DARBHANGA COLLEGE OF ENGINEERING DARBHANGA

INSTRUMENTATION AND CONTROL (SEM-IV:ME)

Course Code- PCC-ME 207

Lecture 8&9

SENSOR AND TRANSDUCERS

1. INTRODUCTION

A basic instrument system consists of three elements:

- i SENSOR or INPUT DEVICE
- ii SIGNAL PROCESSOR
- iii RECEIVER or OUTPUT DEVICE

This tutorial is devoted to input devices but you can never separate it from the rest of the system as in many cases they are all integral (e.g. a mechanical pressure gauge incorporates all of these elements). A block diagram of a basic system is shown but they are usually more complex.

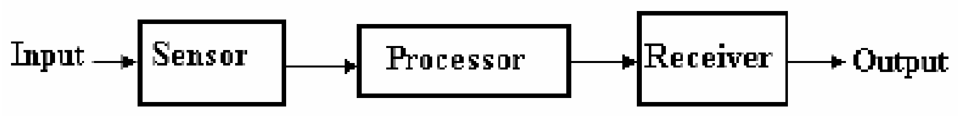


Figure 1

Most modern analogue equipment works on the following standard signal ranges.

- Electric 4 to 20 mA
- Pneumatic 0.2 to 1.0 bar

Older electrical equipment use 0 to 10 V. Increasingly the instruments are digital with a binary digital encoder built in to give a binary digital output. Pneumatic signals are commonly used in process industries for safety especially when there is a risk of fire or explosion.

The advantage of having a standard range or using digital signals is that all equipment may be purchased ready calibrated. For analogue systems the minimum signal (Temperature, speed, force, pressure and so on) is represented by 4 mA or 0.2 bar and the maximum signal is represented by 20 mA or 1.0 bar.

This tutorial is an attempt to familiarise you with the many types of input sensors on the market today. Usually such sensors are called PRIMARY TRANSDUCERS.

Things that we commonly measure are:

- Temperature
- Speed
- Force
- Stress and Strain
- Mass or Weight
- Size or Volume
- Pressure
- Flow rate
- Movement, Velocity and Acceleration
- Level or Depth
- Density
- Acidity/Alkalinity

Sensors may operate simple on/off switches to detect the following:

- Objects(Proximity switch)
- Hot or cold (thermostat)
- Empty or full (level switch)
- Pressure high or low (pressure switch)

The block diagram of a sensor is shown below.

Figure 2

2 TEMPERATURE TRANSDUCERS

2.1 THERMOCOUPLES

When two wires with dissimilar electrical properties are joined at both ends and one junction is made hot and the other cold, a small electric current is produced proportional to the difference in the temperature. Seebeck discovered this effect. It is true no matter how the ends are joined so the cold end may be joined at a sensitive millivolt meter. The hot junction forms the sensor end.

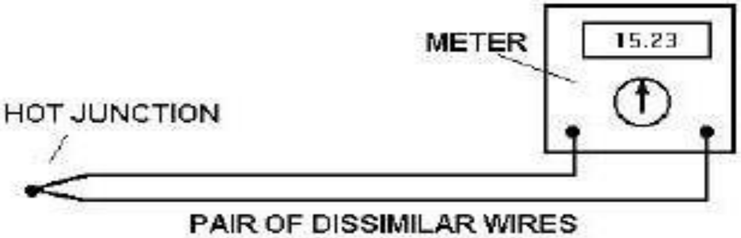


Figure 3

The picture shows a typical industrial probe with a flexible extension and standard plug.

Figure 4

Peltier showed that heat is absorbed at the hot end and rejected at the cold end. Thompson showed that part of the e.m.f. is due to the temperature gradient in the wire as well as the temperature difference between the junctions. Most thermocouple metals produce a relationship between he two temperatures and the e.m.f as follows.

$$e = \alpha(\theta_1 - \theta_2) + \beta(\theta_1^2 - \theta_2^2$$

α and β are constants for the type of thermocouple. The relationship is nearly linear over the operating range. The actual characteristic and suitable operating temperatures depends upon the metals used in the wires. The various types are designated in international and national standards. Typical linear operating ranges are shown for standard types.

