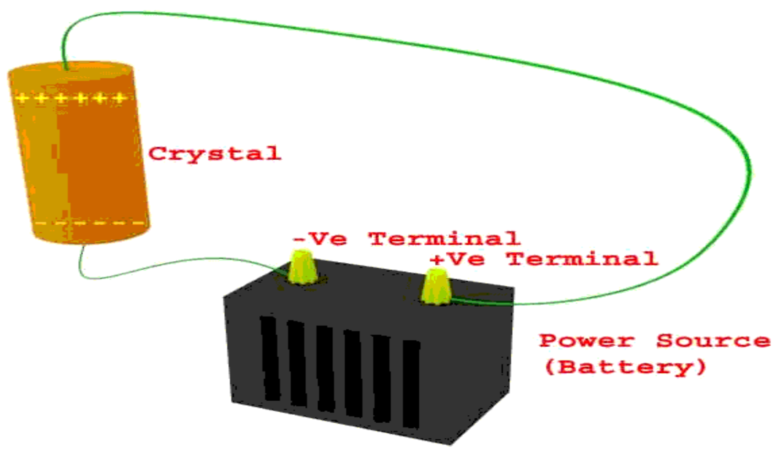
The atoms inside them may not be symmetrically arranged but their electrical charges are balanced means positive charges cancel out negative charge. The quartz crystal has the unique property of generating electrical polarity when mechanical stress applied to it along a certain plane. Basically, There are two types of stress. One is compressive stress and the other is tensile stress.



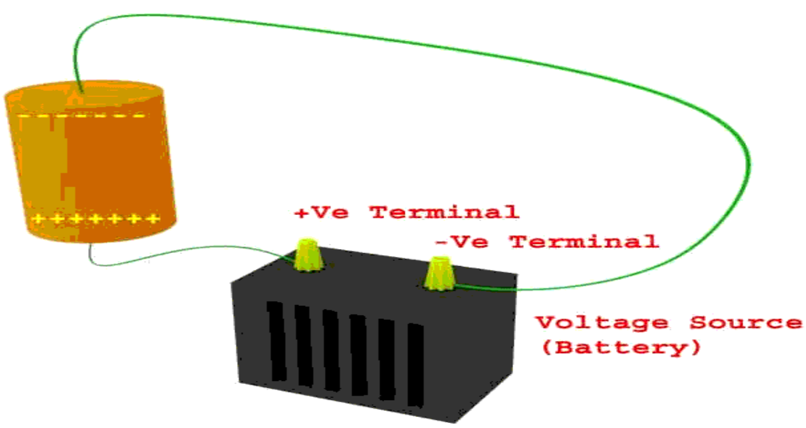
When there is unstressed quartz no charges induce on it. In the case of compressive stress, positive charges are induced on one side and negative charges are induced in the opposite side. The crystal size gets thinner and longer due to compressive stress. In the case of tensile stress, charges are induced in reverse as compare to compressive stress and quartz crystal gets shorter and fatter.

A piezoelectric transducer is based on the principle of the piezoelectric effect. The word piezoelectric is derived from the Greek word piezen, which means to squeeze or press. The piezoelectric effect states that when mechanical stress or forces are applied on quartz crystal, produce electrical charges on the quartz crystal surface. The piezoelectric effect is discovered by Pierre and Jacques Curie. The rate of charge produced will be proportional to the rate of change of mechanical stress applied to it. Higher will be stress higher will be voltage.

One of the unique characteristics of the piezoelectric effect is that it is reversible means when voltage is applied to them, they tend to change dimension along with certain plane i.e quartz crystal structure is placed into an electric field, it will deform quartz crystal by an amount proportional to the strength of the electric field. If the same structure is placed into an electric field with the direction of field reversed, the deformation will be the opposite.



Quartz crystal becomes longer due to the electric field applied



Quartz crystal becomes shorter due to the electric field applied in a reversed direction. It is a self-generating transducer. It does not require an electric voltage source for operation.

The electric voltage produced by the piezoelectric transducer is linearly varied to applied stress or force.

The piezoelectric transducer has high sensitivity. So, it acts as a sensor and used in accelerometer due to its excellent frequency of response. The piezoelectric effect is used in many applications that involve the production and detection of sound, electronic frequency generation. It acts as an ignition source for cigarette lighter and used in sonar, microphone, force, pressure, and displacement measurement

Application of Piezoelectric Materials

Using piezoelectric materials, piezoelectric transducers can be used in a variety of applications, including:

- In microphones, the sound pressure is converted into an electric signal and this signal is ultimately amplified to produce a louder sound.
- Automobile seat belts lock in response to a rapid deceleration is also done using a piezoelectric material.
- It is also used in medical diagnostics.
- It is used in electric lighter used in kitchens. The pressure made on piezoelectric sensor creates an electric signal which ultimately causes the flash to fire up.
- They are used for studying high-speed shock waves and blast waves.
- Used infertility treatment.
- Used in Inkjet printers
- It is also used in restaurants or airports where when a person steps near the door and the door opens automatically. In this, the concept used is when a person is near the door pressure is exerted person weight on the sensors due to which the electric effect is produced and the door opens automatically.

Examples of Piezoelectric Material

The materials are :

- Barium Titanate.
- Lead zirconate titanate (PZT).
- Rochelle salt.

The Piezoelectric Ultrasonic Transducer

It produces frequencies that are far above that which can be heard by the human ear. It expands and contracts rapidly when subjected to any voltage. It is typically used in a vacuum cleaner.

Piezo Buzzer

A buzzer is anything that produces sound. They are driven by the oscillating electronic circuit. A piezoelectric element may be driven by an oscillating electronic circuit or another audio signal source, driven with a piezoelectric audio amplifier. A blick, a ring, or a beep are commonly sued sound to indicate that a button has been pressed.

A piezoelectric buzzer (or piezoelectric beeper) depends on acoustic cavity resonance (or Helmholtz resonance) to produce an audible beep.

Piezoelectric Transducer Advantages

The advantages of piezoelectric transducers are:

- No need for an external force
- Easy to handle and use as it has small dimensions
- High-frequency response it means the parameters change very rapidly

Piezoelectric Transducer Disadvantages

The disadvantages of piezoelectric transducers are:

- It is not suitable for measurement in static condition
- It is affected by temperatures
- The output is low so some external circuit is attached to it
- It is very difficult to give the desired shape to this material and also desired strength

Seismic Pick Up

When a transducer mounted in a more complicated device, the transducer becomes a pickup.

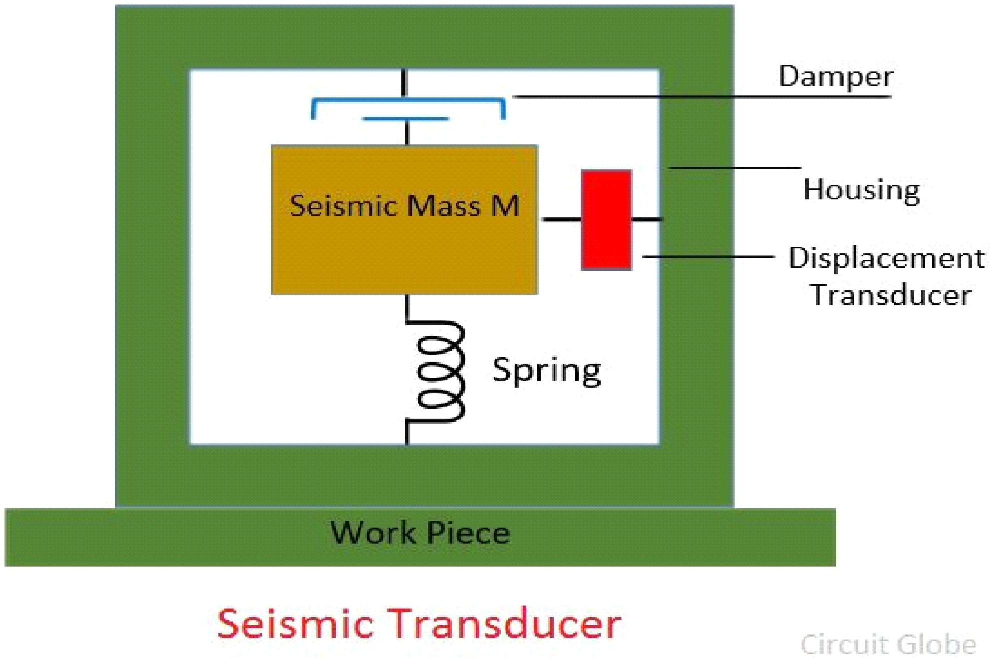
Seismic Transducer

Definition: The seismic transducer is used for measuring the vibration of the ground. The spring mass damper element and the displacement transducer are the two main component of the seismic transducer.

