Chapter 13

Transducers

INTRODUCTION

13.1

A transducer is defined as a device that receives energy from one system and transmits it to another, often in a different form.

Broadly defined, the transducer is a device capable of being actuated by an energising input from one or more transmission media and in turn generating a related signal to one or more transmission systems. It provides a usable output in response to a specified input measurand, which may be a physical or mechanical quantity, property, or conditions. The energy transmitted by these systems may be electrical, mechanical or acoustical.

The nature of electrical output from the transducer depends on the basic principle involved in the design. The output may be analog, digital or frequency modulated.

Basically, there are two types of transducers, electrical, and mechanical.

ELECTRICAL TRANSDUCER

13.2

An electrical transducer is a sensing device by which the physical, mechanical or optical quantity to be measured is transformed directly by a suitable mechanism into an electrical voltage/current proportional to the input measurand.

An electrical transducer must have the following parameters:

1. ***Linearity*** The relationship between a physical parameter and the resulting electrical signal must be linear.
2. ***Sensitivity*** This is defined as the electrical output per unit change in the physical parameter (for example V/°C for a temperature sensor). High sensitivity is generally desirable for a transducer.
3. ***Dynamic Range*** The operating range of the transducer should be wide, to permit its use under a wide range of measurement conditions.
4. ***Repeatability*** The input/output relationship for a transducer should be predictable over a long period of time. This ensures reliability of operation.
5. ***Physical Size*** The transducer must have minimal weight and volume, so that its presence in the measurement system does not disturb the existing conditions.

Advantages of Electrical Transducers The main advantages of electrical transducers (conversion of physical quantity into electrical quantities) are as follows:

1. Electrical amplification and attenuation can be easily done.
2. Mass-inertia effects are minimised.
3. Effects of friction are minimised.
4. The output can be indicated and recorded remotely at a distance from the sensing medium.
5. The output can be modified to meet the requirements of the indicating or controlling units. The signal magnitude can be related in terms of the voltage current. (The analog signal information can be converted in to pulse or frequency information. Since output can be modified, modulated or amplified at will, the output signal can be easily used for recording on any suitable multichannel recording device.)
6. The signal can be conditioned or mixed to obtain any combination with outputs of similar transducers or control signals.
7. The electrical or electronic system can be controlled with a very small power level.
8. The electrical output can be easily used, transmitted and processed for the purpose of measurement.

Electrical transducers can be broadly classified into two major categories, (i) Active, (ii) Passive.

An **active transducer** generates an electrical signal directly in response to the physical parameter and does not require an external power source for its operation. Active transducers are self generating devices, which operate under energy conversion principle and generate an equivalent output signal (for example from pressure to charge or temperature to electrical potential).

Typical example of active transducers are piezo electric sensors (for generation of charge corresponding to pressure) and photo voltaic cells (for generation of voltage in response to illumination).

Passive transducers operate under energy controlling principles, which makes it necessary to use an external electrical source with them. They depend upon the change in an electrical parameter (R, L and C).

Typical example are strain gauges (for resistance change in response to pressure), and thermistors (for resistance change corresponding to temperature variations).

Electrical transducers are used mostly to measure non-electrical quantities. For this purpose a detector or sensing element is used, which converts the physical quantity into a displacement. This displacement actuates an electric transducer, which acts as a secondary transducer and give an output that is electrical in nature. This electrical quantity is measured by the standard method used for electrical measurement. The electrical signals may be current, voltage, or frequency; their production is based on R, L and C effects.

A transducer which converts a non-electrical quantity into an analog electrical signal may be considered as consisting of two parts, the sensing element, and the transduction element.

The sensing or detector element is that part of a transducer which responds to a physical phenomenon or to a change in a physical phenomenon. The response of the sensing element must be closely related to the physical phenomenon.

The transduction element transforms the output of a sensing element to an electrical output. This, in a way, acts as a secondary transducer.

Transducers may be further classified into different categories depending upon the principle employed by their transduction elements to convert physical phenomena into output electrical signals.

The different electrical phenomena employed in the transduction elements of transducers are as follows.

1. Resistive
2. Inductive
3. Capacitive
4. Electro magnetic
5. Piezo-electric
6. Photo-emissive
7. Photo-resistive
8. Potentiometric
9. Thermo-electric
10. Frequency generating

SELECTING A TRANSDUCER 13.3

The transducer or sensor has to be physically compatible with its intended application. The following should be considered while selecting a transducer.

