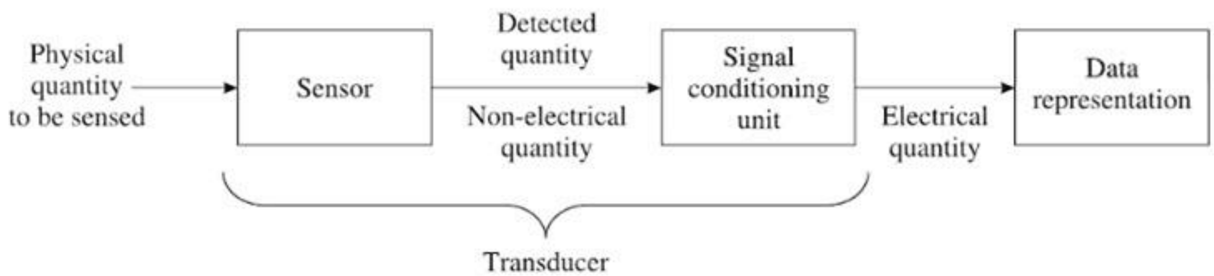
UNIT-1

What are Transducers?

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.

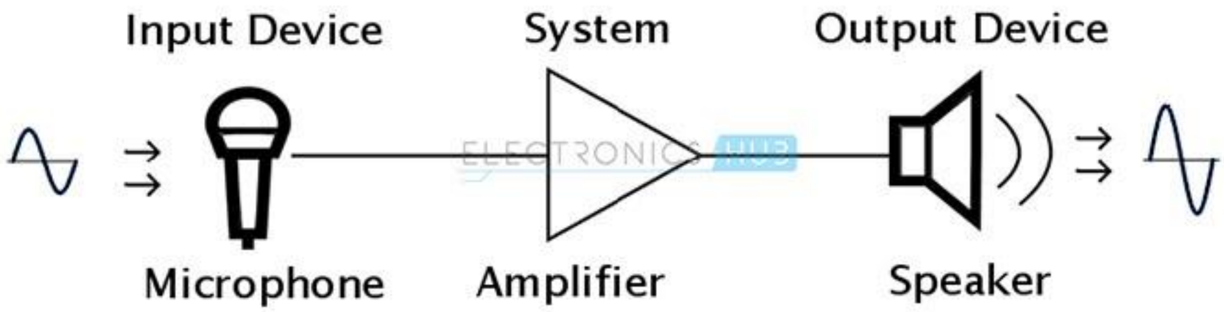
Generally speaking, a Transducer is a device that converts one form of energy into another by the principle of Transduction. Usually, a signal in one form of energy is converted to a signal in another form by a Transducer.

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.



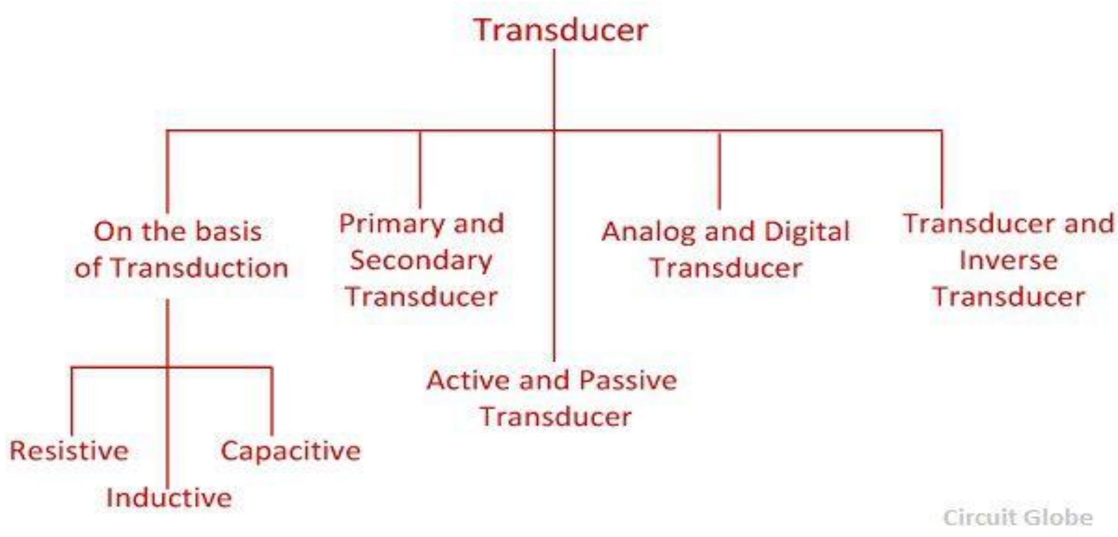
Both Microphone and Loudspeaker are Transducers in the sense that a microphone converts sound energy into electrical energy and a loud speaker converts electrical energy into sound energy.

