REPORT ON TRANSDUCERS

TRANSDUCERS
DEFINITIONS:

TRANSDUCER

A transducer is a device, usually electrical, electronic, electro-mechanical, electromagnetic, photonic, or photovoltaic that converts one type of energy or physical attribute to another for various purposes including measurement or information transfer.

Examples of transducers include:

• Temperature transducers
  ▫ Thermocouples
  ▫ Resistance-Temperature Detectors (RTD)
  ▫ Thermistors
• Resistive position transducers
• Displacement transducers
• Strain gauge

SENSOR

A sensor is an element that senses a variation in input energy to produce a variation in another or same form of energy is called a sensor.
A sensor receives and responds to a signal or stimulus. Here, the term "stimulus" means a property or a quantity that needs to be converted into electrical form. Hence, sensor can be defined as a device which receives a signal and converts it into electrical form which can be further used for electronic devices. A sensor differs from a transducer in the way that a transducer converts one form of energy into other form whereas a sensor converts the received signal into electrical form only.

A sensor is used to detect a parameter in one form and report it in another form of energy (usually an electrical and/or digital signal). For example, a pressure sensor might detect pressure (a mechanical form of energy) and convert it to electricity for display at a remote gauge.

ACTUATOR

An actuator accepts energy and produces movement (action). The energy supplied to an actuator might be electrical or mechanical (pneumatic, hydraulic, etc.). An electric motor and a loudspeaker are both
transducers, converting electrical energy into motion for different purposes.

There are two general types of transducers:

- **Self generating type (Active Transducer)** – do not require an external power, and produce an analog voltage or current when stimulated by some physical form of energy. Examples of these transducers include:
  - Thermocouple
  - Photovoltaic cell
  - Moving coil generator

- **Passive transducers** – require an external power, and the output is a measure of some variation (resistance or capacitance)
  - Slide-wire resistor
  - Resistance strain gauge
  - Differential transformer

**CLASSIFICATION OF TRANSDUCERS**

A transducer may be classified based upon:

1. The stimulus being measured - Based on application.
2. The physical effect employed
CLASSIFICATION BASED ON PHYSICAL EFFECT EMPLOYED

(a) Electromagnetic:
- Antenna - converts electromagnetic waves into electric current and vice versa.
- Cathode ray tube (CRT) - converts electrical signals into visual form
- Fluorescent lamp, light bulb - converts electrical power into visible light
- Magnetic cartridge - converts motion into electrical form
- Photodetector or Photoresistor (LDR) - converts changes in light levels into resistance changes
- Tape head - converts changing magnetic fields into electrical form
- Hall effect sensor - converts a magnetic field level into electrical form only.

(b) Electrochemical:
- pH probes
- Electro-galvanic fuel cell
- Hydrogen sensor

(c) Electromechanical
- Electroactive polymers
- Galvanometer
- Microelectromechanical systems
- Rotary motor, linear motor
- Vibration powered generator
- Potentiometer when used for measuring position
- Load cell converts force to mV/V electrical signal using strain gauge
- Accelerometer
- Strain gauge
- String Potentiometer
- Air flow sensor
- Tactile sensor

(d) Electrostatic:
- Electrometer

(e) Photoelectric:
- Laser diode
- Light-emitting diode

The above convert electrical power into forms of light
- Photodiode
• Photoresistor
• Phototransistor
• Photomultiplier tube

All the above convert changing light levels into electrical form

(f) Thermoelectric:

• RTD Resistance Temperature Detector
• Thermocouple
• Peltier cooler
• Thermistor (includes PTC resistor and NTC resistor)

(g) Electroacoustic:

• Loudspeaker, earphone - converts electrical signals into sound (amplified signal → magnetic field → motion → air pressure)
• Microphone - converts sound into an electrical signal (air pressure → motion of conductor/coil → magnetic field → signal)
• Pick up (music technology) - converts motion of metal strings into an electrical signal (magnetism → electricity (signal))
• Gramophone pick-up - (air pressure → motion → magnetic field → signal)

CLASSIFICATION BASED ON SOURCE OF ENERGY

• Active Transducers
• Passive Transducers

BASIC REQUIREMENTS OF A TRANSDUCER

1. Linearity
   The input-output should be linear.

2. Ruggedness
   The transducer should withstand overloads, with measures for over load protection.

3. Repeatability
   The transducer should produce identical output signal when the same input signal is
applied at different times under the same environmental condition.