1. ***Operating range*** Chosen to maintain range requirements and good resolution.
2. ***Sensitivity*** Chosen to allow sufficient output.
3. ***Frequency response and resonant frequency*** Flat over the entire desired range.
4. ***Environmental compatibility*** Temperature range, corrosive fluids, pressure, shocks, interaction, size and mounting restrictions.
5. ***Minimum sensitivity*** To expected stimulus, other than the measurand.
6. ***Accuracy*** Repeatability and calibration errors as well as errors expected due to sensitivity to other stimuli.
7. ***Usage and ruggedness*** Ruggedness, both of mechanical and electrical intensities versus size and weight.
8. ***Electrical parameters*** Length and type of cable required, signal to noise ratio when combined with amplifiers, and frequency response limitations.

RESISTIVE TRANSDUCER 13.4

Resistive transducers are those in which the resistance changes due to a change in some physical phenomenon. The change in the value of the resistance with a change in the length of the conductor can be used to measure displacement.

Strain gauges work on the principle that the resistance of a conductor or semiconductor changes when strained. This can be used for the measurement of displacement, force and pressure.

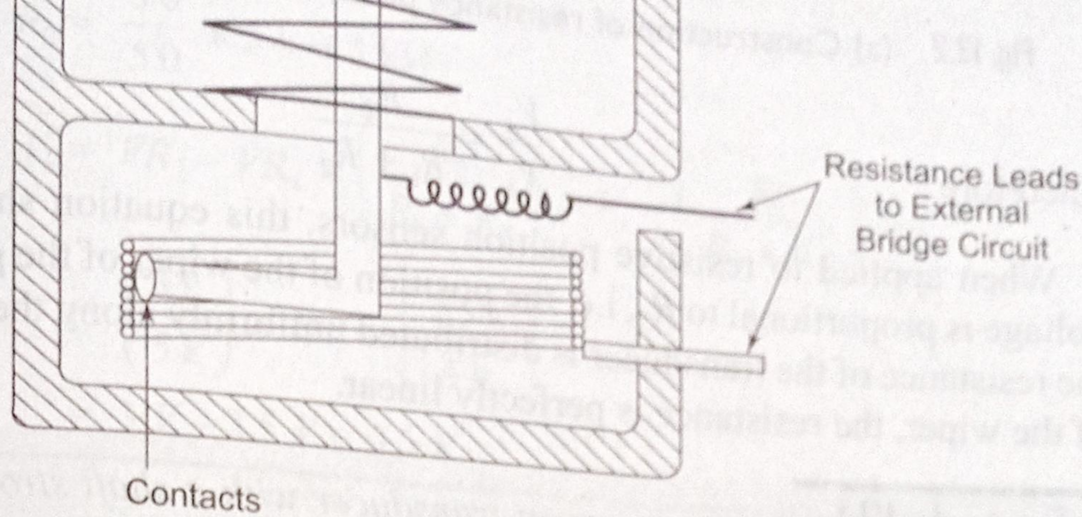

Fig. 13.1(e) Sensitive diaphragm moves the resistance contact

RESISTIVE POSITION TRANSDUCER

13.5

The principle of the resistive transducer is that the physical variable under measurement causes a resistance change in the sensing element. (A common requirement in industrial measurement and control work is to be able to sense the position of an object, or the distance it has moved).

One type of displacement transducer uses a resistive element with a sliding contact or wiper linked to the object being monitored or measured. Thus the resistance between the slider and one end of the resistance element depends on the position of the object. Figure 13.2(a) gives the construction of this type of transducer.

Figure 13.2(b) shows a typical method of use. The output voltage depends on the wiper position and is therefore a function of the shaft position. This voltage may be applied to a voltmeter calibrated in cms for visual display.

(Typical commercial units provide a choice of maximum shaft strokes, from an inch or less to 5 ft or more.) Deviation from linearity of the resistance versus distance specifications can be as low as 0.1 – 1.0%.

Considering Fig. 13.2(b), if the circuit is unloaded, the output voltage V_o is a certain fraction of V_t, depending upon the position of the wiper.