The mass that connected to the damper element and spring without any other support is known as spring mass damper element. And the displacement transducer converts the displacement into the electrical quantity. The seismic transducer is used for measuring the earth vibration, volcanic eruption and other vibrations etc.

Construction of Seismic Transducer

The systematic diagram of the seismic transducer is shown in the figure below. The mass is connected by the help of the damper and spring to the housing. The housing frame is connected to the source whose vibrations need to be measured.



The arrangement is kept in such a way so that the position of the mass remains same in the space. Such type of arrangement is kept for causing the relative motion between the housing frame and the mass. The term relative motion means one of the objects remains stationary, and the other is in motion concerning the first one. The displacement that occurs between the two is sensed and represented by the transducer.

Mode of Transducer

The seismic transducer works in two different modes.

- Displacement Mode
- Acceleration Mode

The selection of the mode depends on the combinations of the mass, spring and damper combinations. The large mass and soft spring are used for the displacement mode measurement while the combination of the small mass and stiff spring is used for the acceleration mode.

Types of Seismic Transducer

Vibrometer and the accelerometer are the two type of the seismic transducer.

1. Vibrometer – The vibrometer or low-frequency meter is used for measuring the displacement of the body. It also measures the high frequency of the vibrating body. Their frequency range depends on the natural frequency and the damping system.

2. Accelerometer – The accelerometer measures the acceleration of the measuring body. The acceleration shows the total force acting on the object.

Accelerometer Sensor Working and Applications

We use sensors along with our devices to monitor and control various physical quantities. The devices interact with the surroundings with the help of sensors. With the advent of technology, today we have a wide range of sensors; both in analog form and digital form to measure physical quantities like temperature, pressure, humidity, direction, light intensity etc….One of such sensors, used to measure the speed and acceleration of the devices, is the accelerometer sensor.

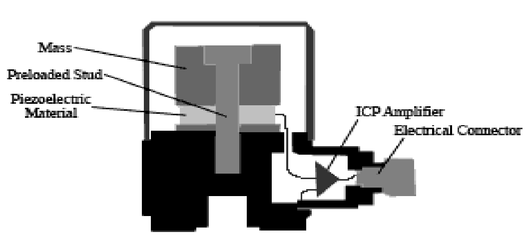
What is an Accelerometer Sensor?

The rate of change of velocity of the body with respect to time is called acceleration. According to relative theory, depending upon the relative object taken to measure acceleration, there are two types of acceleration. The proper acceleration, which is the physical acceleration of the body relative to inertia or the observer who is at rest relative to the object being measured.

The coordinate acceleration depends upon the choice of coordinate system and choice of observers. This is not equal to proper acceleration. Accelerometer sensor is the electromechanical device used to measure the proper acceleration of the object.

Working Principle

The basic underlying working principle of an accelerometer is such as a dumped mass on a spring. When acceleration is experienced by this device, the mass gets displaced till the spring can easily move the mass, with the same rate equal to the acceleration it sensed. Then this displacement value is used to measure the give the acceleration.



Piezo Accelerometer-sensor

Accelerometers are available as digital devices and analog devices. Accelerometers are designed using different methods. Piezoelectric, piezoresistive and capacitive components are generally used to convert the mechanical motion caused in accelerometer into an electrical signal.

Piezoelectric accelerometers are made up of single crystals. These use the piezoelectric effect to measure the acceleration. When applied to stress, these crystals generate a voltage which is interpreted to determine the velocity and orientation.

Capacitive accelerometers use a silicon micro-machined element. Here capacitance is generated when acceleration is sensed and this capacitance is translated into a voltage to measure the velocity values.

Modern accelerometers are the smallest MEMS, consisting of a cantilever beam with proof mass. Accelerometers are available as two-dimensional and three-dimensional forms to measure velocity along with orientation. When the upper-frequency range, high-temperature range, and low packaged weight are required, piezoelectric accelerometers are the best choice.

Applications

The Applications of Accelerometer sensor are as follows:

- For inertial navigation systems, highly sensitive accelerometers are used.
- To detect and monitor vibrations in rotating machinery.
- To display images in an upright position on screens of digital cameras.
- For flight stabilization in drones.
- Accelerometers are used to sense orientation, coordinate acceleration, vibration, shock.
- Used to detect the position of the device in laptops and mobiles.
- High-frequency recording of biaxial and triaxial acceleration in biological applications for discrimination of behavioral patterns of animals.
- Machinery health monitoring.
- To detect faults in rotator machines.
- These are also used for building and structural monitoring to measure the motion and vibration of the structure when exposed to dynamic loads.
- To measure the depth of CPR chest compressions.
- Navigation systems make use of accelerometer sensors for knowing the direction.
- Remote sensing devices also use accelerometers to monitor active volcanoes.

Uses/Examples

Some of the examples of the applications of accelerometer sensor are Aircrafts, missiles, Quake-catcher network for scientific research of earthquakes, pumps, fan, rollers, compressors, Zoll's AED plus, footpods, Intelligent compaction rollers, airbag deployment system, electronic stability control system in automobiles, tilting trains, Gravimetry, camcorders, Glogger VS2, mobile phones etc…

Yes, there is an accelerometer in your smartphone too. It is used along with gyroscope to measure the angle and orientation of the phone.

Shaft Encoders:

Shaft encoders are digital transducers that are used for measuring angular

displacements and angular velocities.

Encoder Types:

Shaft encoders can be classified into two categories depending on the nature and

the method of interpretation of the transducer output:

1. Incremental encoders and

2. Absolute encoders.

Incremental Decoders:

- The output of an incremental encoder is a pulse signal, which is generated when the transducer disk rotates as a result of the motion that is measured.
- By counting the pulses or by timing the pulse width using a clock signal, both angular displacement and angular velocity can be determined.
- With an incremental encoder, displacement is obtained with respect to some reference point which can be the home position of the moving component.
- The index pulse count determines the number of full revolutions.

Absolute Decoders:

- An absolute encoder (or whole-word encoder) has many pulse tracks on its transducer disk. When the disk of an absolute encoder rotates, several pulse trains—equal in number to the tracks on the disk—are generated simultaneously.
- At a given instant, the magnitude of each pulse signal will have one of two signal levels (i.e., a binary state), as determined by a level detector (or edge detector). This

signal level corresponds to a binary digit (0 or 1). Hence, the set of pulse trains gives an encoded binary number at any instant.

- The windows in a track are not equally spaced but are arranged in a specific pattern to obtain coded output data from the transducer. The pulse windows on the tracks can be organized into some pattern (code) so that the generated binary number at a particular instant corresponds to the specific angular position of the encoder disk at that time.

Four techniques of transducer signal generation may be identified for shaft

encoders:

1. Optical (photosensor) method

2. Sliding contact (electrical conducting) method

3. Magnetic saturation (reluctance) method

4. Proximity sensor method

Optical method:

- Since the light from the source is interrupted by the opaque regions of the track, the output signal from the photo sensor is a series of voltage pulses.
- This signal can be interpreted (e.g., through edge detection or level detection) to obtain the increments in the angular position and also the angular velocity of the disk.

Sliding Contact Encoder

- In a sliding contact encoder, the transducer disk is made of an electrically insulating material.
- Circular tracks on the disk are formed by implanting a pattern of conducting areas.
- These conducting regions correspond to the transparent windows on an optical encoder disk.
- All conducting areas are connected to a common slip ring on the encoder shaft.
- A constant voltage is applied to the slip ring using a brush mechanism. A sliding contact such as a brush touches each track, and as the disk rotates, a voltage pulse signal is picked off by it.