4. **High stability and reliability**
The output from the transducer should not be affected by temperature, vibration and other environmental variation and their should be minimum error in measurements.

5. **Good dynamic response**
The transducer should respond to the changes in input as quickly as possible.

6. **Convenient instrumentation**
The transducer should produce a sufficiently high analog output signal with high signal to noise ratio. So that the output can be measured either directly or after suitable amplification.

7. **Good mechanical characteristics**
working conditions – subject to mechanical strains
external forces – deformity /affect performance

**TRANSDUCERS**

**CAPACITIVE TRANSDUCERS**

Capacitor :

It is a most widely used passive elements in circuits. These are devices which can store electric charge.
The capacitance of a parallel plate capacitor is given by
The capacitance between two conductive surfaces varies with three major factors:
- The overlapping area ($A$) of those two surfaces
- The distance between them ($d$)
- The dielectric constant ($\varepsilon_0$ & $\varepsilon_r$) of the material in between the surfaces.

If two out of three of these variables can be fixed (stabilized) and the third allowed to vary, then any measurement of capacitance between the surfaces will be solely indicative of changes in that third variable.

The value of capacitance is determined by:
(a) The area of the plates
(b) The distance between the plates
(c) The type of dielectric between the plates

Some transducers work by making one of the capacitor plates movable, either in such a way as to vary the overlapping area or the distance between the plates. Other transducers work by moving a dielectric material in and out between two fixed plates:

Capacitive transducers can be classified as
1. Variable capacitive transducer
2. Differential capacitive transducer

Variable capacitive transducer varies according to:
(a) Area of overlap,
(b) Distance between plates,
(c) Amount of dielectric between plates.

Transducers with greater sensitivity and immunity to changes in other variables can be obtained by way of differential design.

Differential capacitive transducer varies capacitance ratio by changing:
- (a) Area of overlap
- (b) Distance between plates
- (c) Dielectric between plates.
The differential devices shown above have three wire connections rather than two: one wire for each of the “end” plates and one for the “common” plate. As the capacitance between one of the “end” plates and the “common” plate changes, the capacitance between the other “end” plate and the “common” plate is such to change in the opposite direction. This kind of transducer lends itself very well to implementation in a bridge circuit.

**Examples of Capacitive Transducers**

- Diaphragm Microphones

In capacitor microphone the principle of variation in distance between parallel plates is used. When a force (sound pressure) is applied to a diaphragm which acts as one plate of a capacitor the distance between the diaphragm and the static plate is changed. The resulting change in capacitance can be measured by an a.c bridge or by other measures which gives the measure of the applied force.

In medicine, researchers use capacitive sensing to detect physiological changes in living bodies. In human beings, metal plates are placed on the chest and back, recording respiratory and cardiac action by means of capacitance changes.
INDUCTIVE TRANSDUCER

An Inductor is a passive component used in electronic circuits. It stores energy in the form of magnetic field.
When a force is applied to the ferromagnetic armature, the air gap is changed. The applied force is measured by change of inductance in a single coil.

Principle of operation: if there is a relative motion between a conductor and magnetic field, a voltage is induced in the conductor.

**Linear Variable Differential Transformer (LVDT)**

The linear variable differential transformer (LVDT) is a type of electrical transformer used for measuring linear displacement. The transformer has three coils and a rod shaped ferromagnetic core. The centre coil is the primary, and the two outer coils are the secondary coils. A cylindrical ferromagnetic core, is positioned centrally inside the tube. It slides along the axis of the tube. The primary coil (P) are energised with Alternate Current. This produces an alternating magnetic field in the centre of the transducer which induces a signal (voltage V1 & V2) into the secondary windings (S & S) depending on the position of the core. The secondary coils are connected in series so that the output signal (voltage) is the difference (V1 – V2) (hence "differential") between the two secondary voltages.

