

Chapter One

General Principles of Instrumentation

1.1 Purpose and performance of measurement systems

We begin by defining a process as a system which generates information. Examples are a chemical reactor, a jet fighter, a gas platform, a submarine, a car, a human heart, and a weather system.

Table 1.1 lists information variables which are commonly generated by processes: thus a car generates displacement, velocity and acceleration variables, and a chemical reactor generates temperature, pressure and composition variables.

Table 1.1: Common Information(Measured Variables)

Acceleration	Density
Velocity	Viscosity
Displacement	Composition
Force-Weight	pH
Pressure	Humidity
Torque	Temperature
Volume	Heat/Light flux
Mass	Current
Flow rate	Voltage
Level	Power

We then define the observer as a person who needs this information from the process. This could be the car driver, the plant operator or the nurse. The purpose of the measurement system is to link the observer to the process, as shown in Figure 1.1. Here the observer is presented with a number which is the current value of the information variable.

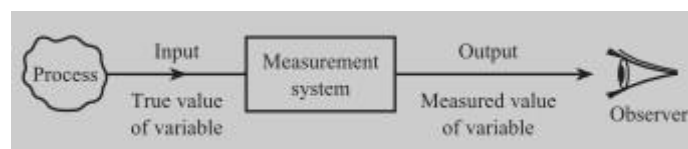


Figure 1.1: Purpose of measurement system

We can now refer to the information variable as a measured variable. The input to the measurement system is the true value of the variable; the system output is the measured value of the variable. In an ideal measurement system, the measured value would be equal to the true value. The accuracy of the system can be defined as the closeness of the measured value to the true value. A perfectly accurate system is a theoretical ideal and the accuracy of a real system is quantified using measurement system error E , where

$$E = \text{measured value} - \text{true value}$$

$$E = \text{system output} - \text{system input}$$

Thus if the measured value of the flow rate of gas in a pipe is $11.0 \text{ m}^3/\text{h}$ and the true value is $11.2 \text{ m}^3/\text{h}$, then the error $E = -0.2 \text{ m}^3/\text{h}$. If the measured value of the rotational speed of an engine is 3140 rpm and the true value is 3133 rpm , then $E = +7 \text{ rpm}$. Error is the main performance indicator for a measurement system.

1.2 Structure of measurement systems

The measurement system consists of several elements or blocks. It is possible to identify four types of element, although in a given system one type of element may be missing or may occur more than once. The four types are shown in Figure 1.2 and can be defined as follows.

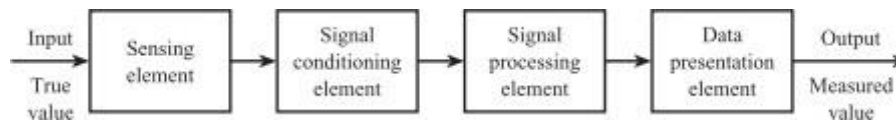


Figure 1.2: General structure of measurement system

Sensing element

This is in contact with the process and gives an output which depends in some way on the variable to be measured. Examples are:

- Thermocouple where mill volt *e.m.f.* depends on temperature
- Strain gauge where resistance depends on mechanical strain
- Orifice plate where pressure drop depends on flow rate

If there is more than one sensing element in a system, the element in contact with the process is termed the primary sensing element, the others secondary sensing elements.

Signal conditioning element

This takes the output of the sensing element and converts it into a form more suitable for further processing, usually a D.C. voltage, D.C. current or frequency signal. Examples are:

- Deflection Bridge which converts an impedance change into a voltage change
- Amplifier which amplifies mill volts to volts
- Oscillator which converts an impedance change into a variable frequency voltage

Signal processing element

This takes the output of the conditioning element and converts it into a form more suitable for presentation. Examples are:

- Analogue-to-digital converter (ADC) which converts a voltage into a digital form for input to a computer
- Computer which calculates the measured value of the variable from the incoming digital data.

Typical calculations are:

- Computation of total mass of product gas from flow rate and density data
- Integration of chromatograph peaks to give the composition of a gas stream

- Correction for sensing element non-linearity

Data presentation element

This presents the measured value in a form which can be easily recognized by the observer.

Examples are:

- Simple pointer–scale indicator
- Chart recorder
- Seven Segment Display
- Liquid Crystal Display
- Light Emitting Diode Display

1.3 Static and dynamic characteristics of measurement systems

1.3.1 Static characteristics:

These are the relationships which may occur between the output O and input I of an element when I is either at a constant value or changing slowly.

1.3.1.1 Systematic characteristics:

Systematic characteristics are those that can be exactly quantified by mathematical or graphical means. These are distinct from statistical characteristics which cannot be exactly quantified.

(a) *Range:*

The input range of an element is specified by the minimum and maximum values of I, i.e. I_{MIN} to I_{MAX} . The output range is specified by the minimum and maximum value of O, i.e. O_{MIN} to O_{MAX} . Thus a pressure transducer may have an input range of 0 to 10^4 Pa and an output range of 4 to 20 mA; a thermocouple may have an input range of 100 to 250 °C and an output range of 4 to 10 mV.

(b) *Span:*

Span is the maximum variation in input or output, i.e. input span is $I_{MAX} - I_{MIN}$, and output span is $O_{MAX} - O_{MIN}$. Thus in the above examples the pressure transducer has an input span of 10^4 Pa and an output span of 16 mA; the thermocouple has an input span of 150 °C and an output span of 6 mV.

(c) *Ideal Straight Line:*

An element is said to be linear if corresponding values of I and O lie on a straight line. The ideal straight line connects the minimum point A (I_{MIN} , O_{MIN}) to maximum point B (I_{MAX} , O_{MAX}) (Figure 2.2) and therefore has the equation

$$O - O_{MIN} = \left[\frac{O_{MAX} - O_{MIN}}{I_{MAX} - I_{MIN}} \right] (I - I_{MIN})$$

$$O_{IDEAL} = KI + a$$

Equ. 1.1

where:

$$K = \text{ideal straight-line slope} = \frac{O_{\text{MAX}} - O_{\text{MIN}}}{I_{\text{MAX}} - I_{\text{MIN}}}$$

and

$$a = \text{ideal straight-line intercept} = O_{\text{MIN}} - KI_{\text{MIN}}$$

Thus the ideal straight line for the above pressure transducer is:

$$O = 1.6 \times 10^{-3}I + 4.0$$

The ideal straight line defines the ideal characteristics of an element. Non-ideal characteristics can then be quantified in terms of deviations from the ideal straight line.

(d) *Non-linearity:*

In many cases the straight-line relationship defined by eqn [1.1] is not obeyed and the element is said to be non-linear. Non-linearity can be defined (Figure 1.3) in terms of a function $N(I)$ which is the difference between actual and ideal straight-line behavior, i.e.

$$N(I) = O(I) - (KI + a)$$

or

$$O(I) = KI + a + N(I)$$

Non-linearity is often quantified in terms of the maximum non-linearity; expressed as a percentage of full-scale deflection (f.s.d.), i.e. as a percentage of spans. Thus:

$$\text{Max. non-linearity as a percentage of f.s.d.} = \frac{\hat{N}}{O_{\text{MAX}} - O_{\text{MIN}}} \times 100\%$$

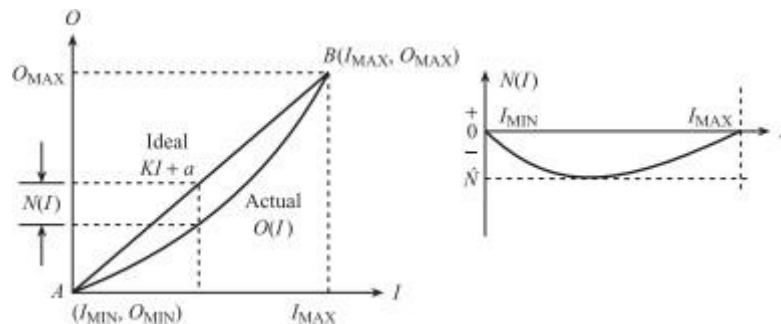


Figure 1.3: Definition of non-linearity

As an example, consider a pressure sensor where the maximum difference between actual and ideal straight-line output values is 2 mV. If the output span is 100 mV, then the maximum percentage non-linearity is 2% of f.s.d.