- The pulse pattern depends on the *conducting & non-conducting* pattern on each track, as well as the nature of rotation of the disk. The signal interpretation is done as it is for optical encoders.
- *The advantages:* high sensitivity (depending on the supply voltage) and simplicity of construction (low cost).
- *The disadvantages:* drawbacks of contacting and commutating devices (e.g., friction, wear, brush bounce due to vibration, and signal glitches and metal oxidation due to electrical arcing).
- A transducer's accuracy is very much dependent on the precision of the conducting patterns of the encoder disk.

Magnetic Saturation Method:

- A magnetic *encoder has high-strength magnetic regions imprinted* on the encoder disk using techniques such as etching, stamping, or recording (similar to magnetic data recording).
- These *magnetic regions correspond to the transparent windows* on an optical encoder disk.
- The signal pick-off device is a micro-transformer, which has primary and secondary windings on a circular ferromagnetic core.
- This pick-off sensor resembles a core storage element in a historical mainframe computer.
- A high-frequency (typically 100 kHz) primary voltage induces a voltage in the secondary windings of the sensing element at the same frequency, operating as a transformer.
- A magnetic field of sufficient strength can saturate the core, however, thereby significantly increasing the reluctance and dropping the induced voltage.
- By *demodulating the induced voltage, a pulse signal is obtained*.
- *Advantage:* non-contacting pick-off sensors.
- *Disadvantage:* more costly than the contacting devices, however, primarily because of the cost of the transformer elements and the demodulating circuitry for generating the output signal.

Proximity Sensor Method:

- A proximity *sensor encoder uses a proximity sensor* as the signal pick-off element. for example, a magnetic induction probe or an eddy current probe .
- In the *magnetic induction probe*, for example, the disk is made of ferromagnetic material.
- The encoder tracks have raised spots of the same material. *As a raised spot approaches the probe the flux linkage increases due to the associated decrease in reluctance. This raises the induced voltage level.*
- The *output voltage is a pulse-modulated signal, which is then demodulated*, and the resulting pulse signal is interpreted.
- Instead of a *disk with a track of raised regions, a ferromagnetic toothed wheel may be used along with a proximity sensor placed in a radial orientation.* In principle, this device operates like a conventional digital tachometer.
- If an eddy current probe is used, the pulse areas in the track have to be plated with a conducting material.

Incremental Optical Encoder:

There are two possible configurations for an incremental encoder disk with the

direction sensing capability:

1. Offset probe configuration (two probes and one track)

2. Offset track configuration (two probes and two tracks)

- The *first configuration* is schematically shown in figure which shows disk has a single circular track with identical and equally spaced transparent windows.
- The area of the opaque region between adjacent windows is equal to the window area. Note: An output pulse is on for half the period and off for the other half, giving a 50% duty cycle.
- Two photodiode sensors probes 1 and 2 are positioned facing the track at a quarter pitch (half the window length) apart. The forms of their output signals , after passing them through pulse-shaping circuitry (idealized), are shown in *figure a and b* for the two directions of rotation.
- The delay between the two signals will change by an integer multiple of 360° (assume constant speed over the delay), that is, no change.

Linear Encoders:

- An arrangement is shown in figure where the code plate is attached to the *moving object whose rectilinear motion* is to be measured.
- An LED light source and a phototransistor light sensor are used to detect the motion pulses, which can be interpreted just like the way it is done for a rotatory encoder.
- The phase plate is used, as with a shaft encoder, to enhance the intensity and the discrimination of the detected signal.
- *Two tracks of windows* in quadrature (i.e., quarter-pitch offset) would be needed to *determine the direction of motion*, as shown in figure.
- Another track of windows at half-pitch offset with the main track (not shown infigure) *may be used as well on the phase plate, to further enhance the discrimination of the detected pulses*.
- Specifically, *when the sensor at the main track reads a high intensity (i.e., when the windows on the code plate and the phase plate are aligned)* the sensor at the *track that is half pitch away will read a low intensity (because the corresponding windows of the phase plate are blocked by the solid regions* of the code plate).

Step-Up Gearing:

The physical resolution of an encoder can be improved by using step-up gearing so that one rotation of the moving object that is monitored corresponds to several rotations of the code disk of the encoder. This improvement is directly proportional to the step-up gear ratio (p).

- Gear ration may introduce backlash error which is significanly smaller than the resolution.
- Gear ratio improvement leads to further enhancement to the digital resolution.

Velocity Measurement:

Two methods are available for determining velocities using an incremental encoder are: *Pulse-counting method* and *Pulse-timing method*

In the first method:

- the pulse count over a fixed time period (the successive time period at which the data register is read) is used to calculate the angular velocity.

- For a given period of data reading, *there is a lower speed limit below which this method is not very accurate*.
- To compute the angular velocity ω using this method, suppose that the count during a time period T is n pulses. Hence, *the average time for one pulse cycle (i.e., window-to-window pitch angle) is T/n*. If there are N windows on the disk, assuming that quadrature signals are not used, the angle moved during one pulse period is 2π/N radians. In the second method:
- The time for one encoder pulse cycle (i.e., window-to-window pitch angle) is measured using a high-frequency clock signal.
- This method is *particularly suitable for accurately measuring low speeds*.
- In this method, suppose that the clock frequency is f Hz. If m cycles of theclock signal are counted during an encoder pulse period (i.e., window pitch, which is the interval between two adjacent windows, assuming that quadrature signals are not used), the time for that encoder cycle (i.e., the time to rotate through one encoder pitch) is given by m/f.
- With a total of N windows on the track, the angle of rotation during this period is 2π/N radians as before.

Carbon Microphone

The carbon microphone was widely used for many years being one of the earliest reliable microphones.

The carbon microphone is not widely used these days, but it has been included here, more for the sake of interest and completeness.

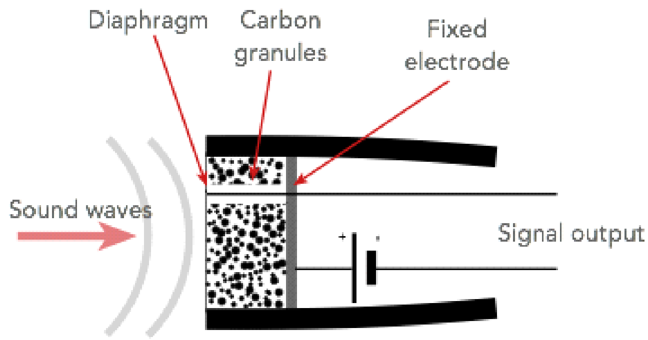
The carbon microphone was developed in the 1870s by Englishman David Edward Hughes. It was the first reliable form of microphone and it was widely used for many years before being supplanted by other types that gave much higher levels of performance.

Carbon microphone basics

The basic concept behind the carbon microphone is the fact that when carbon granules are compressed their resistance decreases. This occurs because the granules come into better contact with each other when they are pushed together by the higher pressure.

The carbon microphone comprises carbon granules that are contained within a small contained that is covered with a thin metal diaphragm. A battery is also required to cause a current to flow through the microphone.

When sound waves strike the carbon microphone diaphragm it vibrates, exerting a varying pressure onto the carbon. These varying pressure levels are translated into varying levels of resistance, which in turn vary the current passing through the microphone.



Construction of a carbon microphone

The varying current can be passed through a transformer or a capacitor to enable it to be used within a telephone, or by some form of amplifier.

The frequency response of the carbon microphone, however, is limited to a narrow range, and the device produces significant electrical noise. Often the microphone would produce a form of crackling noise which could be eliminated by shaking it or giving it a small sharp knock. This would shake the carbon granules and enable them to produce a more steady current.

Carbon microphone applications

Carbon microphones were an ideal choice of microphone in the early days of the telephone. They were widely used in telephone applications because they gave a high output which meant no amplification was used.

Carbon microphones were used in telephones like this vintage British GPO 300 series telephone

As radio started to be used, the carbon microphone was initially used there as well – for broadcasting as well as communications purposes. However their use in broadcast applications soon came to end because of the drawbacks of noise and poor frequency response. Other types of microphone started to become available and their use was preferred because of the better fidelity that was available. The use of the carbon microphone persisted for many years for communications purposes as they gave a high output and they were robust. The poor frequency response was not an issue.