If the coil is placed ideally in the central position V1 = V2 and hence the output voltage is zero.
When the core is displaced in one direction, the voltage in one coil increases as the other decreases, causing the output voltage to increase from zero to a maximum. This voltage is in phase with the primary voltage. When the core moves in the other direction, the output voltage also increases from zero to a maximum, but its phase is opposite to that of the primary. The magnitude of the output voltage is proportional to the distance moved by the core (up to its limit of travel), which is why the device is described as "linear". The phase of the voltage indicates the direction of the displacement.

The distinct advantage of using an LVDT displacement transducer is that the moving core does not touch the inside of the tube and does not make contact with other electrical components of the assembly, offers high reliability and long life. Further, the core can be so aligned that an air gap exists around it, ideal for applications where minimum mechanical friction is required.

The LVDT design is used for
- Position feedback in servomechanisms
- Automated measurement in machine tools and many other industrial and scientific applications
- Applications such as material testing machines, automotive/aerospace test rigs and actuators, etc.

Their small physical size also makes them ideally suited for use in load cells, pressure transducers, weighing systems.

Although the LVDT is a displacement sensor, many other physical quantities can be sensed by converting displacement to the desired quantity via thoughtful arrangements. Some example applications include:

1. **Displacement**: Extensiometers, temperature transducers, butterfly valve control, servo valve displacement sensing
2. **Deflection of Beams, Strings, or Rings**: Load cells, force transducers, pressure transducers
3. **Thickness Variation of Work Pieces**: Dimension gages, thickness and profile measurements, product sorting by size
4. **Fluid Level** fluid level and fluid flow measurement, position sensing in hydraulic cylinders.

Example of an LVDT being used as a fluid level sensor
RESISTANCE TRANSDUCERS

Potentiometers
The excitation voltage maybe ac or dc and output voltage is proportional to the input motion. The wiper displacement can be rotary, translational or both. Electrical device which has a user-adjustable resistance. Usually, this is a three-terminal resistor with a sliding contact in the center (the wiper).
If all three terminals are used, it can act as a variable voltage divider.
If only two terminals are used (one side and the wiper), it acts as a variable resistor.
Such potentiometers suffer from the linked problems of resolution and electrical noise.

The output voltage $V_o$ of the potentiometer is determined by:
Let $R1 = \frac{X_i R_T}{X_T}$

where $X_i = \text{input displacement}$
$X_T = \text{maximum possible displacement}$
$R_T = \text{total resistance of the potentiometer}$
Then output voltage $v_o =$

where $P = \text{maximum power dissipation}$
TEMPERATURE TRANSDUCERS

Temperature is the most frequently measured process variable, and any material with a temperature sensitive characteristic can be used as a thermometer. Electrical temperature sensing devices can be used for remote temperature measuring and signaling.

THERMOCOUPLES

There are three major effects involved in a thermocouple circuit: the Seebeck, Peltier, and Thomson effects.

Peltier effect

Peltier effect describes the temperature difference generated by EMF and is the reverse of Seebeck effect.

Thomson effect

Thomson effect relates the reversible thermal gradient and EMF in a homogeneous conductor

Seebeck Effect

The basis of thermocouples was established by Thomas Johann Seebeck in 1821 when he discovered that a conductor generates a voltage when subjected to a temperature gradient. To measure this voltage, one must use a second conductor material which generates a different voltage under the same temperature gradient. Otherwise, if the same material was used for the measurement, the voltage generated by the measuring conductor would simply cancel that of the first conductor. The voltage difference generated by the two materials can then be measured and related to the corresponding temperature gradient. It is thus clear that, based on Seebeck's principle, thermocouples can only measure temperature differences and need a known reference temperature to yield the absolute readings.

If the ends of the wire have the same temperature, no emf occurs, even if the middle of the wire is hotter or colder.

In normal operation, the cold junction is placed in an ice bath whereas the hot junction is placed at the point who's temperature is to be measured.

If the Seebeck coefficient functions of the two thermocouple wire materials are pre-calibrated and the reference temperature $T_{\text{Ref}}$ is known (usually set by a 0°C ice bath), the temperature at the probe tip becomes the only unknown and can be directly related to the voltage readout.

\[
V_{\text{out}} = (S_A - S_B) \left( T_{\text{Tip}} - T_{\text{Ref}} \right)
\]

\[
\Rightarrow T_{\text{Tip}} = T_{\text{Ref}} + \frac{V_{\text{out}}}{S_A - S_B}
\]
It is important to note that thermocouples measure the temperature difference between two points, not absolute temperature.