(e) *Sensitivity:*

This is the change ΔO in output O for unit change ΔI in input I , i.e. it is the ratio $\Delta O/\Delta I$. In the limit that ΔI tends to zero, the ratio $\Delta O/\Delta I$ tends to the derivative dO/dI , which is the rate of change of O with respect to I . For a linear element dO/dI is equal to the slope

or gradient K of the straight line For a non-linear element $dO/dI = K + dN/dI$, i.e. Sensitivity is the slope or gradient of the output versus input characteristics $O(I)$.

(f) *Hysteresis:*

For a given value of I , the output O may be different depending on whether I is increasing or decreasing. Hysteresis is the difference between these two values of O (Figure 1.4), i.e

$$\text{Hysteresis } H(I) = O(I)_{I\downarrow} - O(I)_{I\uparrow}$$

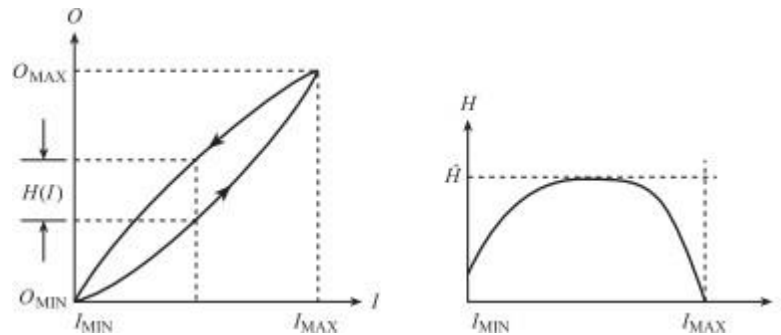


Figure 1.4: Hysteresis

Again hysteresis is usually quantified in terms of the maximum hysteresis \hat{H} expressed as a percentage of f.s.d., i.e. span. Thus:

$$\text{Maximum hysteresis as a percentage of f.s.d.} = \frac{\hat{H}}{O_{\text{MAX}} - O_{\text{MIN}}} \times 100\%$$

A simple gear system (Figure 1.5) for converting linear movement into angular rotation provides a good example of hysteresis. Due to the 'backlash' or 'play' in the gears the angular rotation θ , for a given value of x , is different depending on the direction of the linear movement.

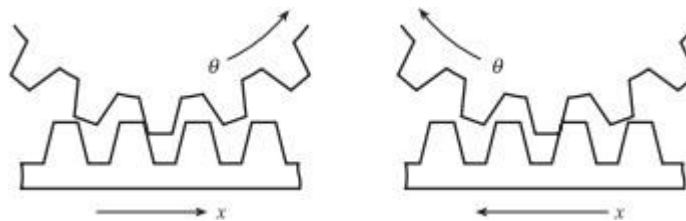


Figure 1.5: Backlash in gears

(g) *Resolution:*

Some elements are characterized by the output increasing in a series of discrete steps or jumps in response to a continuous increase in input (Figure 1.6). Resolution is defined as the largest change in I that can occur without any corresponding change in O .

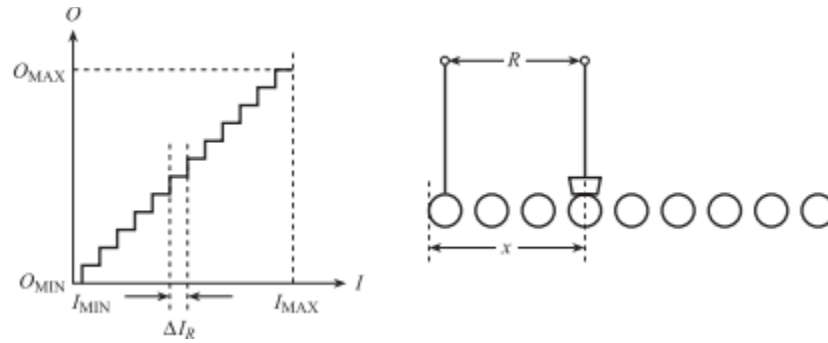


Figure 1.6: Resolution and potentiometer

Thus in Figure 2.5 resolution is defined in terms of the width ΔI_R of the widest step; resolution expressed as a percentage of f.s.d. is thus:

$$\frac{\Delta I_R}{I_{MAX} - I_{MIN}} \times 100\%$$

A common example is a wire-wound potentiometer (Figure 2.5); in response to a continuous increase in x the resistance R increases in a series of steps, the size of each step being equal to the resistance of a single turn. Thus the resolution of a 100 turn potentiometer is 1%. Another example is an analogue-to-digital converter. Here the output digital signal responds in discrete steps to a continuous increase in input voltage; the resolution is the change in voltage required to cause the output code to change by the least significant bit.

1.3.2 Dynamic characteristics:

If the input signals I to an element is changed suddenly, from one value to another, then the output signal O will not instantaneously change to its new value. For example, if the temperature input to a thermocouple is suddenly changed from 25 °C to 100 °C, sometime will elapse before the e.m.f. output completes the change from 1 mV to 4 mV. The ways in which an element responds to sudden input changes are termed its dynamic characteristics, and these are most conveniently summarized using a transfer function $G(s)$.

1.4 Signals and noise in measurement systems

A signal could be deterministic or random. A *deterministic* signal is one whose value at any future time can be exactly predicted. Thus if we record these signals for an observation period T_o (Figure 1.6), the future behavior of the signal, once the observation period is over, is known exactly. The future behavior of real processes, such as chemical reactors, blast furnaces and aircraft, will depend on unknown factors such as the type of feedstock, reliability of equipment, changes in throughput and atmospheric conditions, and cannot be known in advance. This means that the future value of measured variables, such as reactor temperature, flow in a pipe and aircraft speed cannot be exactly predicted. Thus in real measurement applications the input signal to the measurement system is not deterministic but *random*. If a random signal is

recorded for an observation period T_0 (Figure 1.7) the behavior of the signal, once the observation period is over, is not known exactly. However, five statistical quantities – mean, standard deviation, probability density function, power spectral density and autocorrelation function are used to estimate the behaviour of random signals.

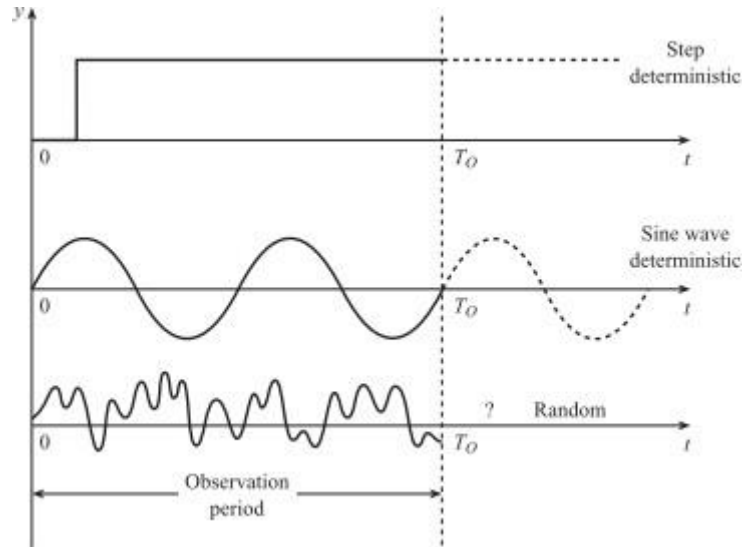


Figure 1.7: Deterministic and random signals

Unwanted electrical signals may also be present in the measurement circuit. These may be due to sources inside the measurement circuit or caused by coupling to sources outside the circuit. The magnitude of the unwanted signal may be comparable to or larger than that of the measurement signal itself, resulting in a measurement error for the overall system. The unwanted signal then may be either random, e.g. signals caused by the random motion of electrons, or deterministic, e.g. sinusoidal signals at 50 Hz caused by power cables. Unwanted random signals are usually referred to as *noise* signals and unwanted deterministic signals as *interference* signals.