The carbon microphone was used for telephones up until the 1970s and 1980s, but even there it became possible to use other types of microphone more conveniently. Also the crackle and noise of the carbon microphone had always been an issue and when other types of microphone became available at a low cost they started t be used, despite the requirement for additional electronics needed.

Carbon microphones are now only used in a very few applications – typically only specialist applications. They are able to withstand high voltage spikes and this property lends itself to use in a small number of applications.

Carbon microphone advantages

- High output
- Simple principle & construction
- Cheap and simple to manufacture

Carbon microphone disadvantages

- Very noisy - high background noise and on occasions it would crackle
- Poor frequency response
- Requires battery or other supply for operation

The carbon microphone has a number of advantages, but today the disadvantages normally outweigh the positives and as a result they are rearely used.

Chapter 6

Principle of Analog Signal Conditioning

Linearization of Non-Linear Signals

Many sensors used in industry exhibit a deviation from an ideal (linear) relationship between input and output. For example, a given change in temperature does not give rise to the same change in emf for most thermocouples when measured over different temperature ranges. Sensors or signals which exhibit this behavior are said to be non-linear. A hypothetical non-linear transfer function is shown in Figure 1.

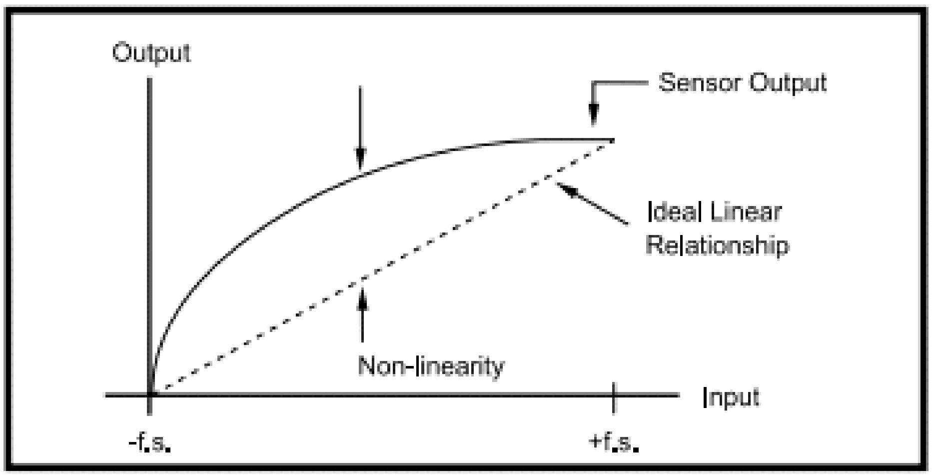


Figure 1: Hypothetical Sensor Non-Linearity

Several of the SCM5B series modules have the capability of creating a non-linear transfer function through the module itself. This non-linear transfer function is configured at the factory and is designed to be equal and opposite to the sensor or signal non-linearity. The net result is that the module output signal is linear with respect to a given input parameter such as temperature. An output signal which has been linearized with hardware internal to the SCM5B modules is beneficial to the customer because it eliminates the need for tedious software routines which determine a linearized signal through the use of high-order polynomials or look-up tables.

A hardware piece-wise linear technique is used in the SCM5B modules to correct the non-linearity of the signal. The difference between the sensor non-linearity and the linearization provided by the SCM5B module is called the Conformity Error. This is a description of how well the linearization technique 'conforms' to the non-linear curve. Breakpoints are placed along the curve so as to equalize the positive and negative conformity errors. SCM5B modules have the capability of using 9 breakpoints (or 10 segments) to correct non-linearity which allows typical conformity of ±0.015% span. A normalized plot of sensor non-linearity and hardware linearization is shown in Figure 2.

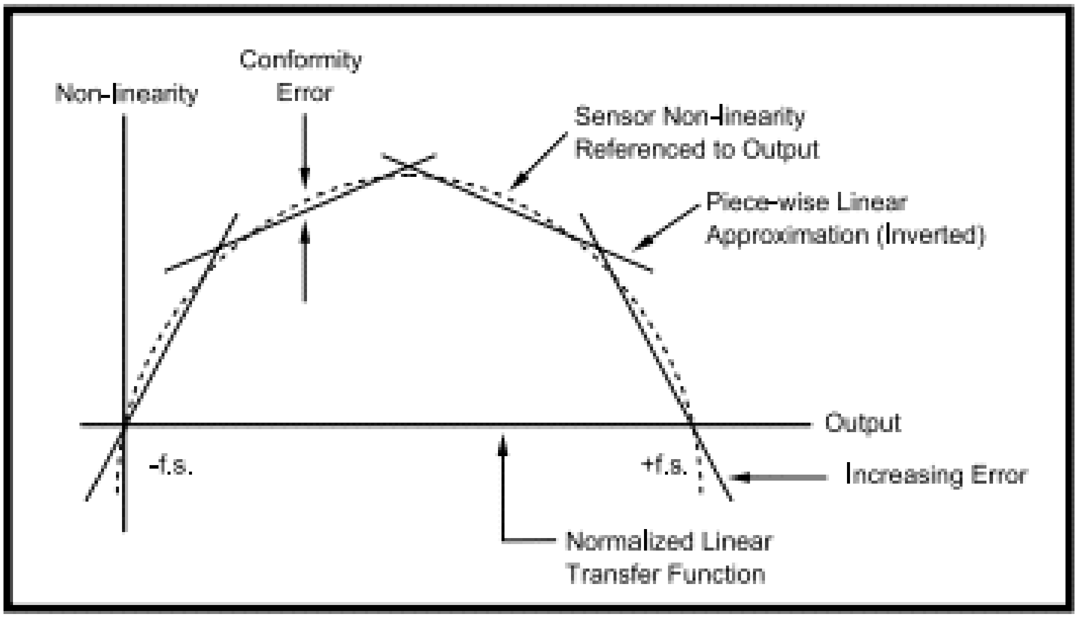


Figure 2: Normalized Plot

Linearization of a given input is based upon the input minimum and maximum values. For any input within these limits, the output of the module will be a linear representation of the input. If the input exceeds the minimum or maximum values, the output of the module is no longer a linear representation of the signal. This is shown in Figure 2. Operation of an SCM5B module beyond the specified input span is not recommended because the output is difficult to calculate. If a standard module input span does not meet customer requirements a custom module can be easily designed for optimum performance in a given system. Consult the factory for details on custom SCM5B modules.

Conversion

Voltage to Frequency Convertor

INTRODUCTION

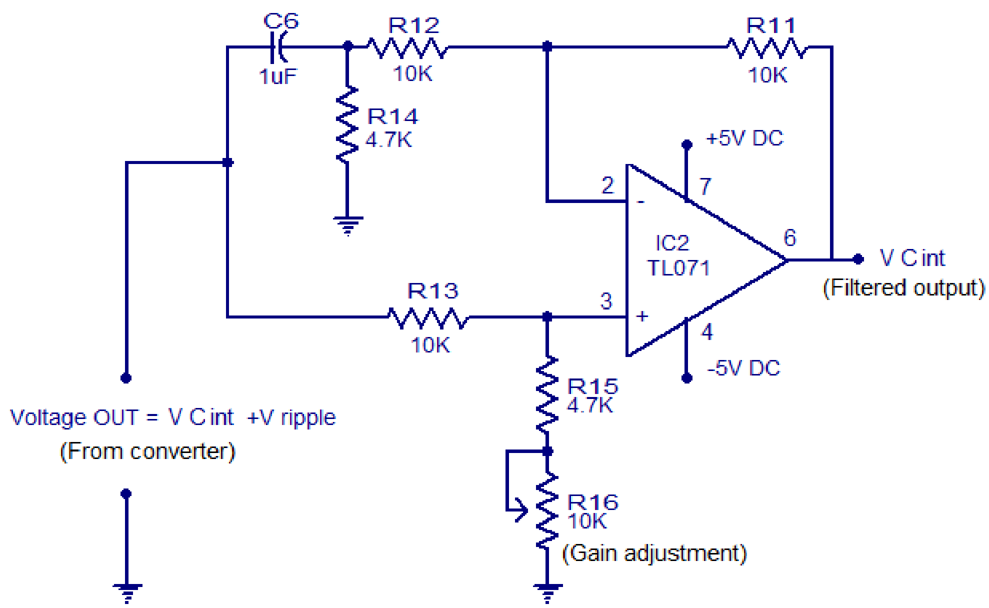
FREQUENCY COUNTER

A voltage-to-frequency converter (VFC) is an oscillator whose frequency is linearly proportional to a control voltage. The VFC/counter ADC is monotonic and free of missing codes, integrates noise, and can consume very little power. It is also very useful for telemetry applications, since the VFC, which is small, cheap and low-powered can be mounted on the experimental subject (patient, wild animal, artillery shell, etc.) and communicate with the counter by a telemetry link as shown in Figure 1.

