Australian Maritime College
Department of Maritime Engineering

Lecture Notes

INSTRUMENTATION AND PROCESS CONTROL

PART I – FUNDAMENTALS OF INSTRUMENTATION

Module 2
(Transducers, AS Drawing Symbols in Instrumentation and Process Control Systems and Temperature Measurement)

Second Version

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AIMS

1.0 Describe transducers in a measuring system, temperature measurement methods and devices and apply AS standard drawing symbols in documentation of control system design.

LEARNING OBJECTIVES

1.1 Describe a resistance transducer and its characteristics.

1.2 Describe a capacitive transducer and its characteristics.

1.3 Describe an inductive transducer and its characteristics.

1.4 Describe a linear variable differential transformer and its characteristics.

1.5 Describe a piezo-electric transducer and its characteristics.

1.6 Describe mechanical transducers and their characteristics.

1.7 Apply AD standard drawing symbols in documentation of instrumentation and control systems.

1.8 State temperature and its units, temperature measurement methods.

1.9 Describe resistance temperature detectors.

1.10 Describe thermocouples.

1.11 Describe radiation pyrometers.
1. Transducers

As mentioned in Module 1, a measuring system consists of sensing element (or transducer) that detects and measures a physical variable and converts the sensed signal into another form, a signal conditioning device and a record or an indicator. In this section, several types of transducer are introduced.

1.1 Definitions

A *transducer* is a device that converts one form of energy or physical quantity to another. Often this energy or physical quantity is “in form” or the same. The energy or stimulus determines the quantity of the signal (R.G. Seippel, 1983).

A *sensor* is a device used to detect, measure, or record physical phenomena such as heat, radiation, and the like and to respond by transmitting the information, initiating changes, or operating controls.

A *detector* is a device used to sense the presence of something such as heat, radiation, or other physical phenomena.

A *transmitter* is a device used to convert the output from a primary element into a useable signal, which is then transmitted either to an indicating instrument or to a controller. Thus, transmitters can be regarded as being forms of secondary element. The most common output signals generated by transmitters are either pneumatic pressure signals, in the 3 to 15 psi (20 to 100kPa) gauge pressure range, or DC currents, in the 4 to 20mA range. However, this latter, electrical range is not exclusive and alternative DC current, DC voltage, AC voltage, and digital transmissions are sometimes used.

The difference between these devices is extremely thin line, especially the difference between a transducer and a transmitter.

1.2 Transducers

Most of transducers consist of a sensing element (sensor) and a conversion or control element (transducer) as shown in Figure 1.

Figure 1 Two block diagram representation of a typical transducer

**Transducer sensitivity**: The relationship between the measurand (the input quantity to be measured or simply input) and the output is usually obtained by calibration tests and is referred to as the transducer sensitivity \( K_t \).
\[ K_i = \frac{\Delta y}{\Delta u} \]  

where \( \Delta y \) = output-signal increment  
\( \Delta u \) = measurand increment

In practice, the transducer sensitivity is usually known, and by measuring the output signal, the input quantity is determined from:

\[ \Delta u = \frac{\Delta y}{K_i} \]  

**Example 1:** If the transducing spring shown in Figure 2 deflects 0.05m when subjected to a force of 10kN, find the input force for an output displacement of 0.075m.

![Figure 2 Loaded spring](image)

**Solution**

Sensitivity \( K_i = \frac{x}{F} = \frac{0.50m}{10kN} \)

The input force required for 0.075m deflection is \( F = \frac{x}{K_i} = 0.075m \times \frac{10kN}{0.05m} = 15kN \)

**Functions of transducers:** Functions of a transducer are often involved in measurement and control. Some transducers can be used for signal analysis such as in an oxygen analyzer.

**Characteristics of an ideal transducer:** According to Haslam et al, an ideal transducer should exhibit the following characteristics:

1. High fidelity: the transducer output waveform shape should be a faithful reproduction of the measurand, i.e. there should be minimum distortion.

2. There should be minimum interface with the quantity being measured, i.e. the presence of the transducer should not alter the measurand in any way.

3. Size: The transducer must be capable of being placed exactly where it is needed.

4. There should be a linear relationship between the measurand and the transduced signal.
5. The transducer should have minimum sensitivity to external effects. Pressure transducers, for example, are often subjected to external effects such as vibration and temperature.

6. The natural frequency of the transducer should be well separated from the frequency and harmonics of the measurand.

**Classification of transducers**: Transducers can be classified as electrical transducers and mechanic transducers. Electrical transducers consist of variable control parameter types such as resistance, capacitance, inductance and mutual inductance transducers, and self-generating types such as electromagnetic, thermoelectric, photoemissive and piezo-electric types. Electric transducers are more common. We will deal with several types of transducers and their features.

### 1.2.1 Resistance Transducers (potential divider group and bridge circuit group)

**Potentiometer**: A potentiometer is an electromechanical device consisting of a resistive element with a movable wiper or slider. Principle of a potentiometer is shown in Figure 3.

![Figure 3 Principle of potentiometer](image)

Let resistance \( R_1 = \frac{x_i}{x_T} R_T \) \( (3) \)

where \( x_i \) = input displacement (m)

\( x_T \) = maximum possible displacement (m)

\( R_T \) = total resistance of the potentiometer (\( \Omega \))

\( V \) = excitation voltage (V)

\( V_o \) = output voltage (V)

Then output voltage \( v_o = V \times \frac{R_1}{R_1 + (R_T - R_1)} \)

\( v_o = V \times \frac{R_1}{R_T} = V \frac{x_i}{x_T} \frac{R_T}{R_T} = V \frac{x_i}{x_T} \) \( (4) \)
This shows that there is a straight-line relationship between the output voltage and input displacement for the unloaded potentiometer.

The maximum value of $V$ is determined by the maximum power dissipation $P$ of the fine wires of the potentiometer winding and is given by

$$ V_{\text{max}} = \sqrt{PR_T} \quad (5) $$

**Example 2**: A potentiometer resistance transducer has a total winding resistance of $10\, \text{k}\Omega$ and a maximum displacement range of $4\, \text{cm}$. If the maximum power dissipation is not to exceed $40\, \text{mW}$, determine the output voltage of the device when the input displacement is $1.2\, \text{cm}$, assuming the maximum permissible excitation voltage is used.

**Solution**

Excitation voltage $V = \sqrt{PR_T} = \sqrt{0.04\, \text{W} \times 10000\, \Omega} = 20\, \text{V}$

From equation $v_o = V \frac{x_i}{x_T}$ we have $v_o = 20\, \text{V} \times \frac{1.2\, \text{cm}}{4\, \text{cm}} = 6\, \text{V}$

**Loaded condition**: When a potentiometer is loaded by placing across its terminals measuring device such as a meter, having a resistance $R_L$, a current flows into the meter. This has a loading effect on the potentiometer and cause the output/input graph to depart from the linear relationship as shown in Figure 4.

![Figure 4 Characteristic of a loaded potentiometer](image)

The relationship between $x_i$ and $V$ in the loaded condition is given as follows:

$$ v_o = V \left[ \frac{x_T}{x_i} + \frac{R_T}{R_L} \left( 1 - \frac{x_i}{x_T} \right) \right]^{-1} \quad (6) $$

This is far from linear, and the non-linearity increases as the ratio of $R_T/R_L$ increases.
Example 3: Calculate the error, at 50% full-scale travel of a wiper, of a resistance potentiometer when loaded with a meter having resistance equal to twice the potentiometer resistance.

