Mechanical Engineering

Mechatronics and Robotics

Comprehensive Theory

with Solved Examples and Practice Questions

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CHAPTER 2

Sensors and Other Devices

2.1 Introduction

A sensor is an electronic element in mechatronic or measurement system that acquires a physical parameter and change it into a signal that can be processed by the system. Often the active element of a sensor is referred as a transducer. The monitoring and control systems require sensors to measure physical quantities such as position, distance, force, strain, temperature, vibration and acceleration.

Design of Sensors and transducer always involves the application of some principles of chemistry and physics. Sensors in manufacturing are used for automation of production processes as well as process monitoring activities.

2.1.1 Definition of Sensor

Sensor is defined as an element which produces a signal corresponding to the quantity under measurement. According to the Instrument Society of America, sensor can be defined as "A device which provides a usable output in response to a specified measurand." Here, the output is usually an 'electrical quantity' and measurand is a 'physical quantity, property or condition which is to be measured'. Thus in the case of, say, a thermister, the quantity being measured is temperature and the sensor transforms an input of temperature into a change in resistance.

2.1.2 Advantages of Sensors

Sensor technology has the important advantages in manufacturing automation as follows:

- Sensors alarm the system operators about the failure of any of the subunits of manufacturing systems. It helps to reduce the downtime of complete manufacturing system by taking preventative measures.
- By employing sensor technology requirement of skilled and experienced labor decreases.
- High quality products with ultra-precision can be achieved.

2.1.3 Transducer

It is defined as an element which, when subjected to a physical change experiences a related change or an element which converts a specified measurand into a usable output by using a transducing principal. It can also be defined as a device that converts a signal from one form of energy to another form.

When a transducer converts a measurable quantity (sound pressure level, optical intensity, magnetic field, etc.) into an electrical voltage or an electrical current then it is called a sensor. When the transducer converts an electrical signal into another form of energy such as sound (which, incidentally, is a pressure field), light, mechanical movement, etc. then it is called as an actuator. A wire of constantan alloy (copper-nickel 55-45% alloy) can be called as a sensor because variation in mechanical displacement (tension or compression) can be sensed as a change in electrical resistance. This wire becomes a transducer with appropriate electrodes and input-output mechanism attached to it. Thus we can say that 'sensors are transducers'.

2.1.4 Sensor Specifications

Sensors or measurement systems are not perfect systems. One should know the capability and shortcoming of a sensors or measurement system to properly assess its performance before using it. Sensor specifications tell the user about variations from the ideal behavior of the sensors. Following are the various specifications of a sensor/transducer system. The sensor or transducer specifications include range, span, error, accuracy, nonlinearity, sensitivity, hysteresis, dead band/time, resolution, stability, Repeatability and response time.

(i) Range

The range of a sensor indicates the limits between which the input can vary. Thus, for example, a pressure sensor for the measurement of pressure might have a range of 1 to 10,000 psi.

(ii) Span

The span is the difference between the maximum and minimum values of the input. Thus, the above-mentioned pressure sensor will have a span of 9,999 psi.

(iii) Error

Error is the difference between the result of the measurement and the true value of the input or the quantity under measurement. For example A thermocouple giving a temperature reading of 38.6 °C, while the actual temperature is 40°C, then the error is –0.4°C.

$$\text{Errors} = \text{Measured value} - \text{True value.}$$

(iv) Accuracy

The accuracy is the closeness of the agreement between the result of the measurement and the actual value of the measurand. It may also be defined as the proximity of measurement results to the true value. It is often expressed as a percentage of the full range output or full-scale deflection. For example a piezoelectric transducer is capable to detect pressures between 1 kPa to 70 MPa. If it is specified with the accuracy of about ±0.5% full scale, then the reading given can be expected to be within ± 0.35 MPa.

(v) Sensitivity

Sensitivity of a sensor is defined as the ratio of change in the output value of a sensor to the change in input value that causes the output change. For example, a hall effect sensor may have a sensitivity of –10 mV/mT (milli volt/ milli tesla; 1 mT = 10 Gauss (G)).

(vi) Nonlinearity

The nonlinearity indicates the maximum deviation of the actual measured curve of a sensor from the ideal curve.