1.4.1 Noise sources

1.4.1.1 Internal noise sources:

The random, temperature-induced motion of electrons and other charge carriers in resistors and semiconductors gives rise to a corresponding random voltage which is called thermal or Johnson noise. This has a power spectral density which is uniform over an infinite range of frequencies (white noise) but proportional to the absolute temperature. A similar type of noise is called shot noise; this occurs in transistors and is due to random fluctuations in the rate at which carriers diffuse across a junction. This is again characterized by a uniform power spectral density over a wide range of frequencies.

1.4.1.2: External noise and interference sources:

The most common sources of external interference are near by *A.C. power circuits* which

usually operate at 240 V, 50 Hz. These can produce corresponding sinusoidal interference signals in the measurement circuit, referred to as *mains pick-up* or *hum*. Power distribution lines and heavy rotating machines such as turbines and generators can cause serious interference.

D.C. power circuits are less likely to cause interference because D.C. voltages are not coupled capacitively and inductively to the measurement circuit. However, **switching** often occurs in both A.C. and D.C. power circuits when equipment such as motors and turbines is being taken off line or brought back on line. This causes sudden large changes in power, i.e. steps and pulses, which can produce corresponding transients in the measurement circuit. **Fluorescent** lighting is another common interference source; arcing occurs twice per cycle so that most of the interference is at twice the power frequency. **Radio-frequency transmitters**, welding equipment and electric arc furnaces can produce radio frequency interference at frequencies of several MHz.

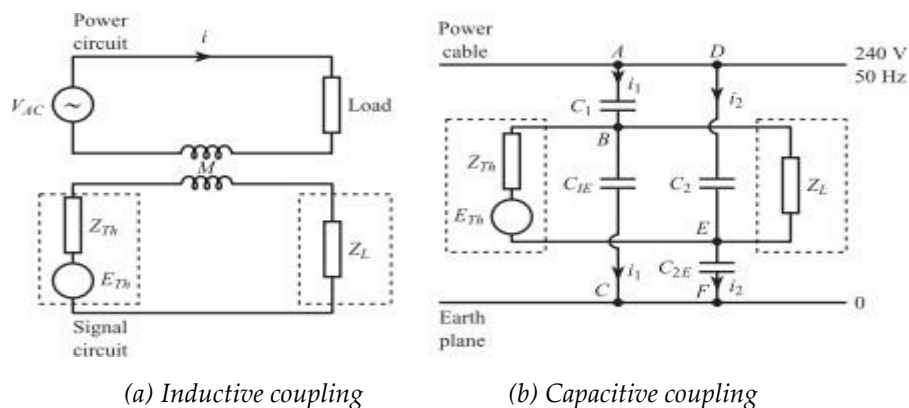
1.4.1.2.1 Noise due to couplings:

(a) Inductive coupling:

Figure 1.8(a) shows inductive or electromagnetic coupling between the measurement circuit and a nearby power circuit. If the circuits are sufficiently close together, then there may be a significant mutual inductance M between them. This means that an alternating current I in the power circuit induces a series mode interference voltage in the measurement circuit of magnitude.

$$V_{SM} = M \frac{di}{dt}$$

Thus if $M \approx 1 \mu\text{H}$ and $di/dt \approx 10^3 \text{A s}^{-1}$ (possible in a 1 horsepower motor) then $V_{SM} \approx 1 \text{mV}$, which can be comparable with the measurement signal. The mutual inductance M depends on the geometry of the two circuits, namely on the overlapping length and separation, but is distributed over the entire length of the circuits rather than the 'lumped' equivalent value shown in Figure 1.8. Inductive coupling will occur even if the measurement circuit is completely isolated from earth.



(a) Inductive coupling

(b) Capacitive coupling

Figure 1.8: Coupling mechanisms to external sources

(b) Capacitive Coupling:

Another important coupling mechanism is capacitive or electrostatic coupling, which is illustrated in Figure 1.8(b). The diagram shows the measurement circuit close to an a.c. power cable which is at a potential of 240 V (r.m.s.) relative to the earth plane. The power cable, earth plane and signal leads are all conductors, so that there may be some capacitance between the power cable and the signal leads and between the signal leads and the earth plane. These capacitances will be distributed over the entire length of the measurement circuit, but are represented by 'lumped' equivalents. C_1 and C_2 are the capacitances between the power cable and signal leads, and C_{1E} and C_{2E} the capacitances between the signal lead and the earth plane; all four capacitances will be proportional to the length of the measurement circuit, which could be tens of meters in an industrial installation. Ignoring the measurement signal voltage E_{Th} for the moment, the potentials at B and E are determined by the potential dividers ABC and DEF:

$$V_B = 240 \left[\frac{1/(j\omega C_{1E})}{1/(j\omega C_{1E}) + 1/(j\omega C_1)} \right] = 240 \frac{C_1}{C_1 + C_{1E}}$$

$$V_E = 240 \left[\frac{1/(j\omega C_{2E})}{1/(j\omega C_{2E}) + 1/(j\omega C_2)} \right] = 240 \frac{C_2}{C_2 + C_{2E}}$$

Thus we have a common mode interference voltage $V_{CM}=V_E$ and a series mode interference voltage:

$$V_{SM} = V_B - V_E = 240 \left(\frac{C_1}{C_1 + C_{1E}} - \frac{C_2}{C_2 + C_{2E}} \right)$$

Thus series mode interference is zero only if there is perfect balance between the coupling capacitances, i.e. $C_1 = C_2$ and $C_{1E} = C_{2E}$; in practice small imbalances are present due to slightly different distances between each signal lead and the power cable/earth plane.

1.4.2 Methods of reducing effects of noise and interference:**1.4.2.1 Physical separation:**

Since mutual inductances and coupling capacitances between measurement and power circuits are inversely proportional to the distance between them, this distance should be as large as possible.

1.4.2.2 Electromagnetic shielding:

The simplest way of reducing the effects of inductive coupling to an external interference source is shown in Figure 1.9. The two conductors A and B of the measurement circuit are twisted into loops of approximately equal area. This arrangement is commonly known as twisted pairs. The

magnitude of the interference voltage induced in a given loop is proportional to the area of the loop and the rate of change of the external magnetic field. The sign of the induced voltage depends on the orientation of conductors A and B. Thus if a voltage V_{XY} is induced in the j^{th} loop between points X and Y, then an opposing voltage V_{YZ} is induced in the $(j+1)^{\text{th}}$ loop between Y and Z. In the ideal case of both loops having the same area and experiencing the same magnetic fields, $|V_{XY}| = |V_{YZ}|$, i.e. there is a zero resultant induced voltage between X and Z. This process is repeated for the whole length of the twisted pair, giving a reduced overall interference voltage.

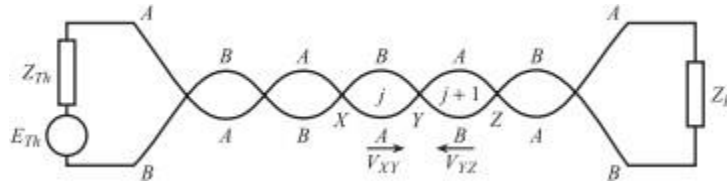


Figure 1.9: Reduction of electromagnetic coupling by twisted pairs.

1.4.2.3 Use of differential amplifiers:

Common mode interference voltages can be successfully rejected by the use of a differential amplifier. Figure 1.10 An ideal differential amplifier has an output:

$$V_{\text{OUT}} = \frac{R_F}{R_1} (V_2 - V_1) = -\frac{R_F}{R_1} E_{\text{TH}}$$

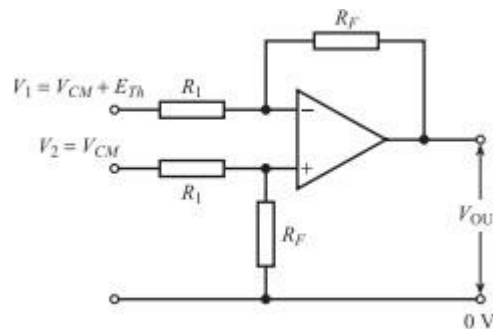


Figure 1.10: Use of differential amplifier

i.e. only the sensor voltage E_{th} is amplified.