Solution

Using equation (4): unloaded $v_o = \frac{V}{2} = 0.5V$

Using equation (6): loaded $v_o = V\left[\frac{1}{2 + \frac{1}{(1 - 0.5)}}\right] = \frac{V}{2.25} = 0.44V$

Hence error $= \frac{0.44V - 0.5V}{0.5V} \times 100\% = -12\%$

Resistance temperature transducer: The materials for these can be divided into two main groups as follows:

1. Metals such as platinum, copper, tungsten, and nickel which exhibit small increases in resistance as the temperature rises, i.e. they have positive temperature coefficient of resistance.

2. Semiconductors, such as thermistors which use oxides of manganese, cobalt, chromium, or nickel. These exhibit large non-linear resistance changes with temperature variation and normally have a negative temperature coefficient of resistance.

Metal resistance temperature transducers: These depend, for many practical purposes and within a narrow temperature range, upon the relationship:

$$R_1 = R_0\left[1 + \alpha(\theta_1 - \theta_o)\right]$$

(7)

where $\alpha =$ temperature coefficient of resistance in °C$^{-1}$

$R_0 =$ resistance in ohms at the reference temperature

Typical characteristic curves for a platinum resistance thermometer shown in Figure 5.
**Example 4:** If the resistance of a platinum resistance thermometer is 100Ω at 0°C, calculate the resistance at 60°C if \( \alpha = 0.00392°C^{-1} \).

**Solution**

Using equation (7): 

\[
R = R_0[1 + \alpha(\theta - \theta_0)] = 100\Omega \times [1 + 0.00392 \times 60] = 123.5\Omega
\]

Thermistor resistance temperature transducers: Thermistors are temperature sensitive resistors which exhibit large non-linear resistance changes in temperature variation. In general, they have a negative temperature coefficient as illustrated in Figure 6.

**Example 5:** Use the characteristic curve for type-1 thermistor shown in Figure 6 to determine the temperature measured when the meter in the circuit shown in Figure 7 reads half full scale.

**Solution:**

Total resistor \( R = \frac{V}{I} = \frac{10V}{0.5 \times 10^{-3} A} = 20k\Omega \)

Thermistor resistance = \( 20k\Omega - 5k\Omega = 15k\Omega \) (neglecting meter resistance)
Hence, from the characteristic curve, temperature \( \approx 20^\circ C \)

### 1.2.2 Capacitive transducers (Variable capacitor):

The capacitance of a parallel plate capacitor is given by

\[
C = \varepsilon_0 \varepsilon_r \frac{A}{d}
\]  

(8)

where \( \varepsilon_0 = \) the permittivity of free space = \( 8.854 \times 10^{-12} \) F/m

\( \varepsilon_r = \) relative permittivity of the material between the plates

\( A = \) overlapping or effective area between plates (m\(^2\))

\( d = \) distance between plates (m)

From the above equation, we can see that the capacitance can thus be made to vary by changing either the relative permittivity \( \varepsilon_r \), the effective area \( A \), or the distance separating the plates \( d \).

Some types of capacitive transducer are illustrated in Figure 8.

The characteristic curves shown in Figure 9 indicate that variations of area \( A \) and relative permittivity \( \varepsilon_r \) give a linear relationship between \( C \) and \( A \) or \( \varepsilon_r \), but variations in spacing \( d \) give linear relationship only over a small range of spacings.

![Figure 8 Examples of capacitive transducers](image)
By differentiating the above equation, one can obtain the sensitivity in farads/m, 

\[
\frac{dC}{dd} = \frac{\varepsilon_0 \varepsilon_r}{d^2}
\]  

(9)

Thus the sensitivity is high for small values of \(d\).

Unlike the potentiometer, the variable distance capacitive transducer has an infinite resolution, making it most suitable for measuring small increments of displacement or quantities which may be change produce a displacement.

**Example 6:** A parallel-place air-spaced capacitor has an effective plate area of \(6.4 \times 10^{-4} \text{m}^2\), and the distance between the plates is 1mm. If the relative permittivity for air is 1.0006, calculate the displacement sensitivity of the device.

**Solution:** Using equation (8), 
\[
C = \varepsilon_0 \varepsilon_r \frac{A}{d}
\]

Differentiating 
\[
\frac{dC}{dd} = \frac{\varepsilon_0 \varepsilon_r A}{d^2} = \frac{8.854 \times 10^{-12} \text{F/m} \times 1.0006 \times 6.4 \times 10^{-4} \text{m}^2}{(1 \times 10^{-3} \text{m})^2}
\]

\[
= -56.6 \times 10^{-10} \text{F/m} = -5.66 \text{nF/m}
\]

1.1.3 **Inductive transducers**

The inductance of a coil wound around a magnetic circuit is given by

\[
L = \mu_0 \mu_r \frac{N^2 A}{l} \text{ (henrys)}
\]  

(10)

where \(\mu_0\) = the permeability of free space = \(4 \times 10^{-7}\) H/m
\( \mu_r = \) relative permeability of the materials between the plates
\( N = \) number of turns on coil
\( A = \) cross-sectional area of magnetic circuit (m²)
\( l = \) length of magnetic circuit (m)

This can be rewritten as

\[
L = \frac{N^2}{S}
\]

(11)

where \( S \) is the magnetic reluctance of the inductive circuit.

The inductance can be made to vary by changing the reluctance of the inductive circuit. Some examples of variable reluctance transducers are shown in Figure 10. A typical characteristic curve for an inductive transducer is shown in Figure 11.

Example 7: Determine the sensitivity of a single coil inductive transducer for (a) variations in relative permeability \( \mu_r \), (b) variation length of magnetic circuit
Solution

Differentiating equation (10) with respect to $\mu_r$: \[ \frac{dL}{d\mu} = \frac{\mu_0 N^2 A}{l} \]

Differentiating equation (10) with respect to $l$, \[ \frac{dL}{dl} = -\frac{\mu_0 H_r N^2 A}{l^2} \]

1.2.4 Linear variable differential transformer (l.v.d.t):

A typical differential transformer, as illustrated in Figure 12, has a primary coil, two secondary coils, and a movable magnetic core.

A high-frequency excitation voltage $V_p$ is applied to the primary winding and, due to transformer action, voltages $V_{s1}$ and $V_{s2}$ are induced in the secondary coils. The amplitudes of these secondary voltages are dependent on the degree of electromagnetic coupling between the primary and secondary coils and hence on the core displacement $x$.

Since the secondary coils are connected in series opposition, the displacement $x$ of the core which produces an increase in $V_{s1}$ will produce a corresponding decrease in $V_{s2}$. Ideally the voltages $V_{s1}$ and $V_{s2}$ should be 180° out of phase with each other, so that at the central position there is zero output voltage. However, the voltages generally are not exactly 180° out of phase and there is a small null output voltage as illustrated in Figure 13.