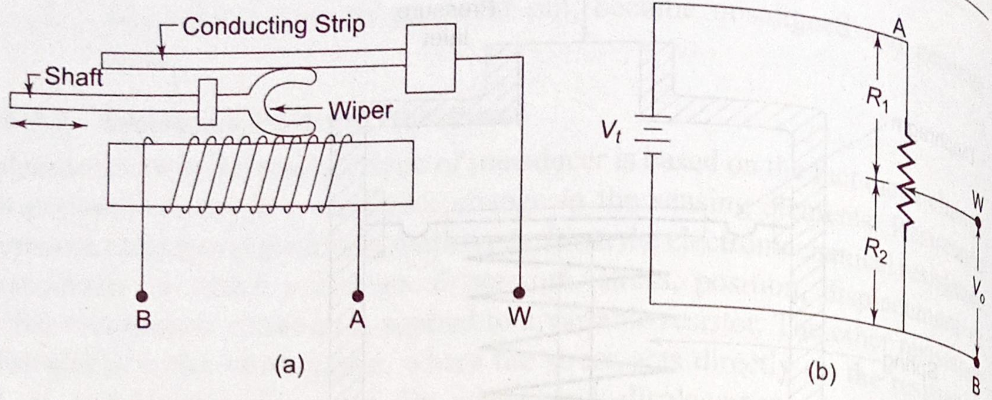

Fig. 13.2 (a) Construction of resistance position transducer (b) Typical method

Therefore, $$\frac{V_o}{V_t} = \frac{R_2}{R_1 + R_2}$$

When applied to resistive position sensors, this equation shows that output voltage is proportional to R_2, i.e. the position of the wiper of the potentiometer. If the resistance of the transducer is distributed uniformly along the length of travel of the wiper, the resistance is perfectly linear.

Example 13.1 *A displacement transducer with a shaft stroke of 3.0 in. is applied to the circuit of Fig. 13.2(b). The total resistance of the potentiometer is 5 kΩ. The applied voltage V_t is 5 V. When the wiper is 0.9 in. from B, what is the value of the output voltage?*

Solution $$R_2 = \frac{0.9\text{ in.}}{3.0\text{ in.}} \times 5\text{ k} = \frac{9}{30} \times 5\text{ k} = 1500\ \Omega$$

Therefore $$\frac{V_o}{V_t} = \frac{R_2}{R_1 + R_2};\ V_o = \frac{R_2}{R_1 + R_2} \times V_t$$

$$V_o = \frac{1500}{5\text{ k}} \times 5\ V = \frac{1500}{1\text{ k}} = 1.5\ V$$

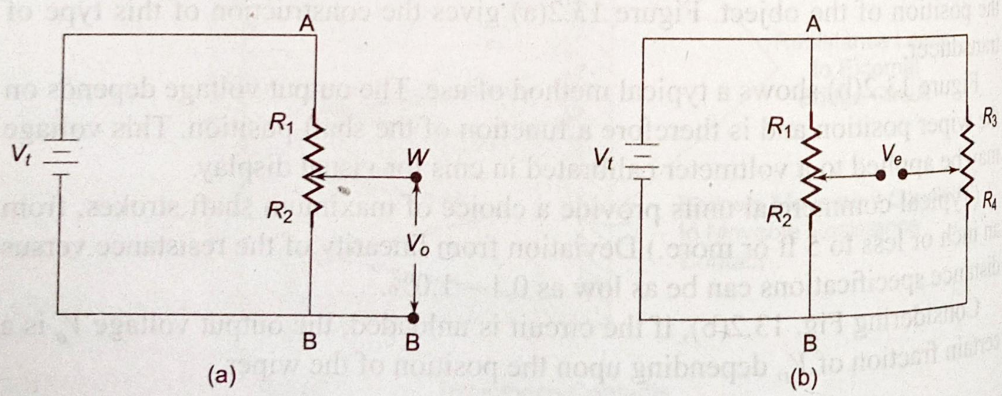

Fig. Ex. 13.1

Example 13.2 *A resistive transducer with a resistance of 5 kΩ and a shaft stroke of 3.0 in. is used in the arrangement in Fig. Ex. 13.1. Potentiometer R_3–R_4 is also 5 k and V_t is 5.0 V. The initial position to be used as a reference point is such that $R_1 = R_2$ (i.e. the shaft is at the centre). At the start of the test, potentiometer R_3–R_4 is adjusted so that the bridge is balanced ($V_e = 0$). Assuming that the object being monitored moves a maximum resistance of 0.5 in. towards A, what will be the new value of V_e? (Shaft distance is 5 in.)*