1.4.2.4 Filtering:

A filter is an element which transmits a certain range (or ranges) of frequencies and rejects all other frequencies. An analogue filters an electrical network, consisting usually of resistors, capacitors and operational amplifiers, which conditions continuous signals. A digital filter is usually a digital computer programmed to process sampled values of a signal. Provided that the power spectrum of the measurement signal occupies a different frequency range from that of the noise or interference signal, then filtering improves the signal-to-noise ratio.

Figures 1.11(a)–(d) show the use of *low pass*, high pass, *band pass* and *band stop* filters in rejecting noise. In all cases the filter transmits the measurement signal but rejects the noise

signal, which occupies a different frequency range. The diagrams show the amplitude ratio $|G(j\omega)|$ for each filter and the power spectral densities $\phi(\omega)$ for signal and noise. Analogue filtering can be implemented at the signal conditioning stage; the a.c. amplifier is an example of a band pass filter. Digital filtering can be implemented at the signal processing stage. If, however, measurement signal and noise spectra overlap, filtering has limited value.

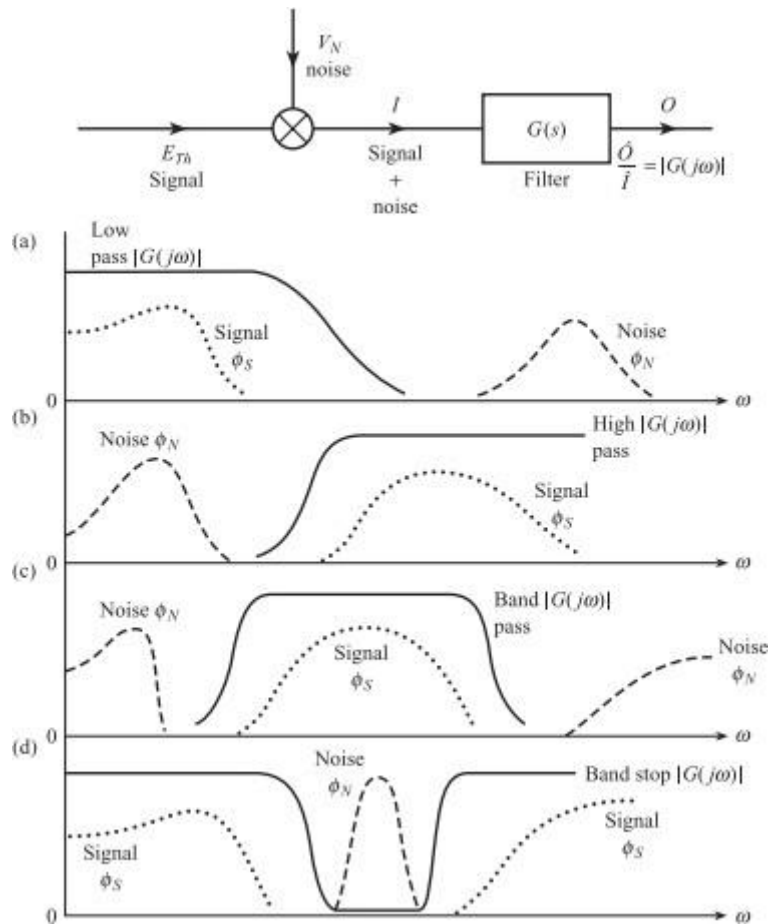


Figure 1.11 Use of filtering to reject noise

1.4.2.5 : Averaging:

Signal averaging can be used to recover a repetitive measurement signal affected by random noise, even if the signal r.m.s. value is much less than that of the noise. The process is shown in Figure 1.12. Suppose that T is the time for each complete cycle of the repetitive signal; p sections of the noise-affected signal, each of duration T , are fed into the averager. N samples from each section are taken and stored, giving pN samples in total; typically we may have $p=50$, $N=100$. The sampling is exactly synchronized: i.e. if the i th sample of the 1st section is taken at time t_0 , the i th sample of the 2nd section is taken at t_0+T , the i th sample of the 3rd at t_0+2T , and so on. Corresponding samples from each section are then averaged: e.g. the first sampled values from each of the p sections are added together and divided by p . Thus the average value of the

i^{th} sample is:

$$y_i^{\text{AV}} = \frac{1}{p}(y_{i1} + y_{i2} + \dots + y_{ip}), \quad i = 1, \dots, N$$

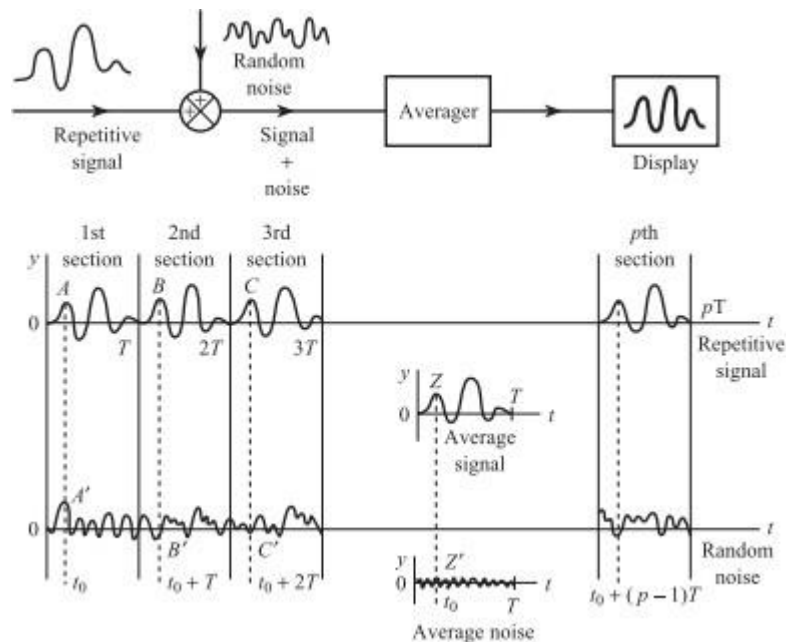


Figure 1.12 Signal averaging.

Each of these N average sample values are then displayed at the appropriate time to give the averaged signal. Corresponding sample values A, B, C, \dots of the signal component are approximately equal, so that the average value Z has a similar magnitude. Corresponding sample values A', B', C', \dots of the noise component are very different, some positive and some negative, so that the average value Z' is reduced in magnitude. Averaging therefore maintains the r.m.s. value of the measurement signal while reducing the r.m.s. value of the random noise.

1.5 Reliability, choice, and economics of measurement systems

Reliability is an important characteristic of a measurement system; it is no good having an accurate measurement system which is constantly failing and requiring repair. The reliability of a measurement element or system can be defined as: 'the probability that the element or system will operate to an agreed level of performance, for a specified period, subject to specified environmental conditions'. In the case of a measurement system 'agreed level of performance' could mean an accuracy of $\pm 1.5\%$. If the system is giving a measurement error outside these limits, then it is considered to have failed, even though it is otherwise working normally. Reliability decreases with time; a measurement system that has just been checked and calibrated should have a reliability of 1 when first placed in service. Six months later, the reliability may be only 0.5 as the probability of survival decreases.

The methods to be used and problems involved in choosing the most appropriate measurement system for a given application can depend on various factors. The accuracy, the reliability, cost, the environmental condition, etc could be some of the factors we depend on.

The total lifetime operating costing (TLOC) of a measurement system is the total cost penalty, incurred by the user, during the lifetime of the system. The TLOC is given by

$$\begin{aligned} \text{TLOC} = & \text{initial cost of system (purchase, delivery, installation and commissioning)} \\ & + \text{cost of failures and maintenance over lifetime of the system} \\ & + \text{cost of measurement error over lifetime of the system} \end{aligned}$$

and therefore takes account of the financial value of each parameter in the job specification. The best system for a given application is then the one with minimum TLOC. This method also enables the user to decide whether a measurement system is necessary at all. If no system is installed, TLOC may still be very large because no measurement implies a large measurement error. A measurement system should be purchased if it produces a significant reduction in TLOC.