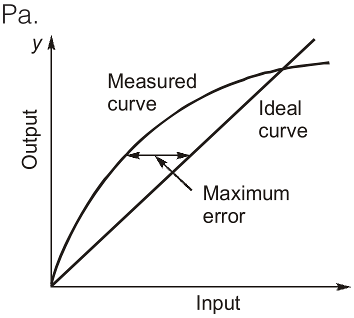

Fig. 2.1: Non-linearity error

Fig. 2.1 shows a somewhat exaggerated relationship between the ideal, or least squares fit, line and the actual measured or calibration line. Linearity is often specified in terms of percentage of nonlinearity, which is defined as:

$$\%\text{ of Non-linearity} = \frac{\text{Maximum deviation between nonlinear and linear curve}}{\text{Output span}} \times 100 \qquad ...(1)$$

The static nonlinearity defined by equation (1) is dependent upon environmental factors, including temperature, humidity, vibration and acoustic noise level. Therefore it is important to know under what conditions the specification is valid.

(vii) Hysteresis

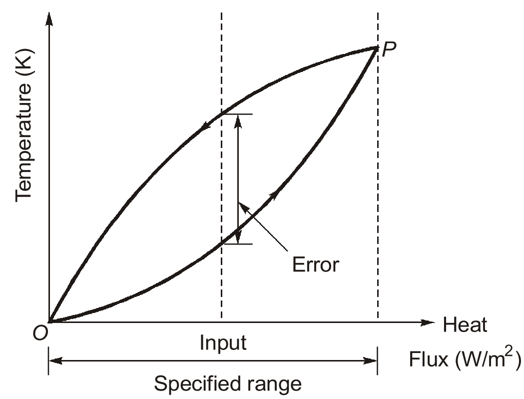

Fig. 2.2: Hysteresis error curve

The hysteresis is an error of a sensor, which is defined as the maximum difference in output at any measurement value within the sensor's specified range when approaching the point first with increasing and then with decreasing the input parameter. Fig. 2.2 shows the hysteresis error (shown exaggerated for clarity) might have occurred during the measurement of temperature using a thermocouple. The hysteresis error is normally specified as a positive or negative percentage of the specified input range.

(viii) Resolution

Resolution is the smallest detectable incremental change of input parameter that can be noticed in the output signal. Resolution is expressed either as a fraction of the full-scale reading or in absolute terms. For example, if an LVDT sensor measures a displacement up to 50 mm and it provides an output as a number between 1 and 200 then the resolution of the sensor device is 0.25 mm.

(ix) Stability

Stability is the ability of a sensor device to give the same output when used to measure a constant input continuously over a period of time. The term 'drift' is used to indicate the change in output that occurs over a period of time. It is expressed as the percentage of full range output.

(x) Dead Band/Time

The dead band or dead space of a transducer is the range of input values for which there is no output. The dead time of a sensor device is the time interval between the application of an input and the moment when output begins to respond or change.

(xi) Repeatability

Repeatability is specified as the ability of a sensor to give the same output for repeated applications of same input value. It may also be defined as the variation in measurements taken by the same person or instrument on the same item, under the same conditions, and in a short period of time. It is usually expressed as a percentage of the full range output:

Repeatability = (maximum – minimum values given) × 100/full range ...(2)

(xii) Response Time

Response time describes the speed of change in the output on a step-wise change in the input or the measurand. It is always specified along with the input step and the output range for which the response time is defined.

2.1.5 Classification of Sensors

The classification of sensors in view of their applications in manufacturing is as follows:

A. Velocity and Motion Sensors:
- Incremental encoder
- Tacho-generator
- Pyroelectric sensors

B. Force Sensors:
- Strain gauge load cell

C. Fluid Pressure Sensors:
- Diaphragm pressure gauge
- Capsules, bellows, pressure tubes
- Piezoelectric sensors
- Tactile sensor

D. Displacement, Position and Proximity Sensors
- Potentiometer
- Strain-gauged element
- Pneumatic sensors
- Proximity switches (magnetic)
- Hall effect sensors
- Capacitive element
- Eddy current proximity sensors
- Differential transformers

E. Liquid flow Sensors:
- Orifice plate
- Turbine meter

F. Liquid level Sensor:
- Differential pressure
- Floats

G. Temperature Sensors:
- Thermo-diodes and transistors
- Thermocouples
- Light sensors
- Resistance temperature detectors
- Thermistors
- Photo resistors
- Photo transistor
- Bimetallic strip

2.1.6 Displacement and Position Sensors

Displacement sensors are basically used for the measurement of movement of an object. Position sensors are used to find the position of an object in relation to some reference point. Proximity sensors are a sort of position sensor and are used to trace when an object has moved within particular critical distance of a transducer.