There are various types of thermocouples:

- Type K: Chromel-Alumel
- Type J: Iron-Constantan
- Type E: Chromel-Constantan
- Type N: Nicros-Nisil
- Type T: Copper-Constantan

The magnitude of the thermal EMF is

\[ E = c(T_1 - T_2) + k(T_1^2 - T_2^2) \]

where

c and k = constants of the thermocouple materials
T1 = the temperature of the ‘hot’ junction
T2 = the temperature of the ‘cold’ or ‘reference’ junction

**Layouts of Typical Thermocouples**
Thermocouple junctions come in three basic forms:

1) Exposed
2) Grounded
3) Ungrounded.

Exposed junction was designed for faster response. Insulation is sealed beyond the exposed junction tip to prevent penetration of moisture or gas to the inner thermocouple. Grounded junction is used for high-pressure gas and liquid applications, provides faster response.

Advantages Of Thermocouples
- Low cost.
- No moving parts, less likely to be broken.
- Wide temperature range.
- Reasonably short response time.
- Reasonable repeatability and accuracy.
Disadvantages Of Thermocouples

- Sensitivity is low, usually 50 µV/°C (28 µV/°F) or less. Its low voltage output may be masked by noise. This problem can be improved, but not eliminated, by better signal filtering, shielding, and analog-to-digital (A/V) conversion.
- Accuracy, usually no better than 0.5 °C (0.9°F), may not be high enough for some applications.
- Requires a known temperature reference, usually 0°C (32°F) ice water. Modern thermocouples, on the other hand, rely on an electrically generated reference.
- Nonlinearity could be bothersome. Fortunately, detail calibration curves for each wire material can usually be obtained from vendors.

Applications of thermocouples

- Thermocouples are most suitable for measuring over a large temperature range, up to 1800 K.
  Example:
  Type K : Chromel-Alumel (-1900°C to 1260°C)
  Type J : Iron-Constantan (-1900°C to 760°C)
  Type E : Chromel-Constantan (-1000°C to 1260°C)

They are less suitable for applications where smaller temperature differences need to be measured with high accuracy, for example the range 0–100 °C with 0.1 °C accuracy. For such applications, thermistors and RTDs are more suitable.

THERMISTORS

A thermistor or thermal resistor is a semiconductor composed of metallic oxides such as manganese, nickel, cobalt, copper, iron, and titanium. Thermistors are fabricated in wafer, disk, bead, and other shapes.
The resistance of thermistors decreases with increasing temperature. Thermistor applications are based on the resistance-temperature characteristic of a thermistor. Thermistors give a relatively large output (change of resistance) for a small temperature change. This output can be transmitted over a large distance. The amount of change per °C is expressed by Beta value (material constant) or Alpha coefficient (resistance temperature coefficient). The larger Alpha or Beta the greater the change in resistance with temperature, and the temperature versus resistance curve is steeper. The thermistor has very high temperature coefficient of resistance of the order of 3 to 5 % per °C, making it an ideal temperature transducer. The resistance versus temperature relationship is not linear. The resistance at any temperature T, is given by

\[ R(T) = R(T_0) \left[ 1 + \alpha_o \Delta T \right] \quad T_1 < T < T_2 \]

where

\[ \alpha_o = \frac{1}{R(T_0)} \left( \frac{R_2 - R_1}{T_2 - T_1} \right) \]

\[ R_T = \text{Thermistor resistance at Temperature } T(\text{K}) \]
\[ R_0 = \text{Thermistor resistance at Temperature } T_0(\text{K}) \]
\[ \alpha = \text{Constant} \]

Thermistor resistance versus temperature is highly nonlinear and usually has a negative slope.
Thermistors are the most sensitive of all the temperature sensing elements. Small dimensions of wafer, bead, disc and chip thermistors result in a rapid response time. This is especially useful for control system feedback.

Thermistors are able to handle mechanical and thermal shocks better than any other temperature measuring device.