ANALOG INPUT

OUTPUT

- **CONNECTION NEED NOT BE DIRECT**
- **CIRCUIT IS IDEAL FOR TELEMETRY**



Ripple filter for F/V converter using 9400

Figure 1: Voltage-to-Frequency Converter (VFC)

There are two common VFC architectures: the *current-steering multivibrator VFC* and the *charge-balance VFC* (Reference 1). The charge-balanced VFC may be made in *asynchronous* or *synchronous* (clocked) forms. There are many more VFO (variable frequency oscillator) architectures, including the ubiquitous 555 timer, but the key feature of VFCs is linearity—few VFOs are very linear.

The current-steering multivibrator VFC is actually a current-to-frequency converter rather than a VFC, but, as shown in Figure 2, practical circuits invariably contain a voltage-to-current converter at the input. The principle of operation is evident: the current discharges the capacitor until a threshold is reached, and when the capacitor terminals are reversed, the half-cycle repeats itself. The waveform across the capacitor is a linear triangular wave, but the waveform on either terminal with respect to ground is the more complex waveform shown.

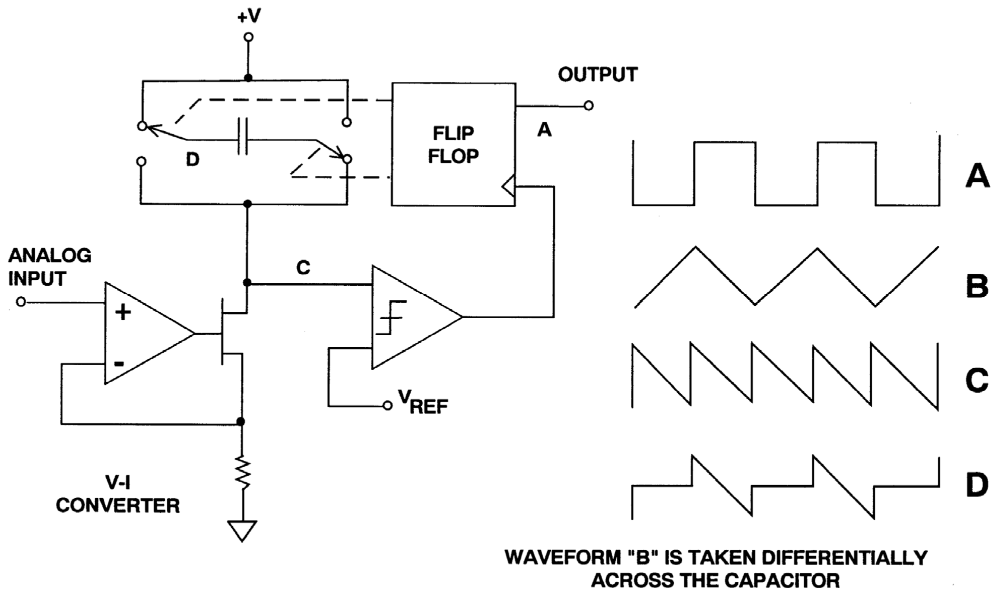


Figure 2: A Current-Steering VFC

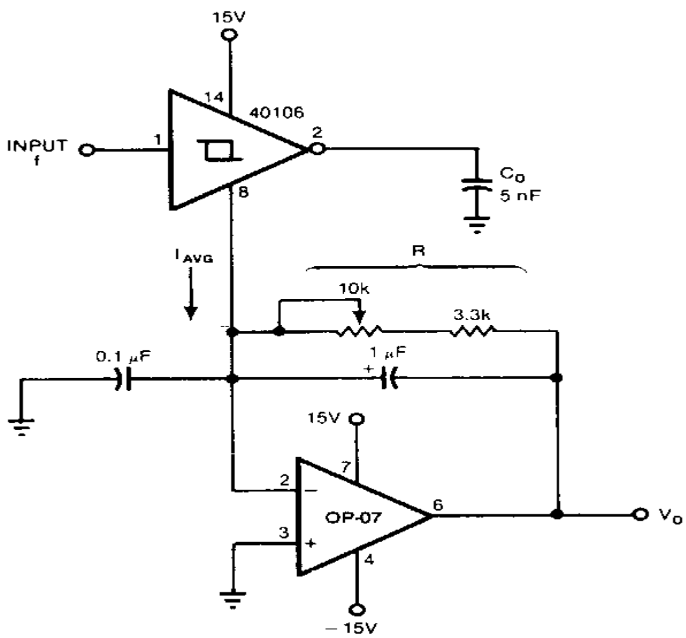
Practical VFCs of this type have linearities around 14-bits, and comparable stability, although they may be used in ADCs with higher resolutions without missing codes. The performance limits are set by comparator threshold noise, threshold temperature coefficient, and the stability and dielectric absorption (DA) of the capacitor, which is generally a discrete component. The comparator/voltage reference structure shown in the diagram is more of a representation of the function performed than the actual circuit used, which is much more integrated with the switching, and correspondingly harder to analyze.

This type of VFC is simple, inexpensive, and low-powered, and most run from a wide range of supply voltages. They are ideally suited for low cost medium accuracy ADC and data telemetry applications.

The charge balance VFC shown in Figure 3 is more complex, more demanding in its supply voltage and current requirements, and more accurate. It is capable of 16-18 bit linearity.

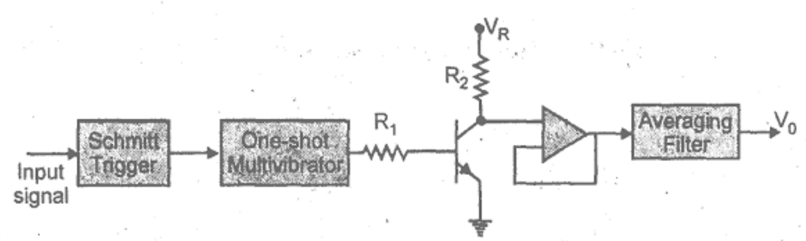
FREQUENCY TO VOLTAGE CONVERTER CIRCUITS

Frequency to voltage converter is an electronic device which converts the sinusoidal input frequency into a proportional current or output voltage.The basic circuit includes operational amplifiers and RC circuits (Resistor Capacitor networks). The operational amplifiers are used for signal processing. And the RC networks are used to remove the frequency dependent ripples. The diagram below shows the basic circuit of frequency to voltage converter using op-amp and RC networks:



The input frequency given to this converter can be in the range of 0-10 kHz. And the output can be between 0 to -10 V.