Chapter Two

Sensing elements and their applications

2.1 Introduction

We saw that, in general, a measurement system consists of four types of element: sensing, signal conditioning, signal processing and data presentation elements. The sensing element is the first element in the measurement system; it is in contact with, and draws energy from, the process or system being measured. The input to this element is the true value of the measured variable; the output of the element depends on this value. The purpose of this chapter is to discuss the principles and characteristics of sensing elements in wide current use.

2.2 Temperature Sensors

The hotness or coldness of a piece of plastic, wood, metal, or other material depends upon the molecular activity of the material. Kinetic energy is a measure of the activity of the atoms which make up the molecules of any material. Therefore, temperature is a measure of the kinetic energy of the material in question. Whether you want to know the temperature of the surrounding air, the water cooling a car's engine, or the components of a nuclear facility, you must have some means to measure the kinetic energy of the material. Most temperature measuring devices use the energy of the material or system they are monitoring to raise (or lower) the kinetic energy of the device. A normal household thermometer is one example. The mercury, or other liquid, in the bulb of the thermometer expands as its kinetic energy is raised. By observing how far the liquid rises in the tube, you can tell the temperature of the measured object.

2.2.1 Resistive Temperature Detector (Sensor) (RTD):

Because temperature is one of the most important parameters of a material, many instruments have been developed to measure it. One type of detector used is the resistance temperature detector (RTD).

RTD Construction and Operation:

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 signals 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.

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 2.1), their high coefficient of resistance, and their ability to withstand repeated temperature cycles.

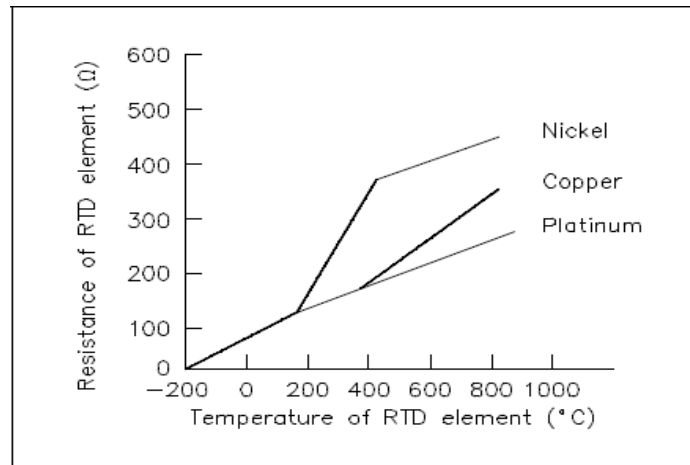


Figure 2.1: Electrical Resistance-Temperature Curves

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 a sheath of metal. Figure 2.2 shows the internal construction of an RTD.

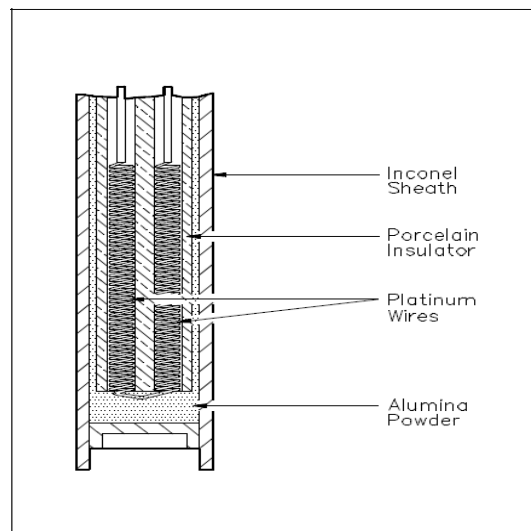


Figure 2.2: Internal Construction of a Typical RTD

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 when we are discussing signal conditioning elements.

Figure 2.3 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.

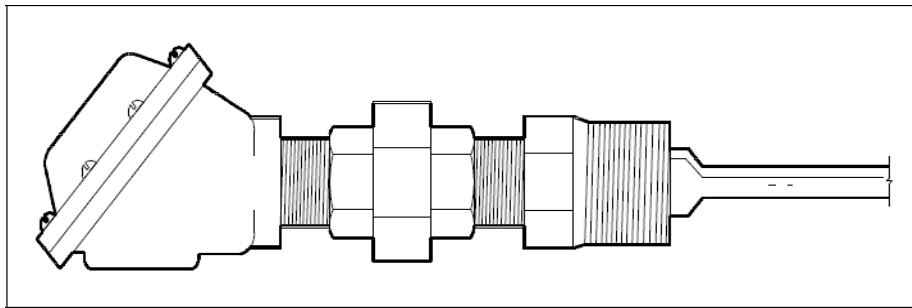


Figure 2.3: RTD Protective Well and Terminal Head

2.2.2 Thermocouples:

A thermocouple is another sensor for measuring temperature. It consists of two dissimilar metals, joined together at one end. When the junction of the two metals is heated or cooled a voltage is produced that can be correlated back to the temperature.

Thermocouple Construction and Operation:

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 2.4 illustrates the characteristics of the more commonly used materials when used with

platinum.

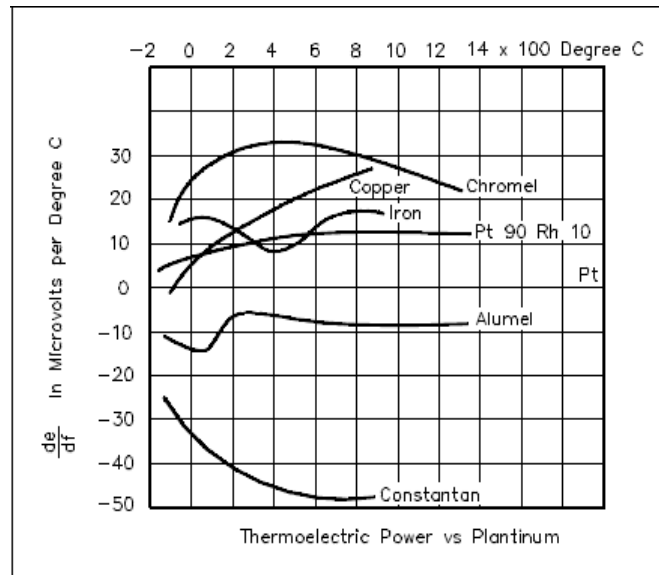


Figure 2.4: Thermocouple Material Characteristics When Used with Platinum

Figure 2.5 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.



Figure 2.5: Internal Construction of a Typical Thermocouple

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 2.6 illustrates a measuring system for a thermocouple. Heating the measuring junction of the thermocouple produces a voltage which is greater than the voltage across the reference junction (tail end). The tail end is maintained in an ice bath made by crushed ice and water in a Dewar flask: this produces a reference temperature of 0°C. All the voltage versus temperature relationships for thermocouples are referenced to 0°C. The difference between the two voltages is proportional to the difference in temperature and can be measured on the voltmeter (in millivolts). For ease of operator use, some voltmeters are set up to read out directly in temperature through use of electronic circuitry.

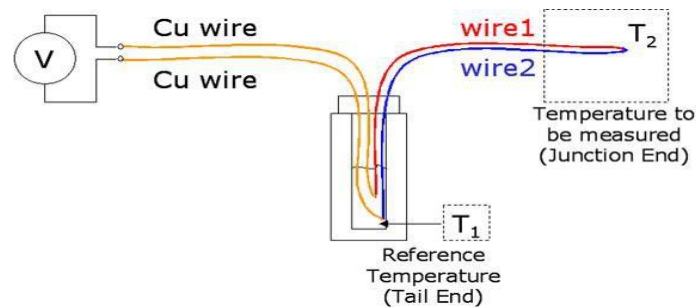


Figure 2.6: A measuring system for thermocouples

Other applications provide only the milli-volt readout. In order to convert the milli-volt reading to its corresponding temperature, you must refer to tables like the one shown in Figure 2.7. These tables can be obtained from the thermocouple manufacturer, and they list the specific temperature corresponding to a series of milli-volt readings.