It is important that thermocouples are standard so that the same e.m.f will always represent the same temperature.

Type J	0 to 800ºC
Type K	0 to 1200ºC
Type T	-199 to 250ºC
Type E	0 to 600ºC
Type R/S	0 to 1600ºC
Type B	500 to 1800ºC
Type N	0 to 1200ºC
Type L	0 to 800ºC

Thermocouples come in several forms. They may be wires insulated from each other with plastic or glass fibre materials. For high temperature work, the wire pairs are put inside a tube with mineral insulation. For industrial uses the sensor comes in a metal enclosure such as stainless steel.

2.2 RESISTANCE TYPE SENSORS

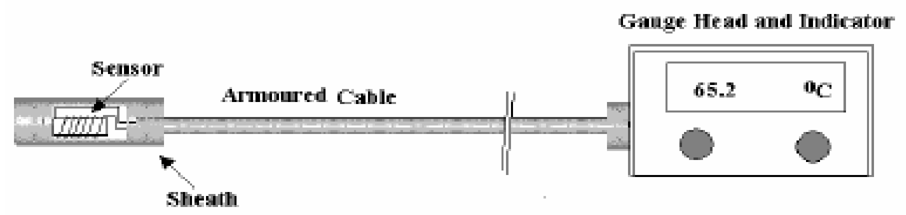


Figure 5

These work on the principle that the electrical resistance of a conductor change with temperature. If a constant voltage is applied to the conductor then the current flowing through it will change with temperature. The resistivity of the conductor change with temperature. This usually means the resistance gets bigger as the conductor gets hotter. The following law relates the resistance and temperature.

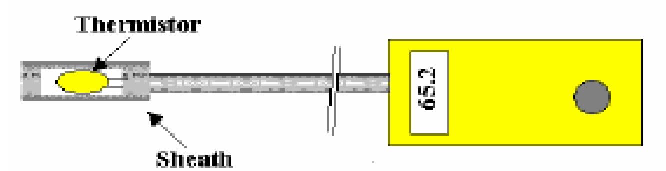
$$R = R_o(1 + \alpha\theta)$$

α is the temperature coefficient of resistance. R_o is the resistance at 0°C. Sometimes the equation is given as

$$R = R_o(1 \quad \alpha\theta - \beta\theta^2)$$

A basic temperature sensor is made by winding a thin resistance wire into a small sensor head. The resistance of the wire then represents the temperature. This has an advantage over a thermocouple in that it is unaffected by the temperature of the gauge end. The main type of wire used is *PLATINUM*. The sensors are usually manufactured to have a resistance of 100 Ω at 0°C and the value of α is 0.00385 to 0.00390. A typical operating range is -200 to 400°C.

A special type of resistance sensor is called a **THERMISTOR**. They are made from a small piece of semi-conductor material. The material is special because the resistance changes a lot for a small change in temperature and so can be made into a small sensor and it costs less than platinum wire. The temperature range is limited. They are only used for a typical range of -20 to 120°C and are commonly used in small hand held thermometers for every day use. The relationship between resistance and temperature is of the form $R = Ae^{B/\theta}$



WORKED EXAMPLE No.1

A Platinum resistance thermometer has a resistance of 100 Ω at 0°C and the value of α is 0.00385. In operation the resistance is 101 Ω. Calculate the temperature.

SOLUTION

Rearrange the formula to make θ the subject and evaluate.

$$? = \frac{\frac{R}{R_o} - 1}{a} = \frac{\frac{105}{100} - 1}{0.00385} = 12.987^{\circ}C$$

WORKED EXAMPLE No.2

A thermocouple produces an e.m.f. in mV according to the temperature difference between the sensor tip θ_1 and the gauge head θ_2 such that

$$e = \alpha(\theta_1 - \theta_2) + \beta(\theta_1{}^2 - \theta_2{}^2)$$

$\alpha = 3.5 \times 10^{-2}$ and $\beta = 8.2 \times 10^{-6}$ The gauge head is at 20°C. The mV output is 12 mV. Calculate the temperature at the sensor.