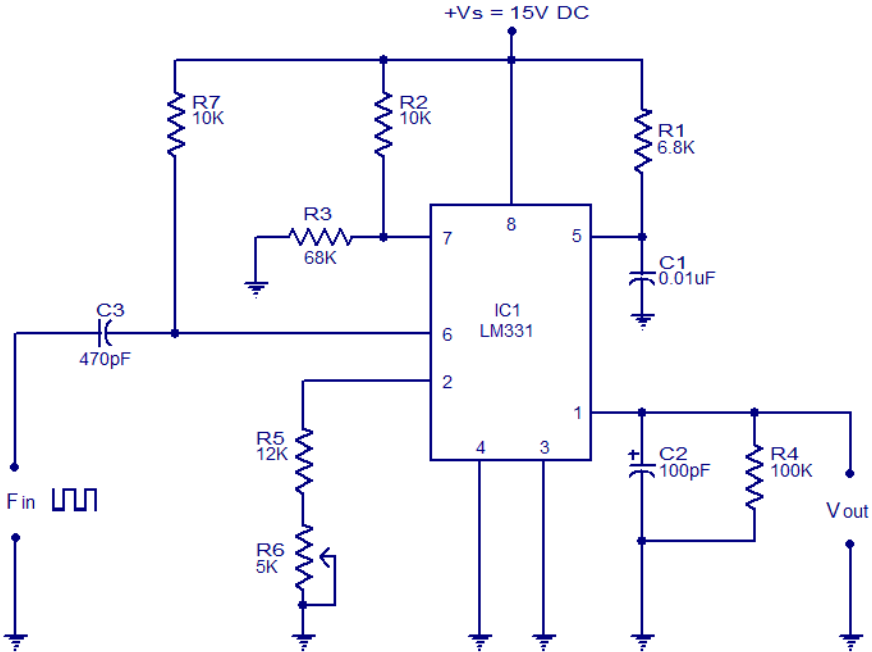
Block Diagram of F-V converter



The above block diagram shows a frequency to voltage converter. The circuit charges the capacitor to a certain level. An integrator is connected in it and the capacitor discharges into this integrator or a low pass circuit. This happens for all the cycles of the input waveform. The precision switch and the monostable multivibrator generate a pulse of a specific amplitude and period which is fed into the averaging network. Hence we get a DC voltage at the output.

F-V CIRCUIT DIAGRAM USING LM331

This is the circuit diagram of frequency to voltage converter using LM331.



Frequency to voltage converter

This IC is basically a voltage to frequency converter but it can be used as a frequency to voltage converter. Its applications also include A to D conversion and long term integration.

FV converter WORKING

In this circuit, lm331 is used to convert frequency into voltage. The voltage on the output is proportional to the frequency at the input. It is an 8 pins IC. The source is connected to pin 8 and supplies 15V DC. Pins 3 and 4 are connected to ground. The input frequency is given at pin 6 and the output voltage is taken from pin 1. The input frequency is differentiated by using the resistor R7 and capacitor C3 and then the resultant pulse train goes to pin 6. The timer circuit gets triggered by the built-in comparator circuit in the IC when the negative edge of the pulse train appears at pin 6.

The current flowing out of pin 6 is proportional to the values of capacitor C1 and resistor R1 (which are also known as the timing components) and the input frequency. Therefore we get the output voltage across the resistor R4 which is proportional to the frequency of the input. 15V DC is used in this circuit but the operating voltage of IC can be between 5 volts to 30 volts DC. The value of the resistor R3 is dependent upon the supply voltage.

APPLICATIONS OF F-V CONVERTERS

These converters are used in wide range of applications such as communication, power control, measurement and instrumentation systems etc.

We will discuss the following applications in detail:

- Frequency to voltage converter in tachometers.
- Frequency difference measurement.

F/V CONVERTER AND DIGITAL TACHOMETER

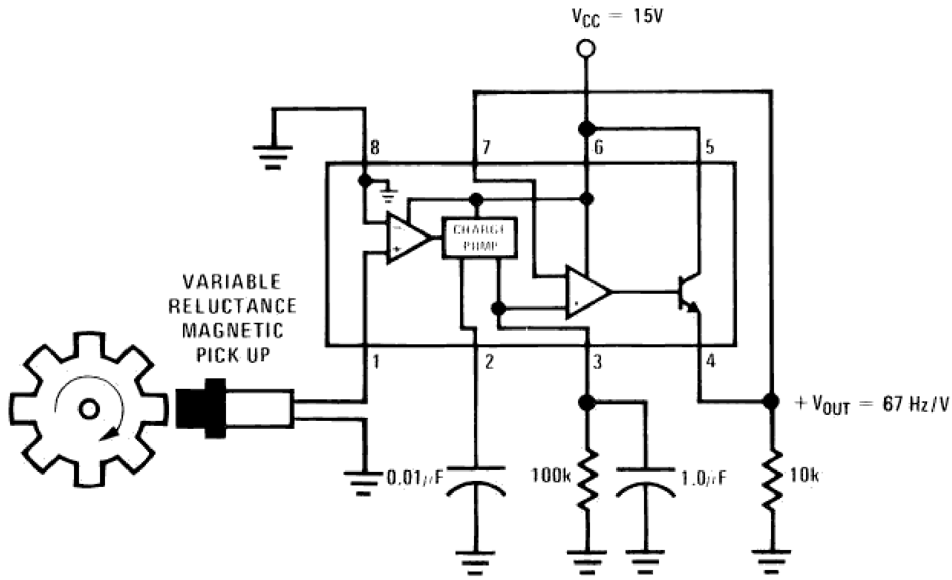
A digital tachometer is an electronic device which measures the rate of rotation of a wheel. They display the rate of rotation in the form of voltage which is why a frequency to voltage converter is required in them. The diagram below shows a digital tachometer.

A digital tachometer

The rate of occurrence of some events can be measured by a rate meter. It counts the events for a certain time period and then divides the number of events by the total time and hence we get a rate. This is the theory of operation of a simple tachometer.

We are using an IC LM2907 for this tachometer circuit. It is an 8 pins IC. At pin 1 we apply a frequency signal at the charge pump's input. At pin 2 the voltage will be between two values that are ¼ (V_{CC}) – V_{BE} and ¾ (V_{CC}) – V_{BE}.

The diagram below shows the configuration of the IC LM2907:



The capacitors C1 and C2 and the resistor R1 have specific values according to the circuit requirements. These values can be studied from the data sheet of LM2907.

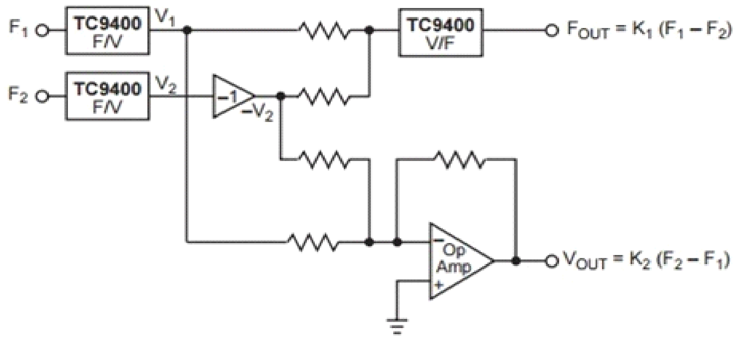
Interfacing of LM2907

The input signal is given at pin 1 and at pin 11 we apply a reference voltage. Pin 8 and pin 9 is supplied with a constant voltage. The op amp's inverting input is connected with the output of the emitter. We get a low impedance voltage at the pin 5 which is proportional to the given input frequency. From the pin 5 and pin 10 we get the output signal of 67 Hz/V. This output is sent to the ADC and then the DSP can read this output.

FREQUENCY DIFFERENCE MEASUREMENT

TC9400 is a frequency to voltage and voltage to frequency converter IC. Its basic circuit connections include three resistors, two capacitors and reference voltage. We can use two TC9400 ICs and operate both of them in the mode of frequency to voltage conversion in order to obtain the frequency difference measurements.

We use two converters and we get V1 and V2 as two separate outputs. A unity gain inverts the voltage V2 coming from the 2nd F/V converter. An op amp is connected which adds both the voltages V1 and the inverted –V2 voltage. This sum will be proportional to the actual frequency difference between F1 and F2. A V/F converter is also connected in the circuit which gives the frequency output which is again proportional to the frequency difference between F1 and F2. Hence we get the frequency difference measurement in terms of frequency as well as in terms of voltages. The diagram below shows the circuit of frequency difference measurement.



Besides these two applications, there are numerous other applications of F/V converters such as frequency divider/multipliers, frequency decoders, frequency meters and motor speed control etc .

Voltage to Current Converter (V to I Converter)

The circuits in instrumentation for analog representation of certain physical quantities (weight, pressure, motion etc), DC current is preferred. This is because DC current signals will be constant throughout the circuit in series from the source to the load. The current sensing instruments also have the advantage of less noise.