![Figure 12 Details of an l.v.d.t. (Haslam et al)](image)

![Figure 13 Output characteristics of an l.v.d.t.](image)
Some important characteristics and features of the l.v.d.t are as follows:

- Infinite resolution;
- Linearity better than 0.5%;
- Excitation frequency 50Hz to 20Hz;
- Null voltage less than 1% of full scale output voltage;
- Maximum displacement available from $2 \times 10^{-4}$m to 0.5m;
- On wear of moving parts;
- Amplitude-modulated output, i.e. the output voltage is a constant frequency waveform with an amplitude depending on the displacement input.

Typical measurands are many quantities which can be transduced into displacement, e.g. pressure, acceleration, vibration, force and liquid level.

1.2.5 Piezo-electric transducer: When a force is applied across the faces of certain crystal materials, electrical charges of opposite polarity appear on the faces due to piezo-electric effect. Piezo-electric transducers are made from natural crystal such as quartz, Rochelle salt, synthetic crystals such as lithium sulphate, or polarised ceramics such as barium titanate. Since these materials generate an output charge proportional to applied force, they are most suitable for measuring force-derived variables such as pressure, load, and acceleration as well as force itself.

Piezo-electric materials are good electrical insulators; therefore, with their connecting plates, they can be considered as parallel-plate capacitors as Figure 14(a). When a force is applied, the capacitor simply “charge-up” due to the piezo-electric effect, as illustrated by the equivalent electric circuit shown in Figure 14(b). Unfortunately, any measuring instrument electrically connected across the capacitor C will tend to discharge it; hence the transducer’s steady-state response is poor. This can be overcome by using measuring amplifiers with very high input impedance ($10^{12}$ to $10^{14}$ ohms being typical) known as charge amplifiers, but these make the measuring system increasingly expensive.

![Figure 14 Piezo-electric transducer](image)

**Example 8:** A piezo-electric pressure transducer has a sensitivity of pC/bar. If it has a capacitance of 1nF, determine its output voltage when the input pressure is 1.4bar.
Solution
Charge \( q = \text{sensitivity} \times \text{pressure} \)
\[
= \frac{80 \text{ pC}}{\text{bar}} \times 1.4 \text{bar} = 112 \text{pC}
\]
Output voltage \( V = \frac{q}{C} = \frac{112 \times 10^{-12} \text{C}}{1 \times 10^{-9} \text{F}} = 0.112 \text{V} = 112 \text{mV} \)

Applications of piezo-electric transducer in pressure measurement

Pressure transducers using the piezo-electric effect use a similar design to the quartz load cells, the quartz discs being compressed by a diaphragm which is in direct contact with the pressure being measured. The high sensitivity of the quartz-crystal modules permits the transducers to be measured in extremely small sizes, e.g. cylinder pressures in petrol engines can be measured using a spark plug modified to include the transducer.

One outstanding feature of quartz transducers is their high sensitivity; e.g. a transducer designed for 250bar maximum pressure will give 7.5pC for a pressure variation of 0.1bar, which with suitable signal conditioning can produce a 750mV output signal.

Example 9: The waveform obtained with a piezo-electric pressure transducing system is shown in Figure 15.

![Figure 15 The pressure waveform](image)

If the transducer sensitivity is 60pC/bar and the charge-amplifier sensitivity is set at 20mV/pC, determine
(a) mean pressure
(b) the peak amplitude of pressure fluctuations

Solution
Overall sensitivity: 1200mV/bar
a) Mean pressure = 600mV/system sensitivity = [0.5bar]
b) Peak amplitude of pressure fluctuations = 10mV/system sensitivity = [8.33bar]
1.2.6 Force-to-displacement transducers

**Spring**: The spring in Example 1 (Figure 2) is the simplest form of mechanical transducer. For equilibrium, we have

\[ F = \lambda x \]

where \( \lambda \) = spring stiffness (N/m)

\[ x = \frac{F}{\lambda} \quad \text{or} \quad \lambda = \frac{F}{x} \quad (13) \]

But transducer sensitivity \( K_t = \frac{x}{F} = \frac{1}{\lambda} \) (14)

That is the stiffer the spring, the smaller the sensitivity.

**Cantilever**: When the cantilever shown in Figure 16 is loaded, it experiences a deflection \( y \). The relationship between the force \( F \) and the deflection is given by

\[ \text{Deflection } y = \text{constant } \times \text{ force or } y = kF \quad (15) \]

where the constant \( k \) depends on the material and dimensions of the cantilever.

\[ F \]
\[ l \]
\[ y \]

**Figure 16 Cantilever**

1.2.7 Pressure-to-displacement transducers

**Diaphragms**: Pressure can be measured using a steel diaphragm as shown in Figure 17. The displacement \( x \) of the diaphragm is proportional to the pressure difference \( (p_1 - p_2) \) if the displacement is less than one third of the diaphragm thickness \( t \). The relationship between pressure differential \( (p_1 - p_2) \) and diaphragm displacement is thus given by

\[ x = k(p_1 - p_2) \quad (16) \]

where \( x \) = deflection

\( k \) = constant (depending on the material and dimensions of the diaphragm)

\( (p_1 - p_2) \) = pressure differential
The diaphragm, usually a thin flat plate of spring steel, may be used with electrical transducer to produce a small transducer having high sensitivity.

**Bellows**: This is basically a pneumatic spring, as illustrated in Figure 18, and general use in pneumatic instruments.

Equating the forces acting on the bellows, for equilibrium

\[ pA = \lambda x \]  

(17)

\[ x = \frac{A}{\lambda} p \]  

(18)

where \( A \) = cross-sectional area of bellows (m\(^2\))

\( p \) = input pressure (N/m\(^2\))

\( \lambda \) = bellows stiffness (N/m)
2. Standard Drawing Symbols

Standard Drawing Symbols are used in drawing schematic diagrams of measuring and control systems.

2.1 Identifying Code Letters

On drawings, code letters and perhaps a serial number usually identify the various instruments. The code system is outlined in the Australian Standards AS 1101.6. In general, the system is as follows.

1st Letter: indicates the type of variable (e.g. “P” for pressure)
2nd Letter: indicates the instrument function (e.g. “T” for transmitter)
3rd Letter: indicates some qualifying function (e.g. “A” for alarm)

Some of the primary code letters used includes:

F for flow-rate
D for density
L for level
P for pressure (or vacuum)
S for speed or frequency
T for temperature
V for vibration

Some of the secondary code letter include:

I for an indicating function
R for a recording function
T for a transmitting function
S for a switching function

Example 10

PI  TR  LIA_H  LRA_L
Pressure Indicator  Temperature Recorder  Level Indicator [High Alarm]  Level Recorder [Low Alarm]

Local  On Panel  Behind Panel

Some additional function designations include:

AVG  Average
PSV  Pressure Relief (Safety) Valve
×  Multiply
\( \sqrt{ } \)  Square Root (Extraction)
\( \sum \)  Addition or Summation
\( \int \)  Integration
f(x)  Characterise

2.2 Instrument Line Symbols

The following are the commonly used methods of identifying types of signals.