(i) Potentiometer Sensors

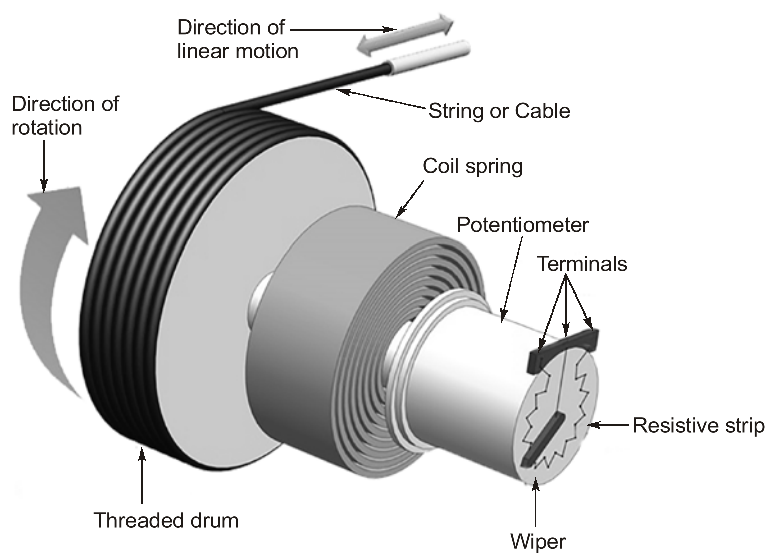

Fig. 2.3: Schematic of a potentiometer sensor for measurement of linear displacement

Fig. 2.3 shows the internal structure of a rotary type potentiometer sensor used for measurement of the linear displacement. The potentiometer can be linear or angular type. It is based on the principle of conversion of mechanical displacement into an electrical signal. It has a resistive element and a sliding contact (wiper). The slider moves along this conductive body, acting as a movable electric contact.

The object, whose displacement is to be measured, is connected to the slider using:

- a moving rod (for linear displacement)
- a rotating shaft (for angular displacement)
- a cable that is kept stretched during operation

The resistive element is a wire wound track or conductive plastic. The track consists of a closely packed resistive coil. Conductive plastic is made up of plastic resin embedded with the carbon powder. Wire wound track has a resolution of the order of ±0.01%, while the conductive plastic may have the resolution of about 0.1 μm.

During the operation of potentiometer, a voltage VS is applied across the resistive element. When the slider comes into contact with the wire, the resistive element is divided into two parts, and hence a voltage divider circuit is formed. The output voltage (VA) is measured as shown in the Fig. 2.3. The output voltage is proportional to the displacement of the slider over the wire. Then the displacement as an output parameter that is to be measured is calibrated against the output voltage VA.

Applications of Potentiometer

These sensors are primarily used in the control systems with a loop of feedback to ensure that the moving member or component reaches its commanded position.

These sensors are used on machine-tool controls, elevators, liquid-level assemblies, forklift trucks, automobile throttle controls etc. In manufacturing process, these sensors are employed in control of injection molding machines, wood working machinery, printing, spraying, robotics, etc.

(ii) Strain Gauges

The strain developed is defined as a ratio of change in length in the same direction in which the load is applied to the original length of the element. The produced strain causes a change in the element's resistance. Therefore, we can say that,

$$\frac{\Delta R}{R} \propto \varepsilon \qquad ...(3)$$

$$\frac{\Delta R}{R} = G\varepsilon \qquad ...(4)$$

where G is the proportionality constant and it is also called gauge factor. G value is considered in between 2 to 4 and the resistances are taken of the order of 100 Ω .