**Resistance Temperature Detector**

Resistance temperature detectors (RTDs), also called resistance thermometers, are temperature sensors that exploit the predictable change in electrical resistance of some materials with changing temperature. An Approximation of Resistance Vs Temperature
A straight line has been drawn between the points of the curve that represent temperature, T1 and T2, and T0 represent the midpoint temperature.

The Equation of the straight line is

$$R(T) = R(T_0)[1 + \alpha_0 \Delta T] \quad T_1 < T < T_2$$

Where
\[ R(T) = \text{approximation of resistance at temperature } T \]
\[ R(T_0) = \text{resistance at temperature } T_0 \]
\[ \alpha_o = \text{fractional change in resistance per degree of temperature at } T_0 \]
\[ \Delta T = T - T_0 \]

\[ \alpha_o = \frac{1}{R(T_0)} \left( \frac{R_2 - R_1}{T_2 - T_1} \right) \]

\[ R_2 = \text{resistance at } T_2 \]
\[ R_1 = \text{resistance at } T_1 \]

A more accurate representation of R-T curve over some span of temperatures can be given by the quadratic approximation:
\[ R(T) = R(T_0)[1 + \alpha_1 \Delta T + \alpha_2 (\Delta T^2)] \quad T_1 < T < T_2 \]

\[ R(T) = \text{quadratic approximation of resistance at temperature } T \]
\[ R(T_0) = \text{resistance at temperature } T_0 \]
\[ \alpha_1 = \text{linear fractional change in resistance with temperature} \]
\[ \alpha_2 = \text{quadratic fractional change in resistance with temperature} \]
\[ \Delta T = T - T_0 \]
$\alpha_1$ = linear fractional change in resistance with temperature
$\alpha_2$ = quadratic fractional change in resistance with temperature
$\Delta T = T - T_0$

**RTD - sensitivity**

- Sensitivity is shown by the value $\alpha_0$
  - Platinum – 0.004/ °C
  - Nickel – 0.005/ °C
- Thus, for a 100Ω platinum RTD, a change of only 0.4 Ω would be expected if the temperature is changed by 1°C
**RTD – response time**
- Generally 0.5 to 5 seconds or more
- The slowness of response is due principally to the slowness of thermal conductivity in bringing the device into thermal equilibrium with its environment.

**RTD Construction**

These elements nearly always require insulated leads attached. At low temperatures PVC, silicon rubber or PTFE insulators are common to 250°C. Above this, glass fibre or ceramic are used. The measuring point and usually most of the leads require a housing or protection sleeve. This is often a metal alloy which is inert to a particular process. Often more consideration goes in to selecting and designing protection sheaths than sensors as this is the layer that must withstand chemical or physical attack and offer convenient process attachment points.
STRESS AND STRAIN MEASUREMENTS

STRESS

Stress is a measure of the average amount of force exerted per unit area. It is a measure of the intensity of the total internal forces acting within a body across imaginary internal surfaces, as a reaction to external applied forces and body forces. It was introduced into the theory of elasticity by Cauchy around 1822. Stress is a concept that is based on the concept of continuum.

Stress is expressed as: \( \sigma = \frac{\text{Force}}{\text{Area}} \)

\( \sigma \) is the average stress, also called the engineering or nominal stress.

STRAIN

Strain is the geometrical expression of deformation caused by the action of stress on a physical body. Strain is calculated by first assuming a change between two body states: the beginning state and the final state. Then the difference in placement of two points in this body in those two states expresses the numerical value of strain. Strain therefore expresses itself as a change in size and/or shape.

Strain is defined as the fractional change in length.

\( \text{Strain} = \frac{\Delta l}{l} \)

STRAIN GAUGE

From the equation of resistance,

\[ R = \frac{\rho L}{A} \]

\( R \) = resistance
\( \rho \) = specific resistance of the conductor material
\( L \) = the length of the conductor in meters
\( A \) = the area of the conductor in square meters
The strain gauge is used for measurement of pressure. When a strain produced by a force is applied on the wires, their Length (L) increases and Cross-Sectional Area (A) decreases.