SOLUTION

$$10 = 0.035(?_1 - 20) + 8.2 \times 10^{-6}(?_1^2 - 20^2)$$

$$10 = 0.035?_1 - 0.7 + 8.2 \times 10^{-6}?_1^2 - 0.00328$$

$$10 = 8.2x10^{-6}?_1^2 + 0.035?_1 - 0.69672$$

$$8.2 \times 10^{-6}?_1^2 + 0.035?_1 - 9.30328 = 0$$

Solving the quadratic equation yields $\theta_1 = 251^{\circ}C$

SELF ASSESSMENT EXERCISE No.1

1. A thermocouple produces an e.m.f. in mV according to the temperature difference between the sensor tip θ_1 and the gauge head θ_2 such that $e = \alpha(\theta_1-\theta_2) + \beta(\theta_1^2-\theta_2^2)$
   Given $\alpha = 3.5 \times 10^{-2}$ and $\beta = 8.2 \times 10^{-6}$ determine the mV output when the tip is at 220°C and the gauge head at 20°C.
   (Answer 7.394 mV)

2. Describe the basic construction of a resistance type temperature sensor and state the reason why it is unaffected by the temperature of the gauge head.

3. State two reasons why instrument systems use standard transmission signal of either 4 - 20 mA or 0.2 - 1 bar.

2.3 LIQUID EXPANSION and VAPOUR PRESSURE SENSORS

These are thermometers filled with either a liquid such as mercury or an evaporating fluid such as used in refrigerators. In both cases the inside of the sensor head and the connecting tube are completely full. Any rise in temperature produces expansion or evaporation of the liquid so the sensor becomes pressurised. The pressure is related to the temperature and it may be indicated on a simple pressure gauge.

Ways and means exist to convert the pressure into an electrical signal. The movement may also directly operate a thermostat. These instruments are robust and used over a wide range. They can be fitted with electric switches to set off alarms.

Figure 6

2.4 BIMETALLIC TYPES

It is a well-known principle that if two metals are rigidly joined together as a two-layer strip and heated, the difference in the expansion rate causes the strip to bend.

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Figure 7

In the industrial type, the strip is twisted into a long thin coil inside a tube. One end is fixed at the bottom of the tube and the other turns and moves a pointer on a dial. The outward appearance is very similar to the pressure type. They can be made to operate limit switches and set off alarms or act as a thermostat. (e.g. on a boiler).

2.5 GLASS THERMOMETER

The ordinary glass thermometer is also a complete system. Again the bulb is the sensor but the column of liquid and the scale on the glass is the processor and indicator. Mercury is used for hot temperatures and coloured alcohol for cold temperatures.

Figure 8

The problems with glass thermometers are that they are

- Brittle
- Mercury solidifies at -40°C.
- Alcohol boils at around 120 °C.
- Accurate manufacture is needed and this makes accurate ones expensive.
- It is easy for people to make mistakes reading them.

Glass thermometers are not used much now in industry but if they are, they are usually protected by a shield from accidental breakage. In order to measure the temperature of something inside a pipe they are placed in thermometer pockets.

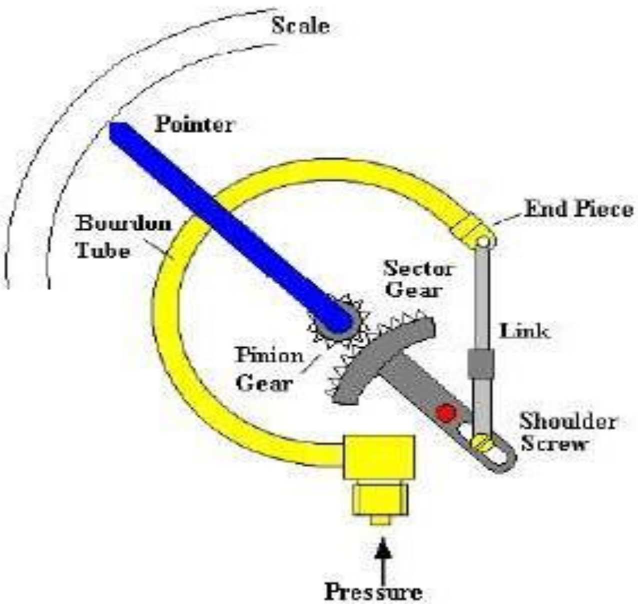
3. PRESSURE TRANSDUCERS

Pressure sensors either convert the pressure into mechanical movement or into an electrical output. Complete gauges not only sense the pressure but indicate them on a dial or scale.