Types of Sensors:

The transducer is of many types, and they can be classified by the following criteria.

1. **By transduction used.**
2. **as a primary and secondary transducer**
3. **as a passive and active transducer**
4. **as analogue and digital transducer**
5. **as the transducer and inverse transducer**

The transducer receives the measurand and gives a proportional amount of output signal. The output signal is sent to the conditioning device where the signal is attenuated, filtered, and modulated.



The input quantity is the non-electrical quantity, and the output electrical signal is in the form of the current, voltage or frequency.

1. Classification based on the Principle of Transduction

The transducer is classified by the transduction medium. The transduction medium may be resistive, inductive or capacitive depends on the conversion process that how input transducer converts the input signal into resistance, inductance and capacitance respectively.

2. Primary and Secondary Transducer

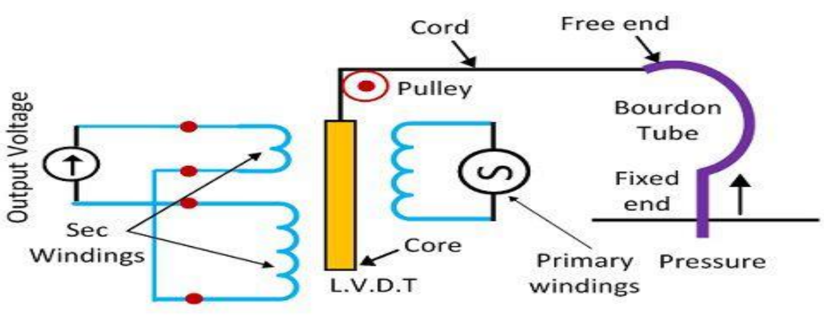
Primary Transducer – The transducer consists the mechanical as well as the electrical devices. The mechanical devices of the transducer change the physical input quantities into a mechanical signal. This mechanical device is known as the primary transducers.

Secondary Transducer – The secondary transducer converts the mechanical signal into an electrical signal. The magnitude of the output signal depends on the input mechanical signal.

Example of Primary and Secondary Transducer

Consider the Bourdon's Tube shown in the figure below. The tube act as a primary transducer. It detects the pressure and converts it into a displacement from its free end. The displacement of the free ends moves the core of the linear variable displacement transformer. The movement of the core induces the output voltage which is directly proportional to the displacement of the tube free end.

Thus, the two type of transduction occurs in the Bourdon's tube. First, the pressure is converted into a displacement and then it is converted into the voltage by the help of the L.V.D.T.



Bourdon's Tube

The Bourdon's Tube is the primary transducer, and the L.V.D.T is called the secondary transducer.

3. Passive and Active Transducer

The transducer is classified as the active and passive transducer.

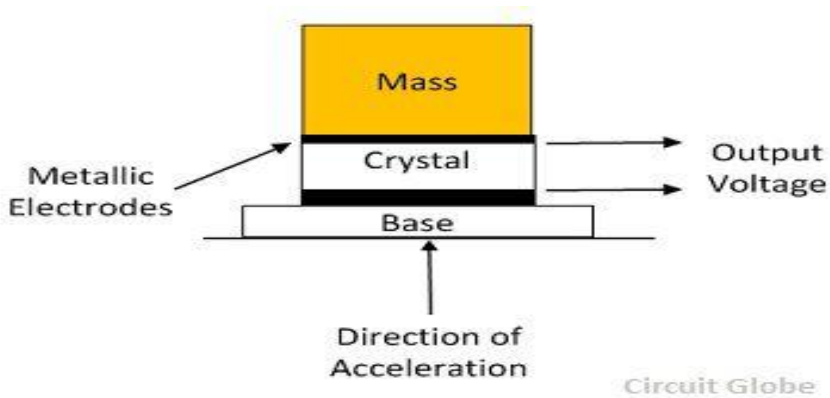
Passive Transducer – The transducer which requires the power from an external supply source is known as the passive transducer. They are also known as the external power transducer. The capacitive, resistive and inductive transducers are the example of the passive transducer.