- **Thick Line**: Process Flow Line (pipe)

- **Thin Line**: Instrument connection or a mechanical link

- **Pneumatic connection**: Pneumatic signal lines crossing

- **Electrical signal**: Lines not connected

- **Capillary tubing**: Lines connected

- **Hydraulic signal**: Junction of pneumatic signal lines

2.3 Identifying Signal Connecting Points
2.4 Correcting Elements

- Two-Port Valve

- Three-Port Valve

Three-port valves should be drawn showing the de-energised (signal failure) position

2.5 Actuating Elements

- Pneumatic Diaphragm and Spring Type

- Pneumatic Diaphragm, Pressure-balance Type

- Rotary Motor Type

- Piston Type

- Solenoid Type
Diaphragm Type with Positioner

Control Valve with Fails Open

Control Valve with Fails Closed

Control Valve, which retains Position on Failure

Control Valve with Mechanical Minimum Stop

Control Valve with Mechanical Maximum Stop

Three-port Valve showing Flow in Failure

Three-port Valve showing Flow when de-energised
1.6 Flow Elements

- Orifice Plate
- Venturi
- Flow Nozzle
- Pitot Tube
- Flow Nozzle
- Variable Area Flowmeter

2.7 Level Instrument Connections

- Integrally Mounted Instrument
- Instrument with Single Connection
- Instrument with Two Connections
2.8 Pressure Regulators

Self-contained Type
Regulator with External Tap
Differential Regulator with External Tap

2.9 Signal Modifiers

Addition
Subtraction
Multiplication
Division
Square Root Extraction
Electro-Pneumatic Converter
Digital to Analogue Converter
High Signal Selector
Low Signal Selector

Example 11: State what type of instruments are depicted by the following symbols and whether they are local or panel mounted.

Solution
(i) Pressure Indicator (gauge), locally mounted
(ii) Temperature Recorder with high temperature alarm, locally mounted
(iii) Flow Indicator with low flow alarm, mounted on panel
(iv) Temperature Transmitter, mounted behind panel
(v) Level Transmitter

Example 12: State what types of signal are shown by the following:

\[
\begin{align*}
\text{(i) Pneumatic connection} \\
\text{(ii) Electrical signal (connection)}
\end{align*}
\]

Example 13: Describe as fully as possible the components shown:

\[
\begin{align*}
\text{(i) A Diaphragm Operated Control Valve, fitted with a “Valve Positioner” and which closes on signal failure (Fails Closed).} \\
\text{(ii) A Diaphragm Operated Three Port (three-way) Valve, flow passes from ‘A’ to ‘C’ on signal failure (Fails Open to ‘C’).}
\end{align*}
\]

Example 14: Describe as fully as possible the following diagram of a flow recording/control system:
Solution
Computer-based Flow Recording and Control System: The system has an Orifice D/P Cell Transmitter (Signal 24) locally mounted, and Flow Indicator (Signal 24) locally mounted, a Computer Flow Recorder/Controller (Signal 24) locally mounted, and a Two-port Control Valve (Automatic Actuating Element) activated by the Computer Controller.

(Also see AS Standard 1011.6 – Section 4 Examples of AS Standard Symbols, pp. 35 - Flow Recording with access in local and indication in central control room. Flow recording and control by computer, operator access in local control room, flow indication in central control room.)
3. Temperature Measurement

3.1 Temperature

In order to measure temperature, a thermometer is used. Temperature is a reference to the “hotness” or “coldness” of a body. With SI units, the Kelvin scale is used where the unit of temperature is the Kelvin (K). Two fixed points are assigned in this scale. Absolute zero, or 0K, is the theoretical minimum temperature possible for any substance. The triple point of water is the second point and is fixed at 273.16K.

The Celsius scale is in normal use and uses 0°C as the temperature of melting ice and 100°C for the temperature of boiling water (each at normal atmosphere pressure). A comparison between scales indicates

\[ X^\circ C = (X + 273.15)K \]  

(19)

Another scale is Fahrenheit (°F). The relationship between Celsius (C) and Fahrenheit (F) is given by:

\[ C = \frac{5}{9}(F - 32) \]  

(20)

\[ F = \frac{9}{5}C + 32 \]  

(21)

The second law of thermodynamics states that heat must flow from a hot body to a cold body. To measure temperature, therefore, an equilibrium must be set up between the sensor and the body. This is rarely achieved in practice and appropriate selection of the sensor must be made in order to obtain an acceptable measurement of temperature. Often the act of measurement, by inserting a sensor, will modify the condition that it is intended to measure. Heat is transferred from body to body by conduction, convection and radiation and due account of the prevailing conditions must be taken when selecting the measurement system. Finally, the transmission and indicating elements of the measuring system may be subject to temperature changes and some form of compensation will therefore be necessary.

Temperature measurement does not take place directly, some effect brought about by temperature changes is used. Because temperature is one of the most important parameter of material, many instruments have been developed to measure it. There are three broad classifications for the methods used to measure temperature: expansion, electrical and radiation. The most common types of temperature measuring instrument are the thermocouples and the resistance temperature detector (RTD).

3.2 Resistance Temperature Detectors (RTDs)

For the measurement of lower temperatures, up to about 600°C, resistance temperature detectors (or electrical resistance thermometers) using various metals are suitable for both laboratory and industrial applications requiring.

i) a high degree of accuracy

ii) long-term stability
In general, the resistance of most metals over a wide temperature range is given by the quadratic relationship

\[ R = R_0 \left( 1 + aT + bT^2 \right) \]  

(22)

where \( R \) = resistance at absolute temperature \( T \)
\( R_0 \) = resistance at 0K
\( a \) and \( b \) = constants obtained experimentally

However, over a limited temperature range around 0°C (273K) the following linear relationship can be applied:

\[ R = R_0 \left( 1 + \alpha \theta \right) \]  

(23)

where \( \alpha \) = the temperature coefficient of resistance of the material in Ω°C or °C⁻¹.
\( R_0 \) = resistance at 0°C
\( \theta \) = temperature relative to 0°C

Some typical values for \( \alpha \) are
- Copper  0.0043°C⁻¹
- Nickel   0.0068°C⁻¹
- Platinum  0.0039°C⁻¹

If a change in temperature from \( \theta_1 \) to \( \theta_2 \) is considered, equation (23) becomes:

\[ R_2 = R_1 + R_0 \alpha (\theta_2 - \theta_1) \]  

(24)

Rearranging gives

\[ \theta_2 = \theta_1 + \frac{R_2 - R_1}{\alpha R_0} \]  

(25)

**Example 15:** A platinum resistance thermometer has a resistance of 138.5Ω at 100°C. If its resistance increases to 281Ω when it is in contact with a hot gas, determine the temperature of gas. The resistance can be taken as 100Ω at 0°C.

**SOLUTION**

Using equation (25) and \( \alpha \) for platinum as 0.0039°C⁻¹,

\[ \theta_2 = \theta_1 + \frac{R_2 - R_1}{\alpha R_0} = 100 + \frac{281 - 138.5}{0.0039 \times 100} = 100°C + 365.5°C = 465.5°C \]

The temperature of the gas is therefore 465.5°C.

**RTD Construction:** The RTD incorporates pure metals or certain alloys that increase in resistance as temperature increases and, conversely, decrease in resistance as temperature decreases. RTDs act somewhat like an electrical transducer, converting changes in
temperature to voltage signal by the measurement of resistance. The metals that are best suited for use as RTD sensors are pure, of uniform quality, stable within a given range of temperature, and able to give reproducible resistance-temperature readings. Only a few metals have the properties necessary for use in RTD elements.