Mechanical movement is produced with the following elements.

- Bourdon Tube.
- Spring and Piston.
- Bellows and capsules.
- Diaphragm.

3.1. BOURDON TUBE



Section through the tube

Picture

-

The Bourdon tube is a hollow tube with an elliptical cross section. When a pressure difference exists between the inside and outside, the tube tends to straighten out and the end moves. The movement is usually coupled to a needle on a dial to make a complete gauge. It can also be connected to a secondary device such as an air nozzle to control air pressure or to a suitable transducer to convert it into an electric signal. This type can be used for measuring pressure difference.

3.2 PISTON TYPE

The pressure acts directly on the piston and compresses the spring. The position of the piston is directly related to the pressure. A window in the outer case allows the pressure to be indicated. This type is usually used in hydraulics where the ability to withstand shock, vibration and sudden pressure changes is needed (shock proof gauge). The piston movement may be connected to a secondary device to convert movement into an electrical signal.

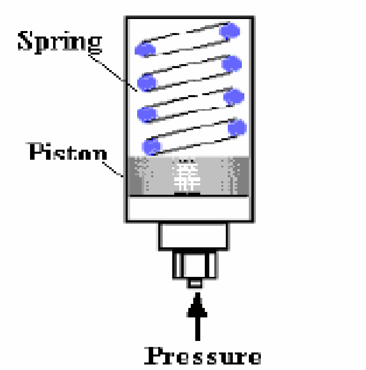


Figure 10

3.3. CAPSULES AND BELLOWS

A bellows is made of several capsules. These are hollow flattened structures made from thin metal plate. When pressurised the bellows expand and produce mechanical movement. If the bellows is encapsulated inside an outer container, then the movement is proportional to the difference between the pressure on the inside and outside. Bellows and single capsules are used in many instruments. They are very useful for measuring small pressures.

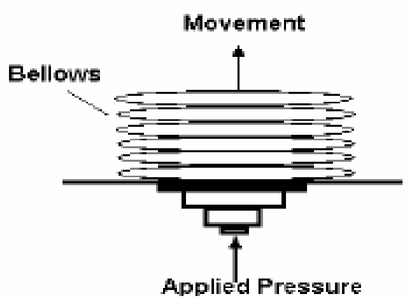


Figure 11

3.4 DIAPHRAGMS

These are similar in principle to the capsule but the diaphragm is usually very thin and perhaps made of rubber. The diaphragm expands when very small pressures are applied. The movement is transmitted to a pointer on a dial through a fine mechanical linkage.

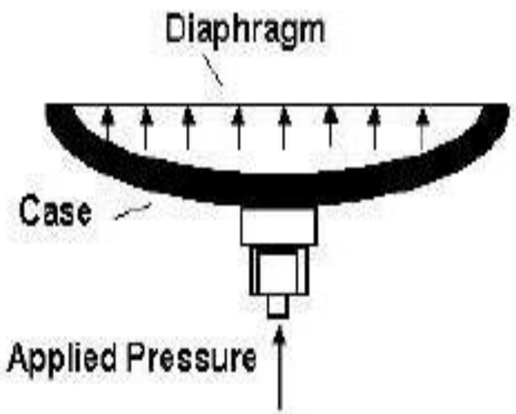


Figure 12

3.5 ELECTRICAL PRESSURE TRANSDUCERS

There are various ways of converting the mechanical movement of the preceding types into an electric signal. Th following are types that directly produce an electric signal

- Strain Gauge types.
- Piezo electric types.
- Other electric effects.