Solution If the wiper moves 0.5 in. towards A from the centre, it will have moved 3 in. from *B*.

$$R_2 = \frac{3.0}{5.0} \times 5\text{ k} = 3\text{ k}\Omega$$

$$V_e = VR_2 - VR_4 = \left(\frac{R_2}{R_1 + R_2}\right) \times V_t - \left(\frac{R_4}{R_3 + R_4}\right) \times V_t$$

$$= \left(\frac{3\text{ k}}{5\text{ k}}\right) \times 5\,V - \left(\frac{2.5\text{ k}}{5\text{ k}}\right) \times 5\,V$$

$$= 3\,V - 2.5\,V = 0.5\,V$$

STRAIN GAUGES 13.6

The strain gauge is an example of a passive transducer that uses the variation in electrical resistance in wires to sense the strain produced by a force on the wires.

It is well known that stress (force/unit area) and strain (elongation or compression/unit length) in a member or portion of any object under pressure is directly related to the modulus of elasticity.

Since strain can be measured more easily by using variable resistance transducers, it is a common practice to measure strain instead of stress, to serve as an index of pressure. Such transducers are popularly known as strain gauges.

If a metal conductor is stretched or compressed, its resistance changes on account of the fact that both the length and diameter of the conductor changes. Also, there is a change in the value of the resistivity of the conductor when subjected to strain, a property called the *piezo-resistive effect*. Therefore, resistance strain gauges are also known as *piezo resistive gauges*.

Many detectors and transducers, e.g. load cells, torque meters, pressure gauges, temperature sensors, etc. employ strain gauges as secondary transducers.

When a gauge is subjected to a positive stress, its length increases while its area of cross-section decreases. Since the resistance of a conductor is directly proportional to its length and inversely proportional to its area of cross-section, the resistance of the gauge increases with positive strain. The change in resistance value of a conductor under strain is more than for an increase in resistance due to its dimensional changes. This property is called the piezo-resistive effect.

The following types of strain gauges are the most important.

1. Wire strain gauges
2. Foil strain gauges
3. Semiconductor strain gauges

13.6.1 Resistance Wire Gauge

Resistance wire gauges are used in two basic forms, the unbonded type, and the bonded type.

1. Unbonded Resistance Wire Strain Gauge An unbonded strain gauge consists of a wire streched between two points in an insulating medium, such as air. The diameter of the wire used is about 25 μm. The wires are kept under tension so that there is no sag and no free vibration. Unbonded strain gauges are usually connected in a bridge circuit. The bridge is balanced with no load applied as shown in Fig. 13.3.