Active Transducer – The transducer which does not require the external power source is known as the active transducer. Such type of transducer develops theirs owns voltage or current, hence known as a self-generating transducer. The output signal is obtained from the physical input quantity.

The physical quantity like velocity, temperature, force and the intensity of light is induced with the help of the transducer. The piezoelectric crystal, photo-voltaic cell, tacho generator, thermocouples, photovoltaic cell are the examples of the active transducers.

Examples – Consider the examples of a piezoelectric crystal. The crystal is sandwiched between the two metallic electrodes, and the entire sandwiched is fastened to the base. The mass is placed on the top of the sandwiched.

The piezo crystal has the special property because of which when the force is applied to the crystal, they induce the voltage. The base provides the acceleration due to which the voltage is generated. The mass applies on the crystals induces an output voltage. The output voltage is proportional to the acceleration.



The above mention transducer is known as the accelerometer which converts the acceleration into an electric voltage. This transducer does not require any auxiliary power source for the conversion of physical quantity into an electrical signal.

4. Analog and Digital Transducer

The transducer can also be classified by their output signals. The output signal of the transducer may be continuous or discrete.

Analog Transducer – The Analog transducer changes the input quantity into a continuous function. The strain gauge, L.V.D.T, thermocouple, thermistor are the examples of the analogue transducer.

Digital Transducer – These transducers convert an input quantity into a digital signal or in the form of the pulse. The digital signals work on high or low power.

5. Transducer and Inverse Transducer

Transducer – The device which converts the non-electrical quantity into an electric quantity is known as the transducer.

Inverse Transducer – The transducer which converts the electric quantity into a physical quantity, such type of transducers is known as the inverse transducer. The transducer has high electrical input and low non-electrical output.

Characteristics of Sensors:

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.

<u>Characteristics of Transducer</u>

1. **Accuracy**: It is defined as the closeness with which the reading approaches an accepted standard value or ideal value or true value, of the variable being measured.

2. **Ruggedness**: The transducer should be mechanically rugged to withstand overloads. It should have overload protection.

3. **Linearity**: The output of the transducer should be linearly proportional to the input quantity under measurement. It should have linear input - output characteristic. -

4. **Repeatability:** The output of the transducer must be exactly the same, under same environmental conditions, when the same quantity is applied at the input repeatedly.

5. **High output**: The transducer should give reasonably high output signal so that it can be easily processed and measured. The output must be much larger than noise. Now-a-days, digital output is preferred in many applications;

6. **High Stability and Reliability:** The output of the transducer should be highly stable and reliable so that there will be minimum error in measurement. The output must remain unaffected by environmental conditions such as change in temperature, pressure, etc.

7. **Sensitivity**: The sensitivity of the electrical transducer is defined as the electrical output obtained per unit change in the physical parameter of the input quantity. For example, for a transducer used for temperature measurement, sensitivity will be expressed in mV/’ C. A high sensitivity is always desirable for a given transducer.

8. **Dynamic Range:** For a transducer, the operating range should be wide, so that it can be used over a wide range of measurement conditions.

9**. Size:** The transducer should have smallest possible size and shape with minimal weight and volume. This will make the measurement system very compact.

10. **Speed of Response:** It is the rapidity with which the transducer responds to changes in the measured quantity. The speed of response of the transducer should be as high as practicable.

11.Reliability: Reliability is the ratio of how many times a system operates properly, divided by how many times it is used.

For continuous, satisfactory operation it is necessary to choose reliable sensors that last a long time while considering the cost and other requirements.