Temperatures (°C) (IPTS 1968).											Reference Junction 0°C.	
°C	0	10	20	30	40	50	60	70	80	90	100	°C
Thermoelectric Voltage in Absolute Millivolts												
- 0	0.000	-0.053	-0.103	-0.150	-0.194	-0.236						- 0
+ 0	0.000	0.055	0.113	0.173	0.235	0.299	0.365	0.432	0.502	0.573	0.645	+ 0
100	0.645	0.719	0.795	0.872	0.950	1.029	1.109	1.190	1.273	1.356	1.440	100
200	1.440	1.525	1.611	1.698	1.785	1.873	1.962	2.051	2.141	2.232	2.323	200
300	2.323	2.414	2.506	2.599	2.692	2.786	2.880	2.974	3.069	3.164	3.260	300
400	3.260	3.356	3.452	3.549	3.645	3.743	3.840	3.938	4.036	4.135	4.234	400
500	4.234	4.333	4.432	4.532	4.632	4.732	4.832	4.933	5.034	5.136	5.237	500
600	5.237	5.339	5.442	5.544	5.648	5.751	5.855	5.960	6.064	6.169	6.274	600
700	6.274	6.380	6.486	6.592	6.699	6.805	6.913	7.020	7.128	7.236	7.345	700
800	7.345	7.454	7.563	7.672	7.782	7.892	8.003	8.114	8.225	8.336	8.448	800
900	8.448	8.560	8.673	8.786	8.899	9.012	9.126	9.240	9.355	9.470	9.585	900
1,000	9.585	9.700	9.816	9.932	10.048	10.165	10.282	10.400	10.517	10.635	10.754	1,000
1,100	10.754	10.872	10.991	11.110	11.229	11.348	11.467	11.587	11.707	11.827	11.947	1,100
1,200	11.947	12.067	12.188	12.308	12.429	12.550	12.671	12.792	12.913	13.034	13.155	1,200
1,300	13.155	13.276	13.397	13.519	13.640	13.761	13.883	14.004	14.125	14.247	14.368	1,300
1,400	14.368	14.489	14.610	14.731	14.852	14.973	15.094	15.215	15.336	15.456	15.576	1,400
1,500	15.576	15.697	15.817	15.937	16.057	16.176	16.296	16.415	16.534	16.653	16.771	1,500
1,600	16.771	16.890	17.008	17.125	17.243	17.360	17.477	17.594	17.711	17.826	17.942	1,600
1,700	17.942	18.058	18.170	18.282	18.394	18.504	18.612					1,700
°C	0	10	20	30	40	50	60	70	80	90	100	°C

Figure 2.7: Temperature-vs-Voltage Reference Table

In order to measure the voltage at the tail end, two copper wires are connected between the thermo elements and the voltmeter: both the Cu wires experience the same temperature difference and as a result the voltage drops along each of them are equal to each other and cancel out in the measurement at the voltmeter.

The ice bath is usually replaced in industrial application with an integrated circuit called *cold junction compensator*: in this case the tail end is at ambient temperature and the temperature fluctuations at the tail end are tolerated; in fact the cold junction compensator produces a voltage equal to the thermocouple voltage between 0°C and ambient temperature, which can be added to the voltage of the thermocouple at the tail end to reproduce the voltage versus temperature relationship of the thermocouple.

2.2.3 Thermistors:

Thermistors, like RTDs, are thermally sensitive semiconductors whose resistance varies with temperature. Thermistors are manufactured from metal oxide semiconductor material encapsulated in a glass or epoxy bead. Also, thermistors typically have much higher nominal resistance values than RTDs (anywhere from 2,000 to 10,000 Ω) and can be used for lower currents.

Thermistors are constructed of semiconductor materials with a resistivity that is especially sensitive to temperature. However, unlike most other resistive devices, the resistance of a thermistor decreases with increasing temperature. That's due to the properties of the semiconductor material that the thermistor is made from.

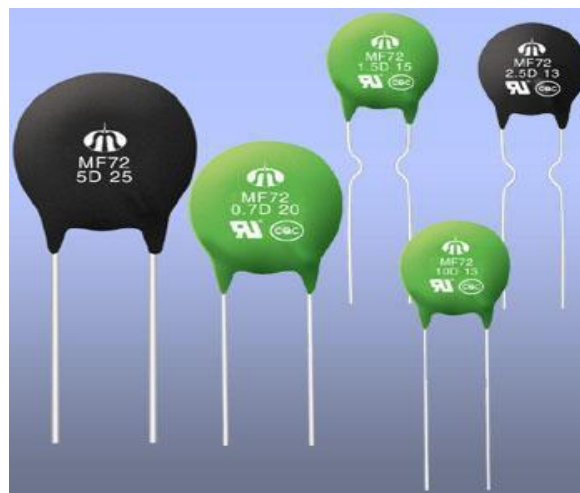


Figure 2.8: Typical samples of thermistors

2.2.4 Functional uses of temperature detectors:

Although the temperatures that are monitored vary slightly depending on the details of facility design, temperature detectors are used to provide three basic functions: indication, alarm, and control. The temperatures monitored may normally be displayed in a central location, such as a control room, and may have audible and visual alarms associated with them when specified preset limits are exceeded. These temperatures may have control functions associated with them so that equipment is started or stopped to support a given temperature condition or so that a protective action occurs.

In the event that key temperature sensing instruments become inoperative, there are several alternate methods that may be used. Some applications utilize installed spare temperature detectors or dual-element RTDs. The dual-element RTD has two sensing elements of which only one is normally connected. If the operating element becomes faulty, the second element may be used to provide temperature indication. If the malfunction is in the circuitry and the detector itself is still functional, it may be possible to obtain temperatures by connecting an external bridge circuit to the detector. Resistance readings may then be taken and a corresponding temperature obtained from the detector calibration curves.

Ambient temperature variations will affect the accuracy and reliability of temperature detection instrumentation. Variations in ambient temperature can directly affect the resistance of components in a bridge circuit and the resistance of the reference junction for a thermocouple.

In addition, ambient temperature variations can affect the calibration of electric/electronic equipment. The effects of temperature variations are reduced by the design of the circuitry and by maintaining the temperature detection instrumentation in the proper environment.

The presence of humidity will also affect most electrical equipment, especially electronic equipment. High humidity causes moisture to collect on the equipment. This moisture can cause short circuits, grounds, and corrosion, which, in turn, may damage components. The effects due to humidity are controlled by maintaining the equipment in the proper environment.

2.2.5 Applications of temperature sensors:

Temperature sensors are used just about everywhere. There are in the homes we live in, the cars we drive, the schools we learn in. They are even in planes, trains and boats. You will also find them in all sorts of electrical appliances and electronic devices. Refrigerators, stoves, hot water

tanks as well as computers, GPS devices and battery chargers all have temperature sensors. Today's digital medical thermometers, which are used in hospitals and millions of home every day, all have a temperature sensor in them. Here below list are some applications of temperature sensor.

Oil Exploration

Today's oil drills must drill far down into the earth in their search for oil. As they drill down deep into the earth, through rocks and dirt, the temperature of the drill increases. Oil workers worry that the oil drill's bit will become too hot and break. To prevent that from happening, these oil drill bits often have a temperature sensor built inside of them. When the temperature reaches a dangerous level, that is, a level that could break the drill bit, the sensor sends an electronic signal to the oil workers to stop drilling.

Radiator Overheating

Your car contains a radiator. In it is a temperature sensor. The reason it is there is to warn you if the water that circulates in your engine becomes too hot. And that's because if it does, your engine could break and will require that you purchase a new one. The temperature sensor in your radiator measures the temperature of the radiator to the temperature gauge in your car. As the temperature of the water increases, the temperature sensor creates a larger electrical current to flow. That current flow causes the needle of your temperature gauge to move further to the right.

Battery Chargers

Battery chargers are used to recharge all sorts of batteries, such as car batteries, flashlight batteries and even batteries in your computer. However, battery chargers must be designed so that they don't overcharge your battery and also so they don't undercharge your battery. Because the amount of charge a battery can store varies with temperature, the battery charger must know the battery's temperature to determine when to stop charging and when to begin charging. In these applications, the temperature sensor is used to turn on or turn off the battery charger.