Figure 19 Electrical resistance temperature curves

RTD elements are normally constructed of platinum, copper, or nickel. These metals are best suited for RTD applications because of their linear resistance-temperature characteristics (as shown in Figure 19), their high coefficient of resistance, and their ability to withstand repeated temperature cycles.

Figure 20 Internal construction of a typical RTD
The coefficient of resistance is the change in resistance per degree change in temperature, usually expressed as a percentage per degree of temperature. The material used must be capable of being drawn into fine wire so that the element can be easily constructed.

RTD elements are usually long, spring-like wires surrounded by an insulator and enclosed in sheath of metal. Figure 20 shows the internal construction of an RTD.

This particular design has a platinum element that is surrounded by a porcelain insulator. The insulator prevents a short circuit between the wire and the metal sheath.

Inconel, a nickel-iron-chromium alloy, is normally used in manufacturing the RTD sheath because of its inherent corrosion resistance. When placed in a liquid or gas medium, the Inconel sheath quickly reaches the temperature of the medium. The change in temperature will cause the platinum wire to heat or cool, resulting in a proportional change in resistance.

This change in resistance is then measured by a precision resistance measuring device that is calibrated to give the proper temperature reading. This device is normally a bridge circuit, which will be covered in detail later in this text.

Figure 21 shows an RTD protective well and terminal head. The well protects the RTD from damage by the gas or liquid being measured. Protecting wells are normally made of stainless steel, carbon steel, Inconel, or cast iron, and they are used for temperatures up to 1100°C.

\[
\text{Figure 21 RTD protective well and terminal head}
\]

**RTD Summary**

Resistance temperature detectors (RTDs) are summarized as follows.

1. The resistance of an RTD varies directly with temperature:
   - As temperature increases, resistance increases
   - As temperature decreases, resistance decrease.
2. RTDs are constructed using a fine, pure, metallic, spring-like wire surrounded by an insulator and enclosed in a metal sheath.
3. A change in temperature will cause an RTD to heat or cool, producing a proportional change in resistance. The change in resistance is measured by a precision device that is calibrated to give the proper temperature reading.
3.2 Thermocouples

**Thermocouple Construction**: A thermocouple is constructed of two dissimilar metal wires joined at one end. When one end of each wire is connected to a measuring instrument, the thermocouple becomes a sensitive and highly accurate measuring device. Thermocouples may be constructed of several different combinations of materials. The performance of a thermocouple material is generally determined by using that material with platinum. The most important factor to be considered when selecting a pair of materials is the "thermoelectric difference" between the two materials. A significant difference between the two materials will result in better thermocouple performance. Figure 22 illustrates the characteristics of the more commonly used materials when used with platinum. Other materials may be used in addition to those shown in Figure 22. For example: Chromel-Constantan is excellent for temperatures up to 2000°F; Nickel/Nickel-Molybdenum sometimes replaces Chromel-Alumel; and Tungsten-Rhenium is used for temperatures up to 5000°F. Some combinations used for specialized applications are Chromel-White Gold, Molybdenum-Tungsten, Tungsten-Iridium, and Iridium/Iridium-Rhodium.

![Figure 22 Thermocouple material characteristics when used with Platinum](image)

![Figure 23 Internal construction of a typical thermocouple](image)
Figure 23 shows the internal construction of a typical thermocouple. The leads of the thermocouple are encased in a rigid metal sheath. The measuring junction is normally formed at the bottom of the thermocouple housing. Magnesium oxide surrounds the thermocouple wires to prevent vibration that could damage the fine wires and to enhance heat transfer between the measuring junction and the medium surrounding the thermocouple.

**Thermocouple Operation:** Thermocouples will cause an electric current to flow in the attached circuit when subjected to changes in temperature. The amount of current that will be produced is dependent on the temperature difference between the measurement and reference junction; the characteristics of the two metals used; and the characteristics of the attached circuit. Figure 24 illustrates a simple thermocouple circuit.

![Simple thermocouple circuit](image)

Figure 24 Simple thermocouple circuit

Heating the measuring junction of the thermocouple produces a voltage which is greater than the voltage across the reference junction. The difference between the two voltages is proportional to the difference in temperature and can be measured on a voltmeter (in millivolts). For ease of operator use, some voltmeters are set up to read out directly in temperature through use of electronic circuitry.

Other applications provide only the millivolt readout. In order to convert the millivolt reading to its corresponding temperature, you must refer to tables like the one shown in Table 1. These tables can be obtained from the thermocouple manufacturer, and they list the specific temperature corresponding to a series of millivolt readings.

**Thermocouple Summary**

- A thermocouple is constructed of two dissimilar wires joined at one end and encased in a metal sheath.
- The other end of each wire is connected to a meter or measuring circuit.
- Heating the measuring junction of the thermocouple produces a voltage that is greater than the voltage across the reference junction.
- The difference between the two voltages is proportional to the difference in temperature and can be measured on a voltmeter.
Table 1 Temperature-vs-voltage reference table

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Thermoelectric Voltage in Absolute Millivolts</th>
<th>Reference Junction 0°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000</td>
<td>- 0</td>
</tr>
<tr>
<td>10</td>
<td>.055</td>
<td>- .013</td>
</tr>
<tr>
<td>20</td>
<td>.133</td>
<td>- .010</td>
</tr>
<tr>
<td>30</td>
<td>.225</td>
<td>- .010</td>
</tr>
<tr>
<td>40</td>
<td>.329</td>
<td>- .036</td>
</tr>
<tr>
<td>50</td>
<td>.432</td>
<td>.020</td>
</tr>
<tr>
<td>60</td>
<td>.537</td>
<td>.073</td>
</tr>
<tr>
<td>70</td>
<td>.645</td>
<td>.123</td>
</tr>
<tr>
<td>80</td>
<td>.750</td>
<td>.152</td>
</tr>
<tr>
<td>90</td>
<td>.850</td>
<td>- .152</td>
</tr>
<tr>
<td>100</td>
<td>.950</td>
<td>- .225</td>
</tr>
</tbody>
</table>

Figure 25 Some types of thermo couple (Megapak)
3.2 Radiation Method – Radiation Pyrometer

All bodies above 0K, i.e. absolute zero, will emit electromagnetic radiation. The intensity of the radiation is a measure of the temperature of the body. The intensity ranges from the invisible infra-red rays to the visible light range and is measured using a radiation pyrometer. The temperature measuring range for radiation pyrometers is about 700 to 2000°C. A pyrometer is generally understood to be a high temperature measuring thermometer. The radiation emitted from the hot body is measured or detected in some way and the instrument is calibrated for black body conditions. Black body conditions are considered ideal for radiation measurement. The black body is a thermodynamic concept of a body, which need not be black, which absorbs all energy incident upon it and also is a good emitter of radiation. The emitted radiation should result only from the temperature of the body itself and not from any other reflected radiation. The nearest practical example is a furnace which is observed through a very small aperture and hence any radiation detected will be only from the furnace.