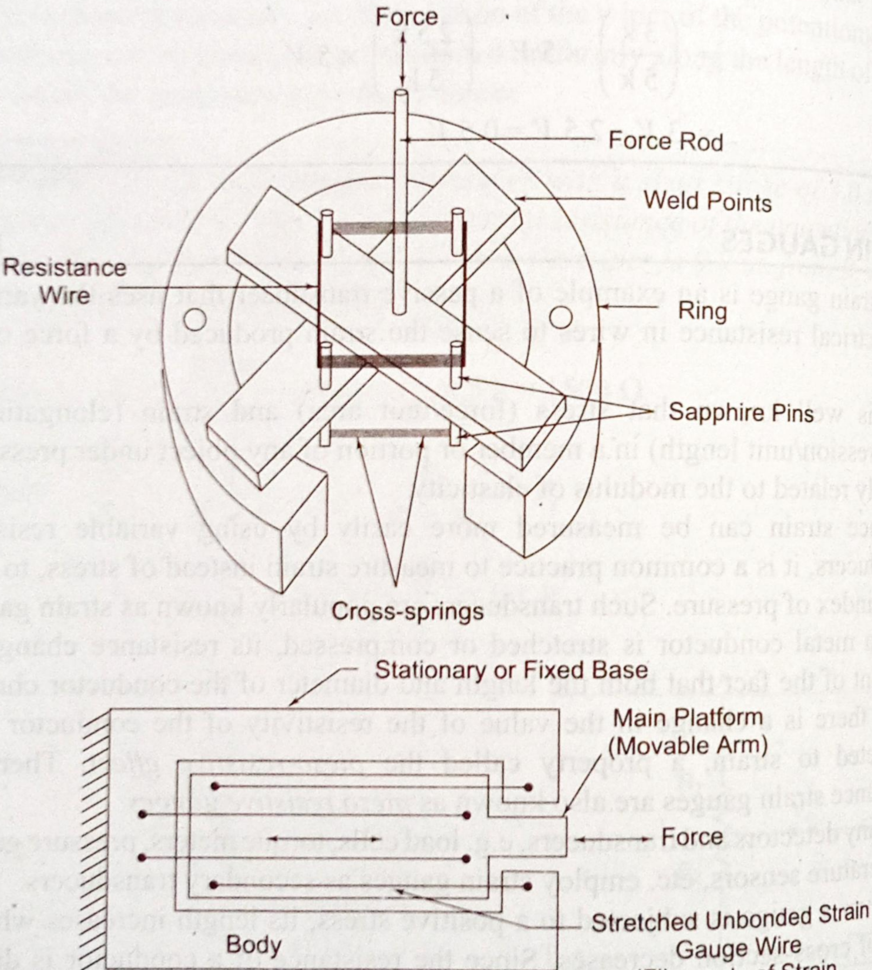

Fig. 13.3 Unbonded strain gauge

When an external load is applied, the resistance of the strain gauge changes, causing an unbalance of the bridge circuit resulting in an output voltage. This voltage is proportional to the strain. A displacement of the order of 50 μm can be detected with these strain gauges.

2. Bonded Resistance Wire Strain Gauges A metallic bonded strain gauge is shown in Fig. 13.4.

A fine wire element about 25 μm (0.025 in.) or less in diameter is looped back and forth on a carrier (base) or mounting plate, which is usually cemented to the member undergoing stress. The grid of fine wire is cemented on a carrier which may be a thin sheet of paper, bakelite, or teflon. The wire is covered on the top with a thin material, so that it is not damaged mechanically. The spreading of the wire permits uniform distribution of stress. The carrier is then bonded or cemented to the member being studied. This permits a good transfer of strain from carrier to wire.

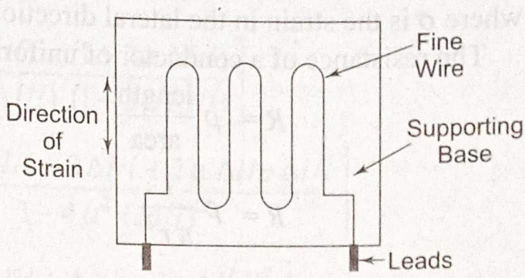

Fig. 13.4 Bonded resistance wire strain gauge

A tensile stress tends to elongate the wire and thereby increase its length and decrease its cross-sectional area. The combined effect is an increase in resistance, as seen from the following equation

$$R = \frac{\rho \times l}{A}$$

where ρ = the specific resistance of the material in Ωm
l = the length of the conductor in m
A = the area of the conductor in m^2

As a result of strain, two physical parameters are of particular interest.

1. The change in gauge resistance.
2. The change in length.

The measurement of the sensitivity of a material to strain is called the gauge factor (GF). It is the ratio of the change in resistance $\Delta R/R$ to the change in the length $\Delta l/l$

i.e. $$\text{GF}(K) = \frac{\Delta R/R}{\Delta l/l} \tag{13.1}$$

where K = gauge factor
ΔR = the change in the initial resistance in Ω's
R = the initial resistance in Ω (without strain)
Δl = the change in the length in m
l = the initial length in m (without strain)

Since strain is defined as the change in length divided by the original length, i.e. $$\sigma = \frac{\Delta l}{l}$$

Eq. (13.1) can be written as

$$K = \frac{\Delta R/R}{\sigma} \tag{13.2}$$

where σ is the strain in the lateral direction.