Hot Air Balloons

For hot air balloons to rise, the temperature of the helium gas that is inside of the balloon must be above a prescribed level. If the temperature of the gas is below that level, the hot air balloon will start to fall. If it is exactly at the prescribed level, it will neither rise nor fall. In order to control the temperature of the helium hot air balloon, and hence to control whether the balloon rises or falls, gas temperature sensors are used to find out the temperature of the helium gas in

the hot air balloon.

2.3 Pressure Sensors

A pressure sensor measures pressure, typically of gases or liquids. Pressure is an expression of the force required to stop a fluid from expanding, and is usually stated in terms of force per unit area. A pressure sensor usually acts as a transducer; it generates a signal as a function of the pressure imposed.

2.3.1 Typical Types of Pressure Sensors

Bourdon tubes or bellows, where mechanical displacements were transferred to an indicating pointer were the first pressure instruments, and are still in use today. Pressure metrology is the technology of transducing pressure into an electrical quantity. Normally, a diaphragm construction is used with strain gauges either bonded to, or diffused into it, acting as resistive elements. Under the pressure-induced strain, the resistive values change. In capacitive technology, the pressure diaphragm is one plate of a capacitor that changes its value under pressure-induced displacement.

Pressure sensing using diaphragm technology measures the difference in pressure of the two sides of the diaphragm. Depending upon the relevant pressure, we use the terms *absolute*, where the reference is vacuum, *gauge*, where the reference is atmospheric pressure, or *differential*, where the sensor has two ports for the measure of two different pressures.

2.3.1.1 Bellows-Type Detectors:

The need for a pressure sensing element that was extremely sensitive to low pressures and provided power for activating recording and indicating mechanisms resulted in the development of the metallic bellows pressure sensing element. The metallic bellows is most accurate when measuring pressures from 0.5 to 75 psig. However, when used in conjunction with a heavy range spring, some bellows can be used to measure pressures of over 1000 psig. Figure 1 shows a basic metallic bellows pressure sensing element.

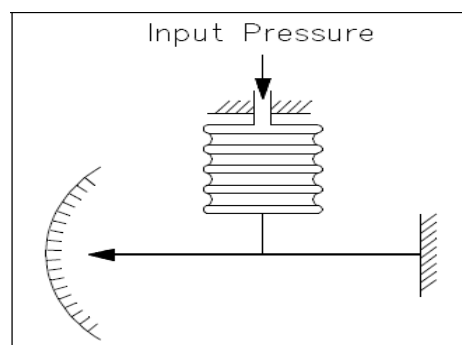


Figure 2.9: Basic Metallic Bellows

The bellows is a one-piece, collapsible, seamless metallic unit that has deep folds formed from very thin-walled tubing. The diameter of the bellows ranges from 0.5 to 12 in. and may have as many as 24 folds. System pressure is applied to the internal volume of the bellows. As the inlet pressure to the instrument varies, the bellows will expand or contract. The moving end of the bellows is connected to a mechanical linkage assembly. As the bellows and linkage assembly moves, either an electrical signal is generated or a direct pressure indication is provided. The flexibility of a metallic bellows is similar in character to that of a helical, coiled compression spring. Up to the elastic limit of the bellows, the relation between increments of load and deflection is linear. However, this relationship exists only when the bellows is under compression. It is necessary to construct the bellows such that all of the travel occurs on the compression side of the point of equilibrium. Therefore, in practice, the bellows must always be opposed by a spring, and the deflection characteristics will be the resulting force of the spring and bellows.

2.3.1.2 Bourdon Tube-Type Detectors:

The bourdon tube pressure instrument is one of the oldest pressure sensing instruments in use today. The bourdon tube consists of a thin-walled tube that is flattened diametrically on opposite sides to produce a cross-sectional area elliptical in shape, having two long flat sides and two short round sides. The tube is bent lengthwise into an arc of a circle of 270 to 300 degrees. Pressure applied to the inside of the tube causes distention of the flat sections and tends to restore its original round cross-section. This change in cross-section causes the tube to straighten slightly. Since the tube is permanently fastened at one end, the tip of the tube traces a curve that is the result of the change in angular position with respect to the center. Within limits, the movement of the tip of the tube can then be used to position a pointer or to develop an equivalent electrical signal to indicate the value of the applied internal pressure.

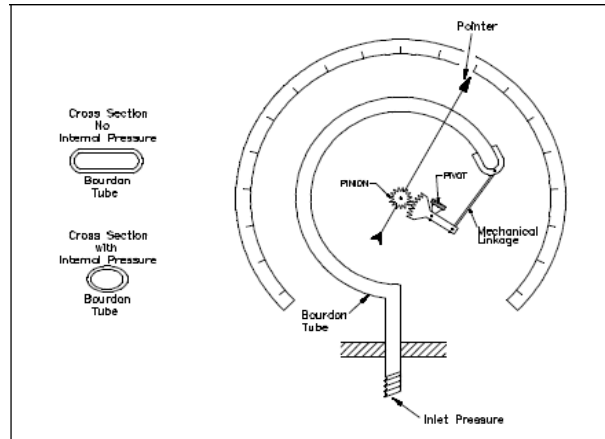


Figure 2.10: Bourdon Tube

2.3.1.3 Strain gauge type pressure transducer:

Pressure transducers use a variety of sensing devices to provide an electrical output proportional to applied pressure. The sensing device employed in the transducers under discussion is bonded, metal foil strain gages.

The metallic foil-type strain gauge consists of a grid of wire filament (a resistor) of approximately 0.025 mm thickness, bonded directly to the strained surface by a thin layer of epoxy resin. When a load is applied to the surface, the resulting change in surface length is communicated to the resistor and the corresponding strain is measured in terms of the electrical resistance of the foil wire, which varies linearly with strain. The foil diaphragm and the adhesive bonding agent must work together in transmitting the strain, while the adhesive must also serve as an electrical insulator between the foil grid and the surface.

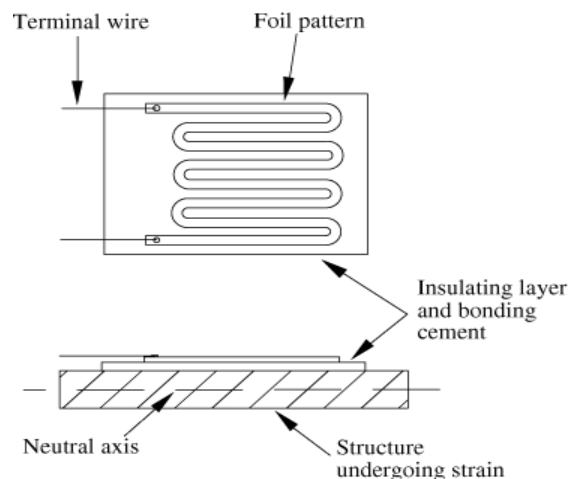


Figure 2.11: An element of strain gauge type of pressure transducer

When selecting a strain gauge, one must consider not only the strain characteristics of the

sensor, but also its stability and temperature sensitivity. Unfortunately, the most desirable strain gauge materials are also sensitive to temperature variations and tend to change resistance as they age. For tests of short duration, this may not be a serious concern, but for continuous industrial measurement, one must include temperature and drift compensation.

2.3.1.4 Capacitive type pressure transducer:

Capacitive pressure sensors use a thin diaphragm, usually metal or metal-coated quartz, as one plate of a capacitor. The diaphragm is exposed to the process pressure on one side and to a reference pressure on the other. Changes in pressure cause it to deflect and change the capacitance. The change may or may not be linear with pressure and is typically a few percent of the total capacitance. The capacitance can be monitored by using it to control the frequency of an oscillator or to vary the coupling of an AC signal. It is good practice to keep the signal-conditioning electronics close to the sensor in order to mitigate the adverse effects of stray capacitance.