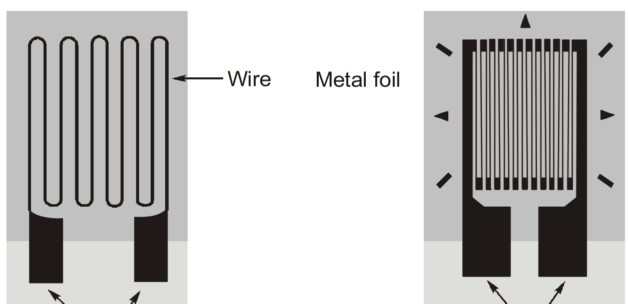

Fig. 2.4: A pattern of resistive foils

Wheatstone's Bridge

Resistance strain gauge follows the principle of change in resistance as per the equation (4). It comprises of resistive foil shown in Fig. 2.4. These foils are made of Constantan alloy (copper-nickel 55-45% alloy) and the foils are stick to a backing material plastic (polyimide), epoxy or glass fiber reinforced epoxy. The strain gauges are fixed to the work material using epoxy or Cyanoacrylate cement Eastman 910 SL. As the shape of the work piece changes due to external loading, the resistance of strain gauge element changes. This resistance change can be sensed using a Wheatstone's resistance bridge principle as shown in Fig. 2.5. In the balanced bridge we can have a relation:

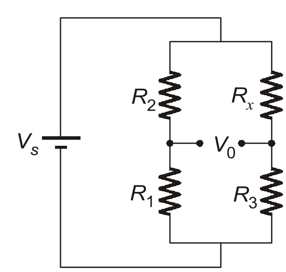

Fig. 2.5: Wheatstone's bridge

$$\frac{R_2}{R_1} = \frac{Rx}{R_2} \qquad ...(5)$$

where R_x is the resistance of strain gauge element, R_2 is balancing/adjustable resistor, R_1 and R_3 are resistors which have constant value. The measured deformation or displacement by the stain gauge is calibrated against change in resistance of adjustable resistor R_2 which makes the voltage across nodes A and B equal to zero.

Applications of strain gauges

Strain gauges are broadly employed in stress analysis and diagnosis of machines and failure analysis. Basically, they are employed for multi-axial stress fatigue testing, proof testing, residual stress and vibration measurement, torque measurement, bending and deflection measurement, compression and tension measurement and strain measurement.

Primarily the strain gauges are used as sensors for machine tools and safety in automobiles. In particular, they are used in the force calculation of machine tools, hydraulic or pneumatic press and as impact sensors in aerospace vehicles.

2.1.7 Velocity, Motion, Force and Pressure Sensors:

(i) Piezoelectric Sensor

Piezoelectric sensors are used for the quantification of pressure, acceleration and dynamic-forces like oscillation, impact forces, or high speed compression or tension. It contains piezoelectric ionic crystal materials such as Quartz (Fig. 2.6). On application of force or pressure these materials get stretched or compressed. As a result of compression the redistribution of the charge of the material takes place. One face of the material becomes positively charged and the other negatively charged.

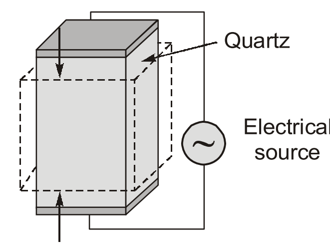

Fig. 2.6: Working principle of Piezoelectric sensor

The charge q on the surface is directly proportional to the distance by which the charge has been moved. The distance moved by the charge is directly proportional to the applied force. Therefore, it can be written,

$$q = SF = kx \quad ...(6)$$

where, k is constant and S is a constant termed the charge sensitivity.