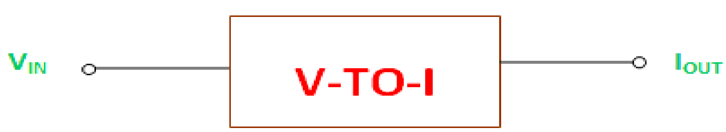
So sometimes it is essential to create current which is corresponding or proportional to a definite voltage. For this purpose **Voltage to Current Converters** (also known as V to I converters) are used. It can simply change the carrier of electrical data from voltage to current.

Simple Voltage to Current Converter

When we confer about the connection between voltage and current, it is obvious to mention the Ohm's law.

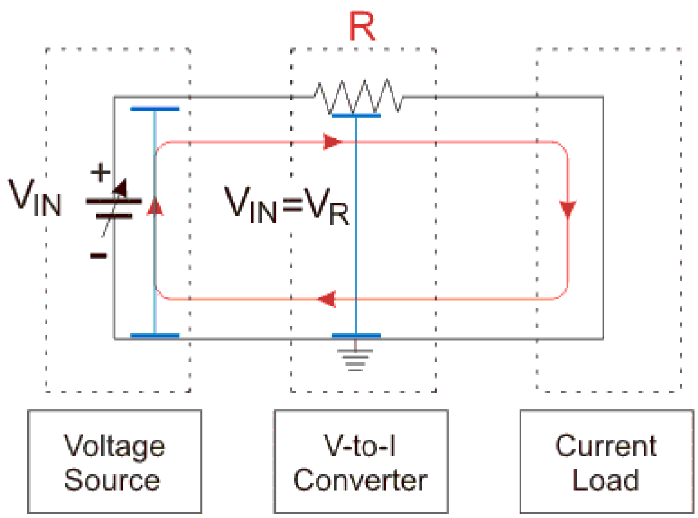
$$V = I \times R$$

We all know that when we supply a voltage as input to a circuit which comprises of a resistor, the proportional current will commence to flow through it. So, it is clear that the resistor decides the current flow in a voltage source circuit or it performs as a simple **voltage to current converter** (i.e. a V to I converter) for a linear circuit.



$$\text{Transfer ratio, K} = \frac{I_{OUT}}{V_{IN}} \left[\frac{mA}{V}\right]$$

The circuit diagram of a resistor which performs as a simple **voltage to current converter** is represented below. In this diagram, the electrical quantities such as voltage and current are represented through bars and loop respectively.



But practically, the output current of this converter depends directly on the voltage drop across the connected load in addition to the input voltage. Since, V_R becomes $V_{IN} - V_L$. This is the reason why this circuit is said to be an imperfect one or bad or passive version.

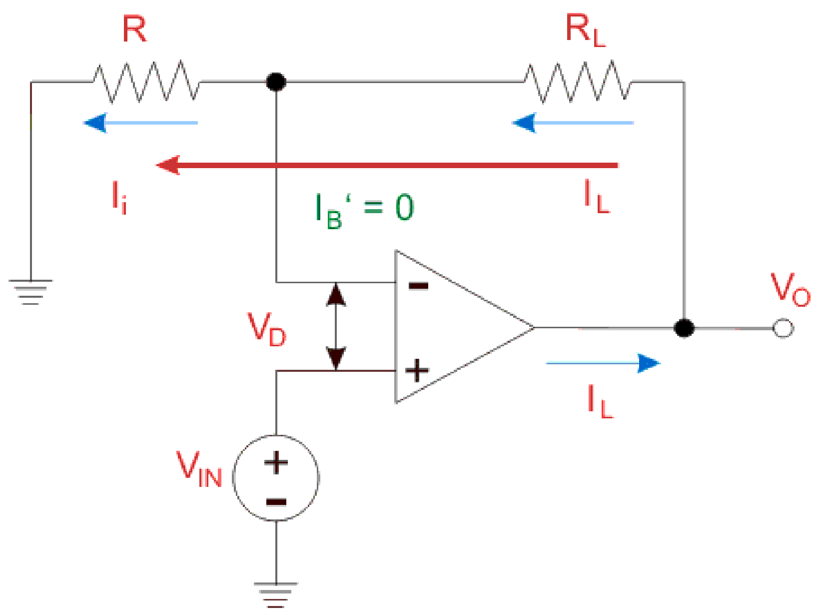
Voltage to Current Converter Using Op-Amp

An op-amp is implemented to simply convert the voltage signal to corresponding current signal. The Op-amp used for this purpose is IC LM741. This Op-amp is designed to hold the precise amount of current by applying the voltage which is essential to sustain that current through out the circuit. They are of two types that are explained in detail below.

Floating Load Voltage to Current Converter

As the name indicates, the load resistor is floating in this converter circuit. That is, the resistor R_L is not linked to ground. The voltage, V_{IN} which is the input voltage is given to the non-inverting input terminal. The inverting input terminal is driven by the feedback voltage which is across the R_L resistor.

This feedback voltage is determined by the load current and it is in series with the V_D, which is the input difference voltage. So this circuit is also known as current series negative feedback amplifier.



For the input loop, the voltage equation is

$$V_{IN} = V_D + V_F$$

Since A is very large, $V_D = 0$

So,

$$V_{IN} = V_F$$

Since, the input to the Op-amp, $I'_B = 0$

$$V_{IN} = I_L \times R$$

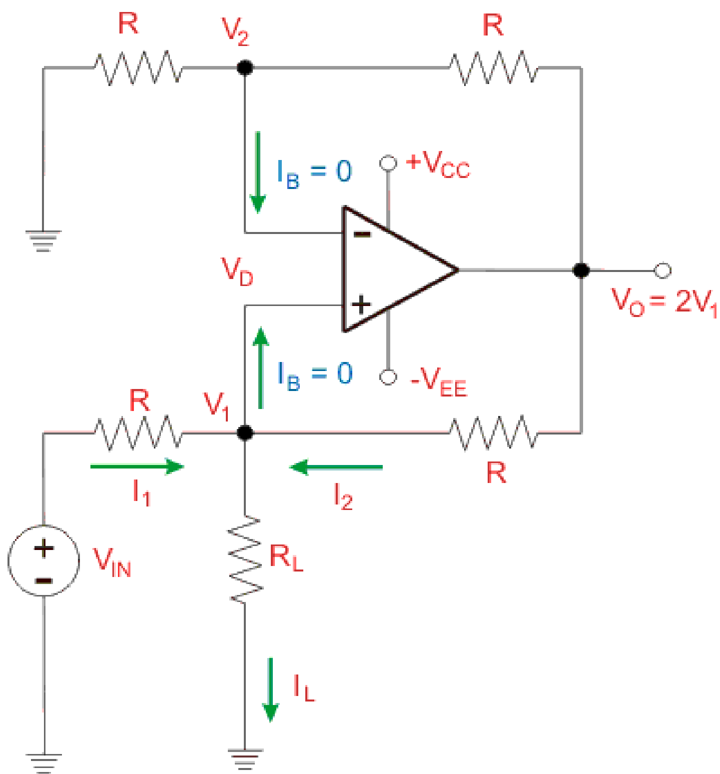
$$\therefore I_I = I_L = \frac{V_{IN}}{R}$$

From the above equation, it is clear that the load current depends on the input voltage and the input resistance. That is, the load current, $I_L \; \alpha \; V_{IN}$, which is the input voltage. The load current is controlled by the resistor, R. Here, the proportionality constant is 1/R. So, this converter circuit is also known as Trans-Conductance Amplifier. Other name of this circuit is Voltage Controlled Current Source.

The type of load may be resistive, capacitive or non-linear load. The type of load has no role in the above equation. When the load connected is capacitor then it will get charge or discharge at a steady rate. Due to this reason, the converter circuit is used for the production of saw tooth and triangular wave forms.

Ground Load Voltage to Current Converter

This V to I converter is also known as Howland Current Converter. Here, one end of the load is always grounded. For the circuit analysis, we have to first determine the voltage, V_{IN} and then the relationship or the connection between the input voltage and load current can be achieved.



For that, we apply Kirchhoff's_current_law at the node V_1

$$I_1 + I_2 = I_L$$

$$\frac{V_{IN} - V_1}{R} + \frac{V_0 - V_1}{R} = I_L$$

$$V_{IN} + V_0 - 2V_1 = I_L R$$

$$V_1 = \frac{V_{IN} + V_0 - I_L}{2}$$

For a non-inverting amplifier, gain is $A = 1 + \frac{R_F}{R_1}$

Here, the resistor,

$R_F = R = R_1$.