The resistance of a conductor of uniform cross-section is

$$R = \rho \frac{\text{length}}{\text{area}}$$

$$R = \rho \frac{l}{\pi r^2}$$

Since $r = \frac{d}{2}$ $\therefore$ $r^2 = \frac{d^2}{4}$

$$\therefore \quad R = \rho \frac{l}{\pi d^2/4} = \rho \frac{l}{\pi/4\, d^2} \tag{13.3}$$

where ρ = specific resistance of the conductor

l = length of conductor

d = diameter of conductor

When the conductor is stressed, due to the strain, the length of the conductor increases by Δl and the simultaneously decreases by Δd in its diameter. Hence the resistance of the conductor can now be written as

$$R_s = \rho \frac{(l + \Delta l)}{\pi/4 (d - \Delta d)^2} = \frac{\rho(l + \Delta l)}{\pi/4\, (d^2 - 2d\, \Delta d + \Delta d^2)}$$

Since Δd is small, Δd^2 can be neglected

$$\therefore \quad R_s = \frac{\rho\, (l + \Delta l)}{\pi/4\, (d^2 - 2d\, \Delta d)}$$

$$= \frac{\rho\, (l + \Delta l)}{\pi/4 d^2 \left(1 - \dfrac{2\Delta d}{d}\right)} = \frac{\rho l\, (1 + \Delta l/l)}{\pi/4 d^2 \left(1 - \dfrac{2\Delta d}{d}\right)} \tag{13.4}$$

Now, Poisson's ratio μ is defined as the ratio of strain in the lateral direction to strain in the axial direction, that is,

$$\mu = \frac{\Delta d/d}{\Delta l/l} \tag{13.5}$$

$$\therefore \quad \frac{\Delta d}{d} = \mu \frac{\Delta l}{l} \tag{13.6}$$

Substituting for $\Delta d/d$ from Eq. (13.6) in Eq. (13.4), we have

$$R_s = \frac{\rho l\,(1 + \Delta l/l)}{(\pi/4)\,d^2\,(1 - 2\mu\,\Delta l/l)}$$

Rationalising, we get

$$R_s = \frac{\rho l\,(1 + \Delta l/l)}{(\pi/4)\,d^2\,(1 - 2\mu\,\Delta l/l)}\,\frac{(1 + 2\mu\,\Delta l/l)}{(1 + 2\mu\,\Delta l/l)}$$

$$\therefore \quad R_s = \frac{\rho l}{(\pi/4)\,d^2}\left[\frac{(1 + \Delta l/l)}{(1 - 2\mu\,\Delta l/l)}\,\frac{(1 + 2\mu\,\Delta l/l)}{(1 + 2\mu\,\Delta l/l)}\right]$$

$$\therefore \quad R_s = \frac{\rho l}{(\pi/4)\,d^2}\left[\frac{1 + 2\mu\,\Delta l/l + 2\,\Delta l/l + 2\mu\,\Delta l/e\,\Delta l/l}{1 - 4\mu^2\,(\Delta l/l)^2}\right]$$

$$\therefore \quad R_s = \frac{\rho l}{(\pi/4)\,d^2}\left[\frac{1 + 2\mu\,\Delta l/l + \Delta l/l + 2\mu\,\Delta l^2/l^2}{1 - 4\mu^2\,\Delta l^2/l^2}\right]$$

Since Δl is small, we can neglect higher powers of Δl.

$$\therefore \quad R_s = \frac{\rho l}{(\pi/4)\,d^2}\,[1 + 2\,\mu\,\Delta l/l + \Delta l/l]$$

$$R_s = \frac{\rho l}{(\pi/4)\,d^2}\,[1 + (2\,\mu + 1)\,\Delta l/l]$$

$$R_s = \frac{\rho l}{(\pi/4)\,d^2}\,[1 + (1 + 2\,\mu)\,\Delta l/l]$$

$$\therefore \quad R_s = \frac{\rho l}{(\pi/4)\,d^2} + \frac{\rho l}{(\pi/4)\,d^2}\,(\Delta l/l)\,(1 + 2\,\mu)$$

Since from Eq. (13.3), $R = \dfrac{\rho l}{(\pi/4)\,d^2}$

$$\therefore \quad R_s = R + \Delta R \tag{13.7}$$

where $\quad \Delta R = \dfrac{\rho l}{(\pi/4)\,d^2}\,(\Delta l/l)\,(1 + 2\,\mu)$

$\therefore$ The gauge factor will now be

$$K = \frac{\Delta R/R}{\Delta l/l} = \frac{(\Delta l/l)\,(1 + 2\mu)}{\Delta l/l}$$

$$= 1 + 2\,\mu$$

$$\therefore \quad K = 1 + 2\,\mu \tag{13.8}$$

Example 13.3 *A resistance strain gauge with a gauge factor of 2 is cemented to a steel member, which is subjected to a strain of 1×10^{-6}. If the original resistance value of the gauge is 130 Ω, calculate the change in resistance.*