(ii) Tachogenerator

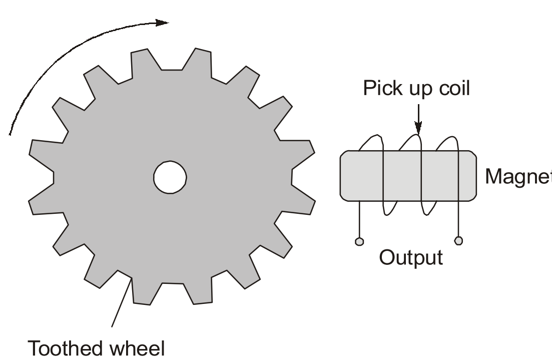

Fig. 2.7: The working principle of Techogenerator

Tachogenerator works on the principle of variable reluctance. It consists of an assembly of a toothed wheel and a magnetic circuit as shown in Fig. 2.7. A toothed wheel is mounted on the shaft or the element of which angular motion is to be measured. The magnetic circuit comprising of an electromagnetic coil wound on a ferromagnetic material. The air gap between the tooth of the wheel and magnetic core changes with the rotation of the wheel, which results in a cyclic change in magnetic flux associated with the coil. The alternating emf is generated which is the measure of angular motion. Finally a pulse shaping signal conditioner is used to transform the output into a number of pulses which are counted by a counter.

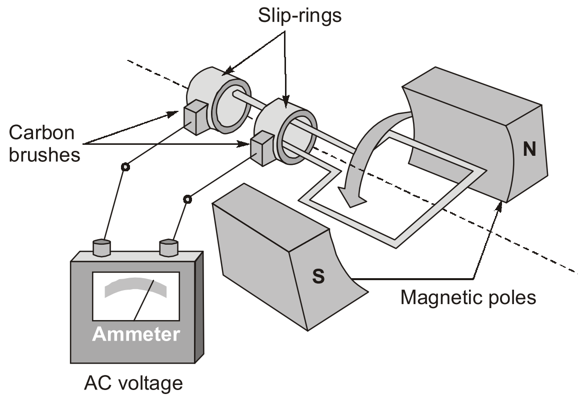

Fig. 2.8: Construction and working of AC generator

An alternating current (AC) generator can also be used as a tachogenerator. It consists of rotor coil which rotates with the shaft. Fig. 2.8 shows the schematic of an AC generator. The rotor rotates in the magnetic field produced by a stationary permanent magnet or an electromagnet. During this process, an alternating emf is generated which is the measure of the angular velocity of the rotor. In general, these sensors have a nonlinearity error of about ± 0.15% and they can be used for maximum speed up to about 10000 RPM.

2.1.8 Light Sensors

A light sensor is a device that is used to identify the light. Todays many types of light sensors such as photocell/photo-resistor and photo diodes are being employed in industrial and other manufacturing applications.

Photoresistor, also called as a light dependent resistor (LDR) has a resistor whose resistance decreases with increasing incident light intensity. It is made of a high resistance semiconductor material, cadmium sulfide (CdS). As per the principle of photoconductivity, the resistance of cadmium sulfide photoresistor decreases with the amount of light incident upon it. This is due to the generation of mobile carriers when photons are absorbed by the semiconductor material.

Fig. 2.9 shows the construction of a photoresistor.

The CdS resistor coil is mounted on a ceramic substrate. This assembly is surrounded by a resin material. The sensitive coil electrodes are connected to the control system through lead wires. When the high intensity light fall on the electrodes, the resistance of resistor coil decreases, which is further converted into the appropriate signals with the help of microprocessor.

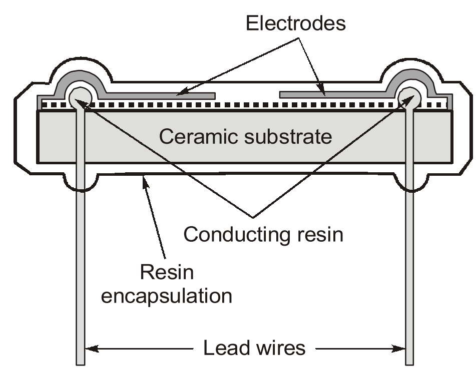

Fig. 2.9: Construction of a photoresistor

Photoresistors are employed in scientific applications and almost any branch of industry for safety, inspection, enjoyment, sound reproduction, and control, measurement.

Photo resistor applications:

- Computers, televisions, wireless phones employ ambient light sensors to auto control the brightness of screen.
- Barcode scanners
- In space and robotics
- Auto flash for camera
- Industrial process control

Example - 2.9 A shaft encoder which is attached to a sensitivity of 500 pulses per revolution A digital pulse counter connected to the output of the encoder indicates 5500 pulses in 1 sec. The speed of the motor in rpm is.............