From the equation of resistance, \( R = \rho \frac{L}{A} \)

It can be seen that the resistance increases.
The Gauge Factor

\[ K = \frac{\Delta R}{R} \frac{\Delta L}{L} \]

K = the gauge factor
R = the initial resistance in ohms (without strain)
\( \Delta R \) = the change of initial resistance in ohms
L = the initial length in meters (without strain)
\( \Delta L \) = Original Change in length in Metres

From the formula of the Gauge Factor, it can be seen that the denominator of the equation is the Strain. Thus

\[ K = \frac{\Delta R}{R} \frac{G}{G} \]
PIEZO-ELECTRIC TRANSDUCERS

Piezoelectricity is the ability of crystals and certain ceramic materials to generate a voltage in response to applied mechanical stress. When a force is applied across the faces of certain crystal materials; electrical charges (proportional to the applied force) of opposite polarity appear on the faces. These transducers are made from natural crystals such as quartz, Rochelle salt, Lithium sulphate or barium titanate.

To enhance the response of the transducer charge amplifier is normally used to give a reasonable voltage output.
ELECTROMAGNETIC TRANSDUCERS

Employs the generator principle of a coil moving in a magnetic field. The output voltage of the transducer is given as follows

Output voltage $V_o = -N \frac{d\phi}{dt}$

$d\phi/dt = \text{rate of flux changes (Wb/s)}$

Where:

$N = \text{number of turns on coil}$

For the single conductor moving in a magnetic field,

Output voltage:
$V_o = Blv$

Where:

$B = \text{flux density (T)}$
$l = \text{length of conductor (m)}$
$v = \text{velocity of conductor perpendicular to flux direction (m/s)}$

These are widely used as velocity transducers.
DISPLACEMENT TRANSDUCERS

RESISTIVE POSITION TRANSDUCERS

Potentiometric displacement sensor.
The resistive displacement transducers can be modeled as above.

The Voltage $V_0$ can be obtained by:

$$V_0 = \frac{R_2}{R_1 + R_2} V_T$$
SIGNAL CONDITIONING

In electronics, signal conditioning means manipulating an analogue signal in such a way that it meets the requirements of the next stage for further processing.

Signal inputs accepted by signal conditioners include DC voltage and current, AC voltage and current, frequency and electric charge.

Outputs for signal conditioning equipment can be voltage, current, frequency, timer or counter, relay, resistance or potentiometer, and other specialized outputs.

Signal conditioning can include amplification, filtering, converting, range matching, isolation and any other processes required to make sensor output suitable for processing after conditioning.

Filtering

Filtering is the most common signal conditioning function, as usually not all the signal frequency spectrum contains valid data. The common example are 50Hz AC power lines, present in most environments, which will produce noise if amplified.

Amplifying

Signal amplification performs two important functions: increases the resolution of the inputed signal, and increases its signal-to-noise ratio. For example, the output of an electronic temperature sensor, which is probably in the millivolts range is probably too low for an Analog-to-digital converter (ADC) to process directly. In this case it is necessary to bring the voltage level up to that required by the ADC.

Commonly used amplifiers on signal conditioning include Sample and hold amplifiers, Peak Detectors, Log amplifiers, Antilog amplifiers, Instrumentation amplifiers or programmable gain amplifiers.

Isolation

Signal isolation must be used in order to pass the signal from the source to the measurement device without a physical connection: it is often used to isolate possible sources of signal perturbations. Also notable is that's it is important to isolate the potentially expensive equipment used to process the signal after conditioning from the sensor.

Magnetic or optic isolation can be used. Magnetic isolation transforms the signal from voltage to frequency, transmitting it without a physical connection (for example, using a transformer). Optic isolation takes an electronic signal and modulates it to a signal coded by light transmission (optical encoding), which is then used for input for the next stage of processing.
Examples of devices that are used for signal conditioning include:

- signal filters
- instrument amplifiers
- sample-and-hold amplifiers
- isolation amplifiers
- signal isolators
- multiplexers
- bridge conditioners
- analog-to-digital converters
- digital-to-analog converters
- frequency converters or translators
- voltage converters or inverters
- frequency-to-voltage converters
- voltage-to-frequency converters
- current-to-voltage converters
- current loop converters
- charge converters.
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