Two main types of radiation pyrometer are in general use, the infra-red pyrometer and the optical pyrometer. The infra-red pyrometer can theoretically measure temperature from about 0K up to 3300K but would normally be used only for high temperature measurements, i.e. greater than 750K. The optical pyrometer by measuring visible radiation is only able to measure temperatures greater than about 900K. It is interesting to note that with these instruments the sensing device does not come into physical contact with the hot body.

Errors can arise when pyrometers are used to measure temperatures ‘out in the open’, especially of hot flowing streams of molten metal; however, manufacturers supply radiation pyrometers calibrated for particular applications, which minimise these errors.

The relationship between a ‘non-black’ body and a ‘black body’ is given by emissivity, where

\[
\text{Emissivity } \varepsilon = \frac{\text{total radiation emitted by body}}{\text{total radiation emitted by a 'black body' at the same temperature}}
\]

and the power radiated per unit area from any body is given by Stefan’s law as

\[
P = \varepsilon \sigma T^4
\]

where
- \( P \) = total radiated power (W)
- \( T \) = body temperature (K)
- \( \sigma \) = Stefan’s constant = \( 5.67 \times 10^{-8} \text{Wm}^{-2}\text{K}^{-4} \)
- \( \varepsilon \) = emissivity

Example 16: The power radiated from a molten metal is measured and the temperature is determined to be 1500°C, assuming a surface emissivity of 0.82. If it is later found that a more accurate estimation of this emissivity is 0.75, calculate the actual temperature of the metal.

SOLUTION:
Rearranging equation (26) gives

\[
T = \left( \frac{P}{\varepsilon \sigma} \right)^{1/4}
\]
Incorrect temperature  \[ T_i = \left( \frac{P}{\varepsilon_1 \sigma} \right)^{1/4} \]

Actual temperature  \[ T_{act} = \left( \frac{P}{\varepsilon_2 \sigma} \right)^{1/4} \]

\[
\frac{T_{act}}{T_i} = \left( \frac{\varepsilon_1}{\varepsilon_2} \right)^{1/4} \quad \Rightarrow \quad T_{act} = T_i \times \left( \frac{\varepsilon_1}{\varepsilon_2} \right)^{1/4}
\]

\[
T_{act} = (1500 + 273)K \times \left( \frac{\varepsilon_1}{\varepsilon_2} \right)^{1/4} = 1800K
\]

Actual temperature = 1813 – 273 = 1540°C.

**Optical Pyrometers:** The disappearing filament type of optical pyrometer is most common. The arrangement is shown in Figure 26. A heated filament lamp is positioned in the path of incoming light from the hot body. The current flowing through the filament is varied until the filament “disappears”. The current through the lamp is thus a measure of the temperature of the hot body. The absorption screen is used to absorb some of the radiant energy from the source and thus extend the measuring range of the instrument. The monochromatic filter produces single colour, usually red, light to simplify filament matching.

Figure 26 Radiation pyrometer
Infra-red Pyrometers: The infra-red pyrometer operates by focusing the infra-red radiation from the hot-body on to a temperature-sensing element such as a resistance temperature detector or thermopile. The focusing system for an infra-red pyrometer is similar to a telescope arrangement, as illustrated in Figure 28, so that the radiation from the hot source can be focused accurately on to the temperature-sensing element. The infra-red pyrometer uses the thermopile at the focus of the light rays instead of a filament lamp. There is no requirement for either screen or filter and the unit will produce a continuous reading of temperature.

Since the temperature is sensed using electrical sensors, continuous recording or indicating is possible. If thermocouples are used, care must be taken by the manufacturer to ensure that the cold junction is well protected from the radiated heat from the source. Figure 29 shows an infra-red in market.
Module 2 is summarized as follows:

1. Transducers: resistance transducers, capacitive transducers, inductive transducers, linear variable differential transformers, piezo-electric transducers and mechanical transducers
2. AS Standard drawing symbols using in instrumentation and process control engineering
3. Temperature measurements: temperature, temperature methods, RTDs, thermocouples and radiation pyrometers.

**Exercises**

1. The output voltage of a potentiometer-type resistance transducer is to be measured by a recorder having an input resistance of 20kΩ. If the error of measurement is not to exceed –2% at 50% f.s.d, determine resistance value of the potentiometer. [1.633kΩ]

2. The following is a typical specification for potentiometer-type resistance transducer. Examine the specification and explain the meaning and significance of each item.

   - Type: wire-wound resistance displacement potentiometer
   - Terminal resistance: 10kΩ
   - Range: 0-25mm
   - Resolution: 0.4%
   - Power rating: 0.25W
   - Maximum wiper current: 15mA
   - Thermal drift: 0.05% per °C
   - Life expectancy: 10^8 cycles

3. A linear variable differential transformer is excited with a 100Hz 6V peak-to-peak waveform. The input core motion is sinusoidal at 10Hz and has a displacement amplitude of ±3mm. If the l.v.d.t sensitivity is 2V/mm, draw the waveforms of the excitation voltage, input displacement and output voltage.

4. The specification for the l.v.d.t in question 3 is as follows:

   - Linearity: 0.4%
   - Resolution: infinite
   - Residual voltage: 0.5%
   - Drift: better than 0.1% per °C
   - Output impedance: 2.5kΩ
   - Response time: 1ms

   Explain the meaning and significance of the specification.

5. (a) Describe the principle of operation and construction details of the piezo-electric (quartz) transducer.

(b) A quartz pressure transducer has a sensitivity of 80pC/bar. If, when the input pressure is 3bars, an output voltage of 1V is produced, determine the capacitance of the device. [240pF]

6. At any particular instant, a resistance thermometer indicates a temperature θ₂ of 50°C while the actual temperature θ₁ is 100°C. If the dynamic relationship for resistance thermometer is given by

   \[
   \frac{d\theta_s}{dt} = k(\theta_i - \theta_s) \quad \text{where} \quad k = 0.2s^{-1}
   \]

   determine the time constant for the thermometer. [5s]
7. A type-K thermocouple is exposed to a temperature of 1200°C. If the indicator is used as the cold junction and its temperature is 50°C. Use the following figure to calculate the e.m.f indicated. [47mV]

8. Using the above figure, determine (a) the sensitivity of the type-T thermocouple in the range of 0°C to 300°C, (b) the sensitivities of the type-E and type-S thermocouples in the range of 400°C to 1000°C. [0.5mV/°C] [0.08mC/°C] [0.01mV/°C]

9. Explain the principle of operation of the resistance temperature detectors.

10. Explain the principle of operation of the thermocouples.

11. Explain the principle of operation of the radiation pyrometers.
Appendices

Appendix 2.1 Signal Conditioning

A2.1.1 Introduction

The transduced signal is rarely in a form ready for display or recording. It may need to be increased in magnitude or modified in some way before display. The process of preparing the signal before display/indication or recording is referred to as signal conditioning.

The signal conditioning devices may have one or all of the following functions:

**Amplification**: The small signal from the transducer is increased in magnitude by a device referred to as an amplifier, e.g. levers, gears, and electronic, pneumatic and hydraulic amplifiers. The amount by which the signal is increased in magnitude is referred to as either gain or amplification or magnification.

**Signal modification**: The form of the signal or amplified signal is changed, e.g. by rack-and-pinion gears, electronic modulators, bridge circuits, potentiometric circuits, and analogue-to-digital converters.