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
	Column Load Cell	Displacement and Strain
Torque	Dynamometer	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
		Photoconductive Transducers
	Photoelectric Transducers	Photoemissive Transducers
		Photovoltaic Force Transducers
		Piezoelectric Strain Transducers
		Piezoelectric Acceleration Transducers
	Piezoelectric Transducers	Piezoelectric Pressure Transducers
		Piezoelectric Torque Transducers
Active Electrical Transducers		Piezoelectric Force Transducers
		Magnetostrictive Acceleration Transducers
	Magnetostrictive Transducers	Magnetostrictive Force Transducers
		Magnetostrictive Torsion Transducers
		Tachometers
		Electrodynamic Pressure Transducers
	Electromechanical 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

Calibration of various component in sensors

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)

Sensor Calibration:

We use different systems and types of equipment for measuring various physical quantities. The accuracy of the measurement depends upon various factors. The equipment used for measurements can lose their precision when used at higher temperatures, high moisture or humidity conditions, subjected to degradation, subjected to external shocks, etc. This can be observed as the error in the measurement. To tackle this error and make necessary changes to the equipment calibration methods are used. Today sensors are being used for making various measurements. There are sensors to measure temperature, colour, humidity, etc…Sensor Calibration plays a crucial role in removing the errors in sensor measurements.

Sensors are electronic devices. They are sensitive to the changes in their working environment. Undesirable and sudden changes in the working environments of the sensors give undesired output values. Thus, the expected output differs from the measured output. This comparison between the Expected output and measured output is called **Sensor Calibration.**

Sensor calibration plays a crucial role in increasing the performance of the sensor. It is used to measure the Structural errors caused by sensors. The difference between the expected value and true value.

Working Principle

Sensor calibration helps in improving the performance and accuracy of the sensors. There are two well-known processes in which sensor calibration is done by industries. In the first method companies add an In-house calibration process to their manufacturing unit to perform individual calibration of the sensors. Here the company also add necessary hardware to their design for sensor output correction. By this process, the sensor calibration can be changed to match the application-specific requirements. But this process increases the time to market.

The alternative of this In-house calibration process, several manufacturing companies provides sensor packages with high-quality automotive-grade MEMS sensor along with complete system-level calibration. In this process, the companies include an onboard digital circuitry and software to help designers to improve the functionality and performance of the sensors. To reduce the product design time and component count, digital circuitry such as voltage regulation and Analog signal filtering techniques are included. To improve the overall performance and functionality, the onboard processor is provided with sophisticated sensor fusion algorithms. Some of the sophisticated onboard signal processing algorithms also help in reducing the manufacturing time enabling the faster time to market.

Standard Reference Method

Here the sensor output is compared with a standard physical reference to know the error in some sensors. Examples of the standard references are Rangefinders such as rulers and meter sticks, For temperature sensors- Boiling water at 100C, Triple point of water, For Accelerometers- ”gravity is constant 1G on the surface of the earth”.

Calibration Methods

There are three standard calibration methods used for sensors. They are-

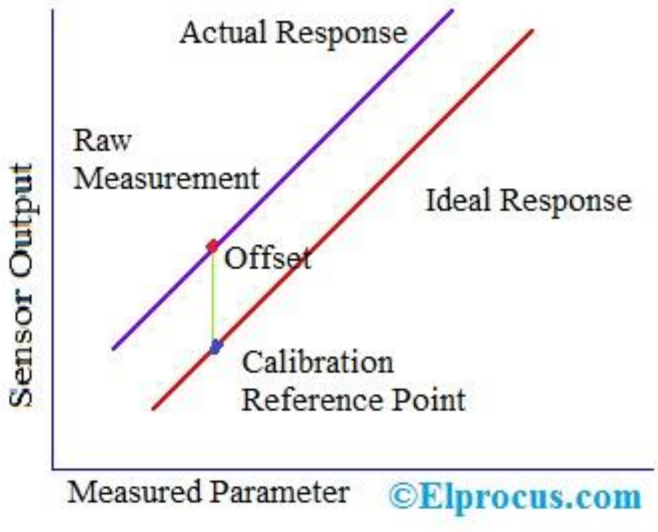
- One point calibration.
- Two-point calibration.
- Multi-Point Curve Fitting.

Before knowing these methods we have to know the concept of Characteristic curve. Every sensor has a characteristic curve that shows the response of the senor to the given input value. In the calibration process, this characteristic curve of the sensor is compared with its ideal linear response.