3.5.1 STRAIN GAUGE TYPES

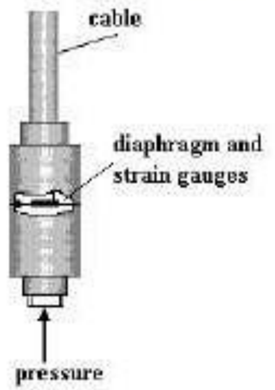


Figure 13

The principles of electric strain gauges are covered later. Strain gauges are small elements that are fixed to a surface that is strained. The change in length of the element produces changes in the electrical resistance. This is processed and converted into a voltage. A typical pressure transducer would contain a metal diaphragm which bends under pressure.

3.5.2. PIEZO ELECTRIC TYPES

The element used here is a piece of crystalline material that produces an electric charge on its surface when it is mechanically stressed. The electric charge may be converted into voltage. This principle is used in the pick up crystal of a record player, in microphones and even to generate a spark in a gas ignitor. When placed inside a pressure transducer, the pressure is converted into an electric signal.

3.5.3. OTHER ELECTRIC EFFECTS

Other electric effects commonly used in transducers are CAPACITIVE and INDUCTIVE. In these cases, the pressure produces a change in the capacitance or inductance of an electronic component in the transducer. Both these effects are commonly used in an electronic oscillator and one way they may be used is to change the frequency of the oscillation. The frequency may be converted into a voltage representing the pressure.

4. SPEED TRANSDUCERS

Speed transducers are widely used for measuring the output speed of a rotating object. There are many types using different principles and most of them produce an electrical output.

4.1 OPTICAL TYPES

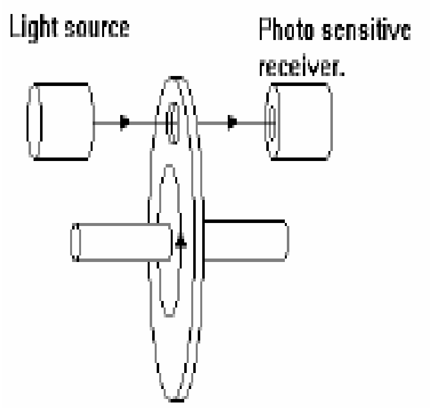


Figure 14

These use a light beam and a light sensitive cell. The beam is either reflected or interrupted so that pulses are produced for each revolution. The pulses are then counted over a fixed time and the speed obtained. Electronic processing is required to time the pulses and turn the result into an analogue or digital signal.

4.2 MAGNETIC PICK UPS

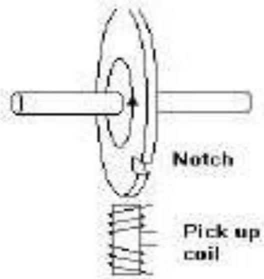


Figure 15

These use an inductive coil placed near to the rotating body. A small magnet on the body generates a pulse every time it passes the coil. If the body is made of ferrous material, it will work without a magnet. A discontinuity in the surface such as a notch will cause a change in the magnetic field and generate a pulse. The pulses must be processed to produce an analogue or digital output.

4.3 TACHOMETERS

There are two types, A.C. and D.C. The A.C. type generates a sinusoidal output. The frequency of the voltage represents the speed of rotation. The frequency must be counted and processed. The D.C. type generates a voltage directly proportional to the speed. Both types must be coupled to the rotating body. very often the tachometer is built into electric motors to measure their speed.

Figure 16

SELF ASSESSMENT EXERCISE No.4

1. State what each of the sensors below measures (flow, temperature and so on)

a. Thermocouple.
b. Potentiometer.
c. Thermistor.
d. Optical fringes.
e. Venturi meter.
f. Pitot tube.
g. Bimetallic type.
h. Platinum resistance probe.
i. D.C. type generator.
j. L.V.D.T.
k. Bourdon tube.
l. Orifice meter.
m. Piezo electric.

2. State two types of sensors that could be used to measure each of the following.

a. Speed of revolution.
b. Flow rate of liquids.
c. Pressure.
d. Temperature.