Solution:

$$1 \text{ Rev} = 500 \text{ pulses}$$
$$5500 \text{ pulses} = 11 \text{ Rev}$$
$$11 \text{ Rev} = 1 \text{ sec}$$
$$11 \times 60 = 1 \text{ min} = 660 \text{ rpm}$$

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PRACTICE QUESTIONS

1. Hall voltage is directly proportional to _______.
   (a) current
   (b) electric field
   (c) magnetic flux density
   (d) all of above

2. What does a Hall Effect measurement measure?
   (a) The mobility
   (b) The Hall mobility
   (c) The carrier density and carrier type
   (d) The Hall carrier density and the carrier type
   (e) The effective mass

3. Hall Effect may be used to
   (a) Determine whether semiconductor is p-type or n-type
   (b) Determine the carrier concentration
   (c) Calculate the mobility
   (d) All the above

4. Electric field strength related to hall voltage is given by
   (a) VHd (b) VH/d
   (c) VHE (d) Ed

5. Measurement of Hall coefficient enables the determination of
   (a) mobility of charge carriers
   (b) type of conductivity and concentration of charge carriers
   (c) temperature coefficient and thermal conductivity
   (d) none of the above

6. Hall probe is made up of
   (a) Metals (b) Non metals
   (c) Semiconductor (d) Radioactive material

7. In Hall Effect, voltage across probe is known as
   (a) Hall voltage
   (b) Electro motive force
   (c) Potential difference
   (d) None of the above

8. A Hall effect device is sensitive to
   (a) Magnetic field (b) Moisture
   (c) Infrared (d) Ultrasound

9. Measurement of the Hall coefficient in a semiconductor provides information on the
   (a) Sign and mass of charge carriers
   (b) Mass and concentration of charge carriers
   (c) Sign of charge carriers alone
   (d) Sign and concentration of charge carriers

10. Hall Effect is observed in a specimen when it (metal or a semi conductor) is carrying current and placed in a magnetic field. The resultant electric field inside the specimen will be in
    (a) a direction normal to both current and magnetic field.
    (b) the direction of current.
    (c) a direction anti parallel to the magnetic field.
    (d) none of the above.

11. What does a Hall Effect sensor sense?
(a) Temperature (b) Magnetic field
(c) Moisture (d) Pressure

12. The Hall Effect voltage in intrinsic silicon is
(a) Positive (b) Negative
(c) Zero (d) None of the above

13. Which type of signal resolvers transmit?
(a) Analog
(b) Digital
(c) Both Analog and Digital
(d) None of the above

14. On increasing the speed of a resolver, the absolute information is ____________
(a) lost
(b) gain
(c) neither lost nor gain
(d) either lost either gain

15. A controller, essentially, is ____________
(a) sensor (b) clipper
(c) comparator (d) amplifier

16. Inductosyn position Transducers can be used as:
(a) Ratiometric comparisons of sine and cosine output signals
(b) Amplitude measurement or nulling of error output signals
(c) Phase shift of error output signals
(d) All of the above

17. What does an inductosyn resembles to in terms of operation?
(a) Multipole resolver
(b) Synchros
(c) LVDT
(d) Hall Effect sensors

18. At what transformation ratio does an inductosyn operate on?
(a) 1 : 100 (b) 1000 : 1
(c) 100 : 1 (d) 1 : 1000

19. What is the sine output of an inductosyn if S is the distance between pitches, and X is the slider displacement within a pitch, and the scale is energized with a voltage V sin$t$?
(a) V sinw$t$ cos[2pX/S]
(b) V sinw$t$ sin[2p X/S]
(c) V cosw$t$ sin[2p X/S]
(d) V cosw$t$ cos[2p X/S]

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ANSWERS

1. (d)	2. (d)	3. (d)	4. (b)	5. (b)	6. (c)	7. (a)
8. (a)	9. (d)	10. (a)	11. (b)	12. (b)	13. (a)	14. (a)
15. (c)	16. (d)	17. (a)	18. (c)	19. (b)		