**Impedance matching**: The signal conditioner acts as a buffer stage between the transducing and recording elements, the input and output impedances of the matching devices being arranged to prevent loading of the transducer and maintain a high signal level at the recorder.

The following sections introduce some common signal conditioners.

A2.1.2 Amplifiers

An amplifier is a device which increases the magnitude of, or amplifies, its input signal. Let us consider the block diagram representation (see Module 8) of an amplifier shown in Figure A2.1.1. The input signal \( u \) is amplified by an amount \( K \), resulting in an output \( y \) which is given by:

\[
y = Ku
\]

Figure A2.1.1 An amplifier block diagram

\[
\frac{y}{u} = K, \text{ the gain or amplification}
\]

Example: A displacement magnifier has an amplification of 20000 the output displacement is 40 mm, determine the corresponding input displacement.
SOLUTION
Using the above equation, we have

\[ \frac{y}{u} = K \Rightarrow u = \frac{y}{K} = \frac{4 \times 10^{-3} \text{ m}}{2000} = 2 \times 10^{-6} \text{ m} \]

If an amplifier having a gain \( K_1 \) is arranged that the output signal becomes the input signal of another amplifier having a gain \( K_2 \), as in Figure A2.1.2, the two amplifiers are said to be in cascade and the overall gain or amplification of the combined devices is:

\[
\frac{y}{u} = K_1K_2
\]

(A2.1.2)

Example: Two amplifiers A and B are cascaded so that their combined gain is the product of their individual gains. Given that gain of amplifier A = 100 and gain of amplifier B = 300, determine the output produced by an input of 4 units.

SOLUTION
Using equation (A2.1.2), we have

\[ \frac{y}{u} = K_1K_2, \text{ so } \]

\[ y = uK_1K_2 = 4 \text{ units} \times 100 \times 300 = 120,000 \text{ units}. \]

Amplifiers can be divided into 1) mechanic amplifiers (simple lever, Huggenberger extensometer, simple gears, compound gears), 2) optical amplifiers (optical lever) and 3) electronic amplifiers. Electronic amplifiers are common in control systems.

A2.1.3 Bridge Circuits (Wheatstone Bridge Circuits)

Electrical bridge circuits are used extensively in industrial instrumentation. They may be used with resistors, capacitors or inductors. For simplicity, we consider a Wheatstone bridge circuit with resistors as shown in Figure A2.1.3. In general, the Wheatstone circuit in Figure A2.1.3 can be analysed by the following equations:

\[
\begin{align*}
\text{ABCA:} & \quad V = I_1R_1 + (I_1 - I_3)R_3 \\
\text{ADCA:} & \quad V = I_2R_2 + (I_2 + I_3)R_4 \\
\text{ABDCA:} & \quad V = I_1R_1 + I_3R_5 + (I_2 + I_3)R_4 \\
\text{ABDCA:} & \quad V = I_2R_2 - I_3R_5 + (I_1 - I_3)R_3 \\
\text{ABDA:} & \quad 0 = I_1R_1 - I_3R_5 - I_2R_2 \\
\text{BCDB:} & \quad 0 = (I_1 - I_3)R_3 - (I_2 + I_3)R_4 - I_3R_5 \\
\text{ABCDA:} & \quad 0 = I_1R_1 + (I_1 - I_3)R_3 - (I_2 + I_3)R_4 - I_2R_2
\end{align*}
\]
1. Null-balance and deflection methods:

Consider the Wheatstone bridge circuit in Figure A2.1.3. For zero output voltage, referred to as the ‘balanced condition’, the following relationships exist:

\[ v_{AB} = v_{AD}, \text{ i.e. } i_1R_1 = i_2R_4 \]
\[ v_{BC} = v_{DC}, \text{ i.e. } i_2R_1 = i_2R_3 \]

Therefore, we have:
This condition for balance is used in 'null-balance’ bridge where one resistor is variable and has an indicator dial calibrated in the applicable engineering units or variables such as strain or temperature which produce the resistance changes of the sensing element. The scale calibration of the output-voltage measuring devices, possibly a meter, is unimportant since it is used only as a null or zero-voltage indicator.

The value of the calibrated resistor is adjusted to give zero output voltage and the calibrated dial gives an indication of the resistance changes required to balance the system. When the bridge is used so that its output voltage \( v_o \) is used to give an indication of resistance changes, the bridge is then referred to as a deflection bridge since its output voltage may be used to produce a deflection of the pointer on an electrical metre.

2) Wheatstone Bridge Circuit Analysis

Let’s consider the Wheatstone bridge shown in Figure A2.1.3, made up of four resistors and excited with a voltage \( V \). The output voltage from the bridge will change as the bridge becomes unbalanced. Inserting the following initial conditions simplifies the analysis.

Assume the bridge is initially balanced and let

\[
R_1 = R_2 = R_3 = R_4 = R
\]

then \( v_{AD} = v_{AB} = V/2 \) and \( v_o = v_{AB} - v_{AD} = 0 \)

Let \( R_1 \) change by an amount \( \Delta R_1 \) to \( R_1 + \Delta R_1 \) so that \( v_{AB} \) will change. New value of \( v_{AB} \) is

\[
v_{AB} = \frac{R_1 + \Delta R_1}{R_1 + \Delta R_1 + R_2} V
\]

but if \( R_1 = R_2 = R \) then

\[
v_{AB} = \frac{R + \Delta R}{2R + \Delta R} V
\]

\[
v_o = v_{AB} - v_{AD} = V \left( \frac{R + \Delta R}{2R + \Delta R} - \frac{1}{2} \right) = \frac{\Delta R}{4R + 2\Delta R} V
\]

and if \( \Delta R \ll R \) we have

\[
v_o = \frac{V \Delta R}{4R}
\]
By a similar analysis it can also be shown that if two resistors $R_1$ and $R_2$ vary, the expression becomes

$$v_o = \frac{V}{4} \left( \frac{\Delta R_1}{R} - \frac{\Delta R_2}{R} \right) \quad (A2.1.5)$$

Thus if the resistance changes are of the same sign and magnitude they cancel each other out and the output voltage is zero. This effect is put to good use in strain-gauge temperature compensation.

If the resistance changes are of opposite sign and equal in magnitude the output voltage $v_o$ becomes:

$$v_o = \frac{V}{2} \frac{\Delta R}{R} \quad (A2.1.6)$$

Similarly, if the changes are to $R_1 + \Delta R_1$, $R_2 - \Delta R_2$, $R_3 + \Delta R_3$, and $R_4 - \Delta R_4$ as used in a full active bridge circuit where all the resistors vary in value, the corresponding output voltage is given by:

$$v_o = V \frac{\Delta R}{R} \quad (A2.1.7)$$

where $\Delta R = \Delta R_1 = \Delta R_2 = \Delta R_3 = \Delta R_4$.

**Example:** A resistance Wheatstone bridge circuit made up of four resistors each of value 120 $\Omega$ has an excitation voltage of 5 V. Determine the output voltage change when one resistor’s value changes by 1.2 $\Omega$.