Some of the terms used with the characteristic curve are-

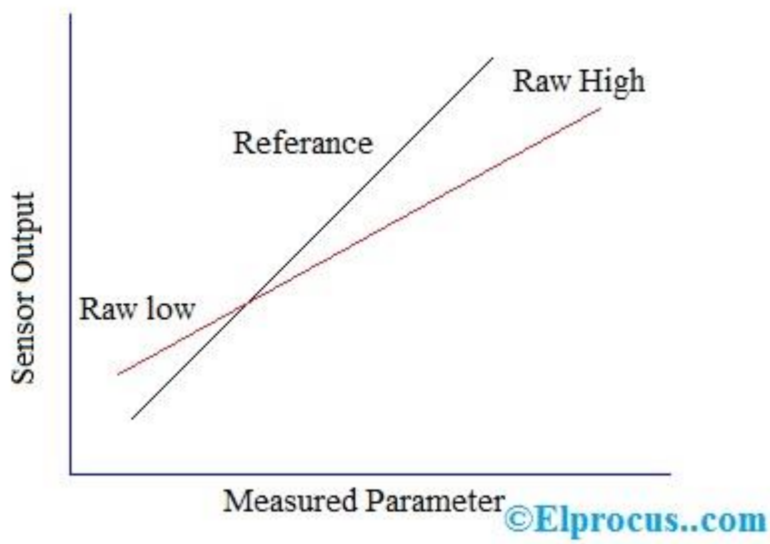
- Offset – This value tells us whether the sensor output is higher or lower than the ideal linear response.
- Sensitivity or Slope – This gives the rate of change of sensor output. A difference in slope shows that the sensor output changes at a different rate than the ideal response.
- Linearity – Not all sensors have a linear characteristic curve over the given measurement range.

One point calibration is used to correct the sensor offset errors when accurate measurement of only a single level is required and the sensor is linear. Temperature sensors are usually one point calibrated.



One-Point-Calibration

Two-point calibration is used to correct both slope and off-set errors. This calibration is used in the cases when the sensor we know that the sensor output is reasonably linear over a measurement range. Here two reference values are needed- reference High, reference Low.



Two-Point-Calibration

Multi-point Curve fitting is used for sensors that are not linear over the measurement range and require some curve-fitting to get the accurate measurements. Multi-point curve fitting is usually done for thermocouples when used in extremely hot or extremely cold conditions.

For all the above calibration process, the characteristic curves of the sensors are drawn and compared with the linear response and error is known.

Applications of Sensor Calibration

Sensor Calibration in simple terms can be defined as the comparison between the desired output and the measured output. These errors can be caused by various reasons. Some of the errors seen in sensors are errors due to improper zero-reference, errors due to shift's in sensor range, error due to mechanical damage, etc…Calibration is not similar to adjustment.

Calibration process includes placing the DUT-'Device Under Test' into configurations whose inertial input stimuli for the sensor is known, which helps us to determine the actual errors in the measurements.

The calibration process helps us to determine the following results-

- No error noted on the DUT.
- An error is noted and no adjustment is made.
- An adjustment is made to remove the error and the error is corrected to the desired level.

For sensor calibration sensor models are used. Sensor calibration is applied in Control systems to monitor and adjust the control processes. Automatic systems also apply te sensor calibration to get error-free results.

Use of Sensor Calibration

The calibration process is used to increase the performance and functionality of the system. It helps in reducing errors in the system. A calibrated sensor provides accurate results and can be used as a reference reading for comparison.

With the increase in the embedded technology and low size of sensors, many sensors are integrated over a single chip. Undetected error in one sensor can cause the whole system to degrade. It is important to calibrate the sensor to get the accurate performance of the automated systems. What are the standard references used for the calibration of the temperature sensors?

Stimulus	Quantity used for Calibration
Acoustic	Wave (amplitude, phase, polarization), Spectrum, Wave Velocity
Biological & Chemical	Fluid Concentrations (Gas or Liquid)
Electric	Charge, Voltage, Current, Electric Field (amplitude, phase, polarization), Conductivity, Permittivity
Magnetic	Magnetic Field (amplitude, phase, polarization), Flux, Permeability
Optical	Refractive Index, Reflectivity, Absorption
Thermal	Temperature, Flux, Specific Heat, Thermal Conductivity
Mechanical	Position, Velocity, Acceleration, Force, Strain, Stress, Pressure, Torque