Hence the voltage in the output will be

$$A = 1 + \frac{R}{R} = 2$$

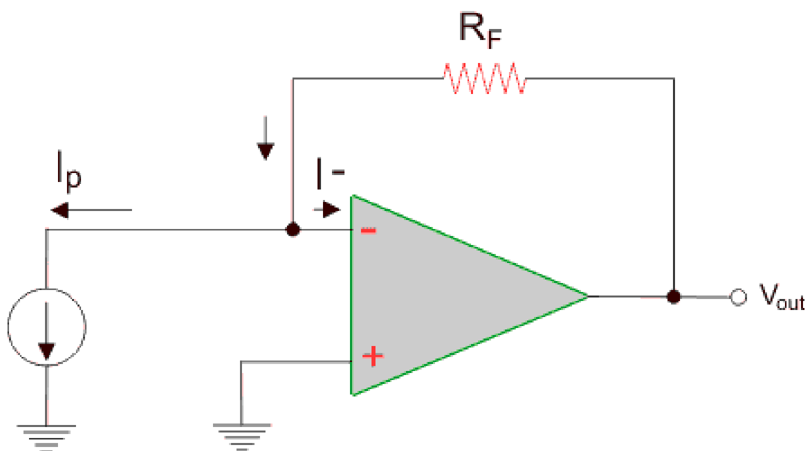
$$V_0 = 2V_1 = V_{IN} + V_0 - I_L R$$
$$0 = V_{IN} - I_L R$$
$$\therefore V_{IN} = I_L R$$
$$I_L = \frac{V_{IN}}{R}$$

Thus, we can conclude from the above equation that the current I_L is related to the voltage, V_{IN} and the resistor, R.

Application of Voltage to Current Converter

- Zener diode tester
- Low AC and DC Voltmeters
- Testing LED
- Testing Diodes

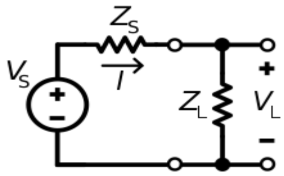
Current to Voltage Converter



Op-amp can be used as a current to voltage converter using a very simple circuit as shown above. All we need is a feedback resistance connected to the output of the op-amp. The current source is fed into the inverting terminal and the non-inverting terminal is grounded. Here the output voltage is proportional to the input current. As an ideal op-amp has infinite resistance, the current cannot flow through the op-amp. The current flows through the feedback resistance and the voltage across it depends on the current source. $V_{out} = -R_f I_{in}$

Impedance matching and filtering

Impedance matching is the practice of designing the input impedance of an electrical load or the output impedance of its corresponding signal source to maximize the power transfer or minimize signal reflection from the load. A source of electric power such as a generator, amplifier or radio transmitter has a source impedance which is equivalent to an electrical resistance in series with a reactance. An electrical load, such as a light bulb, transmission line or antenna similarly has an impedance which is equivalent to a resistance in series with a reactance. The maximum power theorem says that maximum power is transferred from source to load when the load resistance equals the source resistance and the load reactance equals the negative of the source reactance. Another way of saying this is that the load impedance must equal the complex conjugate of the source impedance. If this condition is met the two parts of the circuit are said to be *impedance matched*.



In a direct current (DC) circuit, the condition is satisfied if the load resistance equals the source resistance. In an alternating current (AC) circuit the reactance depends on frequency, so circuits which are impedance matched at one frequency may not be impedance matched if the frequency is changed. Impedance matching over a wide band will generally require complex, filter-like structures with many components except in the trivial case of constant source and load resistances when a transformer can be used.

In the case of a complex source impedance Z_S and load impedance Z_L, maximum power transfer is obtained when $Z_S = Z_L^*$

where the asterisk indicates the complex conjugate of the variable. Where Z_S represents the characteristic impedance of a transmission line, minimum reflection is obtained when

$Z_S = Z_L$

The concept of impedance matching found first applications in electrical engineering, but is relevant in other applications in which a form of energy, not necessarily electrical, is transferred between a source and a load. An alternative to impedance matching is impedance bridging, in which the load impedance is chosen to be much larger than the source impedance and maximizing voltage transfer, rather than power, is the goal.

Impedance-matching devices

Adjusting the source impedance or the load impedance, in general, is called "impedance matching". There are three ways to improve an impedance mismatch, all of which are called "impedance matching":

- Devices intended to present an apparent load to the source of $Z_{load} = Z_{source}*$ (complex conjugate matching). Given a source with a fixed voltage and fixed source impedance, the maximum power theorem says this is the only way to extract the maximum power from the source.
- Devices intended to present an apparent load of $Z_{load} = Z_{line}$ (complex impedance matching), to avoid echoes. Given a transmission line source with a fixed source impedance, this "reflection less impedance matching" at the end of the transmission line is the only way to avoid reflecting echoes back to the transmission line.
- Devices intended to present an apparent source resistance as close to zero as possible, or presenting an apparent source voltage as high as possible. This is the only way to maximize energy efficiency, and so it is used at the beginning of electrical power lines. Such an impedance bridging connection also minimizes distortion and electromagnetic interference; it is also used in modern audio amplifiers and signal-processing devices.

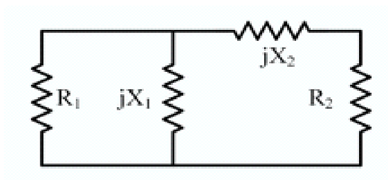
There are a variety of devices used between a source of energy and a load that perform "impedance matching". To match electrical impedances, engineers use combinations of transformers, resistors, inductors, capacitors and transmission lines. These passive (and active) impedance-matching devices are optimized for different applications and include antenna tuners (sometimes called ATUs or roller-coasters, because of their appearance), acoustic horns, matching networks, and terminators.

Filters

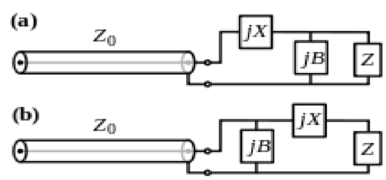
Filters are frequently used to achieve impedance matching in telecommunications and radio engineering. In general, it is not theoretically possible to achieve perfect impedance matching at all frequencies with a network of discrete components. Impedance matching networks are designed with a definite bandwidth, take the form of a filter, and use filter theory in their design.

Applications requiring only a narrow bandwidth, such as radio tuners and transmitters, might use a simple tuned filter such as a stub. This would provide a perfect match at one specific frequency only. Wide bandwidth matching requires filters with multiple sections.

L-section



Basic schematic for matching R_1 to R_2 with an L pad. $R_1 > R_2$, however, either R_1 or R_2 may be the source and the other the load. One of X_1 or X_2 must be an inductor and the other must be a capacitor.



L networks for narrowband matching a source or load impedance Z to a transmission line with characteristic impedance Z_0. X and B may each be either positive (inductor) or negative (capacitor). If Z/Z_0 is inside the 1+jx circle on the Smith chart (i.e. if $Re(Z/Z_0)>1$), network (a) can be used; otherwise network (b) can be used.

A simple electrical impedance-matching network requires one capacitor and one inductor. In the figure to the right, $R_1 > R_2$, however, either R_1 or R_2 may be the source and the other the load. One of X_1 or X_2 must be an inductor and the other must be a capacitor. One reactance is in parallel with the source (or load), and the other is in series with the load (or source). If a reactance is in parallel *with the source*, the effective network matches from high to low impedance.

the reactance in parallel, has a negative reactance because it is typically a capacitor. This gives the L-network the additional feature of harmonic suppression since it is a low pass filter too.

The inverse connection (impedance step-up) is simply the reverse—for example, reactance in series with the source. The magnitude of the impedance ratio is limited by reactance losses such as the Q of the inductor. Multiple L-sections can be wired in cascade to achieve higher impedance ratios or greater bandwidth. Transmission line matching networks can be modeled as infinitely many L-sections wired in cascade. Optimal matching circuits can be designed for a particular system using Smith charts.