**SOLUTION**
Using Equation (A2.1.4) we have:

$$v_o = \frac{5V \times 1.2\Omega}{4 \times 120\Omega} = 12.5 \text{ mV}$$

**Example:** A symmetric Wheatstone bridge is made up of four equal-value resistors. When all four resistors change in value by 10%, the sense of the changes being such that maximum sensitivity is obtained, the output voltage alters by 100 mV. Determine the value of the excitation voltage.

**SOLUTION**
Using Equation (A2.1.7)

$$v_o = V \frac{\Delta R}{R} \Rightarrow V = \frac{v_o}{\Delta R} = 100 \times 10^{-3}(V) \times \frac{100}{1} = 10 \text{ V}.$$  

3) **AC and D.C. Excitation of Bridges**
The bridge circuit may be excited by either a d.c. voltage or a high frequency sinusoidal carrier signal. The later is a particular application of amplitude modulation where the bridge output voltage is modulated by the input signal. In AC bridges, the resistive elements are replaced with impedance and the bridge supply is an ac voltage as shown in Figure A2.1.4. The output (differential) voltage $v_o$ across BD (S) is then given by:

$$v_o = V \frac{Z_2Z_3}{(Z_1+Z_3)(Z_2+Z_4)}$$  \hspace{1cm} (A2.1.8)

where $V$ is the ac supply emf.

![Figure A2.1.4 AC bridges (a) using block impedance and (b) bridge with R an C components](image)

When the bridge is balanced $v_o = 0$ and equation (A2.1.8) reduces to

$$Z_2Z_3 = Z_1Z_4$$  \hspace{1cm} (A2.1.9)

Example: What are the conditions for the bridge circuit in Figure A2.1.4(b) to be balanced?

To be balanced Equation (A2.1.9) applies. There are two conditions must be met for this equation to be balanced because of the phase shift produced by the capacitors. First, the resistive component must balance, and this gives:

$$R_2R_3 = R_1R_4$$  \hspace{1cm} (A2.1.10)

Second, the impedance component must balance, and this gives

$$C_4R_2 = C_3R_1$$  \hspace{1cm} (A2.1.11)
Appendix 2.2 Recording, Display and Indicating Devices

A2.2.1 Introduction

The recorder or display unit is the last element in the measuring system and is the component that provides the results of the measurement. Its selection is therefore just as critical as that of the correct transducer or signal conditioner. The recorder produces a permanent record of the signal while display or indicating unit does not. There exists a large range of complicated recording equipment which uses microprocessors and semiconductor memories to record transient signals. Examples of records are u.v. recorders, pen recorders, and X-Y plotters. Some examples of displays are CRTs, CRT oscilloscopes, LCDs and plasma displays.

Recording, display and/or indicating devices can be classified into the following categories:

- Mechanical pointers,
- Moving coil mechanisms,
- Cathode ray tube (CRT) displays (including oscilloscopes),
- Liquid crystal displays (LCD)
- Plasma-driven flat panel displays
- Electroluminescent displays
- Light-emitting diode (LED) displays
- Graphic recorders (pen recorders, chart recorders, ultra-violet recorders or u.v galvanometer, X-Y plotters and servo recorders)
- Data acquisition systems (including computers)
- Magnetic and optical recorders
- Printers

A2.2.2 Graphical Recorders

A graphic recorder is essentially a measuring apparatus that is able to produce in real time a hard copy of a set of time functions with the purpose of immediate and/or later visual inspection. The curves are most drawn on a long strip of paper (from a roll or X-fold), as such, the instrument is indicated as a strip chart recorder. The independent variable time t then corresponds to the strip length axis and the physical variables are related to the chart width. Tracings are obtained by a writing process at sites on the chart short axis (y) corresponding to the physical variables magnitudes with the strip being moved at a constant velocity to generate the time axis. Graphs cannot be interpreted if essential information is absent; scales and reference levels for each physical variable recorded and form time are all a necessity (Webster, 1999).

Graphic recorders can be divided into the following categories:

- Translational pen recorders, thermal dot array recorders,
- Analogue graphic recorders and digital graphic recorders
- Paperless graphic recorders and paper chart recorders
Figure A2.1.5 shows an example of paperless graphic recorder and Figure A2.1.6 shows an example of paper chart recorder.

**Figure A2.1.5 Paperless graphic recorder (Series 6100A, Courtesy of Eurotherm)**

**Figure A2.1.6 Paper chart recorder (Series of 4101x 100mm Chart Recorder, Courtesy of Eurotherm)**

### A2.2.3 Oscilloscopes

The oscilloscope is essentially a voltage-measuring device where the deflection of an electron beam is caused by an input voltage. When the beam of high-velocity electrons strikes the phosphor-coated screen, a spot of light is produced which can be deflected in both the X and Y-axes. The input signal to be displayed is normally applied to the Y-deflection system, while the X deflection occurs at a constant rate to give a ‘time base’ to the display. It is, however, possible to apply one input signal to the Y channel and another signal to the X channel to give an X-Y rather than a Y-t display.

According to Haslam et al (1981), three main factors make the oscilloscopes the ideal device to carry out an initial examination of the output from an electrical measuring system. They are:
- the excellent frequency response of typically up to 50 MHz. This is due to the electron having negligible mass and so being able to respond rapidly to changes of deflection.
- the high input impedance of approximately 1 MΩ. The signal source is therefore not loaded excessively.
- a visual display of the waveform is obtained, allowing the frequency and maximum values to be determined.

The basic construction of the CRT is shown in Figure A2.1.7. There are two types of deflection: electrostatic and electromagnetic.

![Figure A2.1.7 Basic construction of a CRT (Wikipedia, 2006)](image)

Figure A2.1.7 Basic construction of a CRT (Wikipedia, 2006)

Figure A2.1.8 shows different types of oscilloscopes in market.

![Figure A2.1.8 Different types of oscilloscope in market (Wikipedia, 2006)](image)

Figure A2.1.8 Different types of oscilloscope in market (Wikipedia, 2006)

### A2.2.4 Data Acquisition Systems

Nowadays computer has more and more been used in many instrumentation and control systems. A measuring system that has a computer as a recording device is called a data acquisition system.
as illustrated in Figure A2.1.9. The fundamental task of a data acquisition system is the measurement or generation of real world physical signals. Before a physical signal and be measured by a computer-based system, a sensor or transducer is used to convert the physical signal into an electrical signal, such as voltage or current. A complete data acquisition system consists of sensors, signal conditioning devices, data acquisition board (interface hardware), a computer and software (McConnel, 1999).

Figure A2.1.9 Data acquisition system

Figure A2.1.10 shows an example of data acquisition unit.

Figure A2.1.10 Example of data acquisition unit (Series 5000B, Eurotherm)

Features of Eurotherm 5000B Data Acquisition Unit:

- Full Bridge 5000 as standard
- High noise rejection and isolation
- Up to 12 freely configurable input channels
- Up to 7 changeover relay outputs
- 125ms parallel sampling
- Ethernet communications
- Modbus TCP
- Client and server File Transfer Protocol as standard
- Time synchronisation using Simple Network Time Protocol (SNTP)
- RS232/485 serial communications option
- Data archiving over Ethernet
- Review software as standard
- 16.25Mbyte internal Flash for storage of process data
- Adaptive recording
- 24 configurable, event driven messages