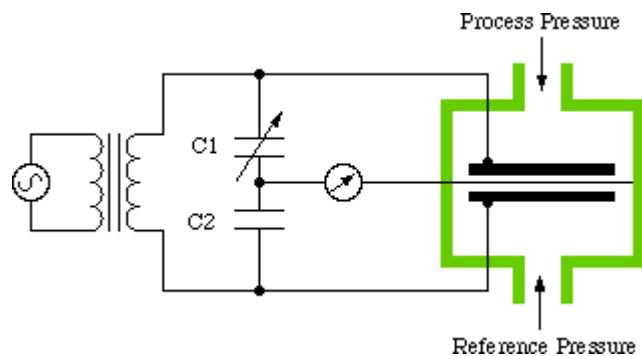


Figure 2.12: A sample of capacitive pressure sensor

2.3.2 Functional uses of pressure detectors:

Although the pressures that are monitored vary slightly depending on the details of facility design, all pressure detectors are used to provide up to three basic functions: indication, alarm, and control. Since the fluid system may operate at both saturation and sub cooled conditions, accurate pressure indication must be available to maintain proper cooling. Some pressure detectors have audible and visual alarms associated with them when specified preset limits are exceeded. Some pressure detector applications are used as inputs to protective features and control functions.

If a pressure instrument fails, spare detector elements may be utilized if installed. If spare detectors are not installed, the pressure may be read at an independent local mechanical gauge, if available, or a precision pressure gauge may be installed in the system at a convenient point. If the detector is functional, it may be possible to obtain pressure readings by measuring voltage

or current values across the detector leads and comparing this reading with calibration curves. Pressure instruments are sensitive to variations in the atmospheric pressure surrounding the detector. This is especially apparent when the detector is located within an enclosed space. Variations in the pressure surrounding the detector will cause the indicated pressure from the detector to change. This will greatly reduce the accuracy of the pressure instrument and should be considered when installing and maintaining these instruments.

Ambient temperature variations will affect the accuracy and reliability of pressure detection instrumentation. Variations in ambient temperature can directly affect the resistance of components in the instrumentation circuitry, and, therefore, affect the calibration of electric/electronic equipment. The effects of temperature variations are reduced by the design of the circuitry and by maintaining the pressure detection instrumentation in the proper environment. The presence of humidity will also affect most electrical equipment, especially electronic equipment. High humidity causes moisture to collect on the equipment. This moisture can cause short circuits, grounds, and corrosion, which, in turn, may damage components. The effects due to humidity are controlled by maintaining the equipment in the proper environment.

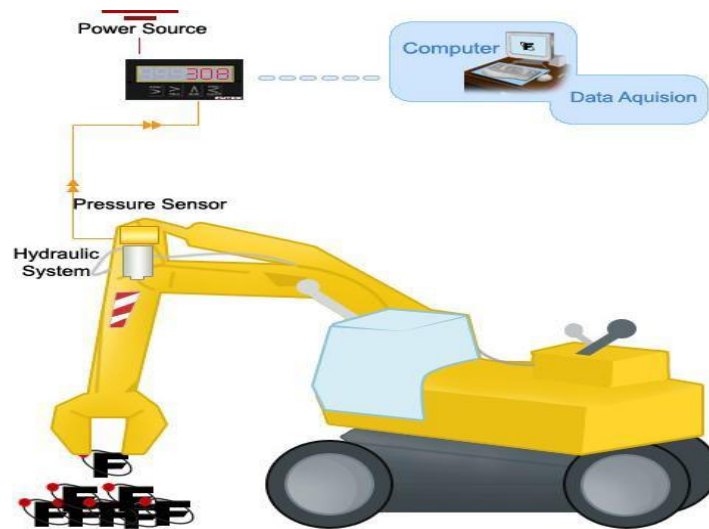
2.3.3 Applications of pressure sensors:

Pressure sensors are used in a wide variety of applications. When used directly to measure pressure, applications include weather instrumentation, aerospace and defence, research and development, automotive and many other machinery or equipment that has pressure functionality implemented.

Potential uses of pressure sensors are hydraulic systems, water depth, pneumatics, marine, sewage, gas, medical, food and beverage processing, tank level/contents, HVAC systems, agricultural equipment, aerospace and chemicals. Explained below are some of the applications of pressure sensors.

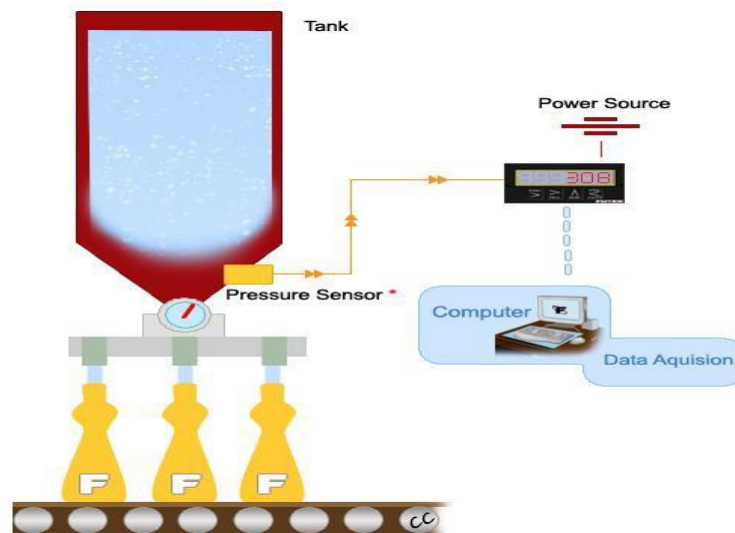
Hydraulic Systems

Most cranes, earthmovers and similar equipment are operated using hydraulic systems. In order to control the movement, holding, gripping or applied force, pressure sensors are utilized to monitor and provide pressure feedback to these systems. Using pressure sensors will also allow the operator to fully control the mechanical devices and apply known high force or load effortlessly. The pressure sensor can also be used to monitor the hydraulic fluid level for preventive maintenance. If and when the fluid pressure begins to reach an unsafe level, the user would be notified



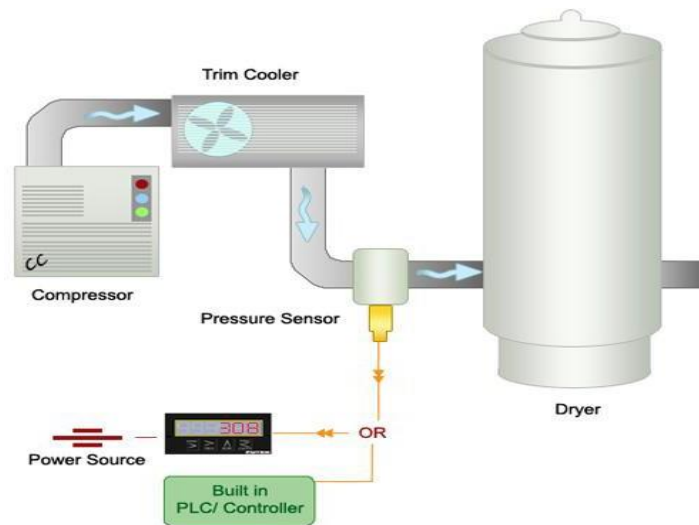
Automation

Pressure sensors can be placed on the bottom of a silo or tank in order to monitor how full or empty it is by measuring & monitoring the pressure while knowing the volume & liquid density. Utilizing digital display controller, PLC, computer, or data acquisition sensor, you can measure and control the weight of the amount dispensed and/or the flow of liquid during the automation process.



Pressure Verification

Pressure sensors are used to measure pressure in fluid or gas applications. In this particular example, gas is compressed in the compressor. When the gas is let out it needs to be cooled down since compression of gas usually increases its temperature. The pressure sensor monitors the actual pressure of the air before it gets transferred to the dryer.



Altitude Sensing

This is useful in commercial and military aircraft, rockets, satellites and weather instrumentation. These types of application all make use of the relationship between changes in pressure relative to the altitude.

2.4 Level Sensors

Level sensors detect the level of substances that flow, including liquids, slurries, granular materials, and powders. Fluids and fluidized solids flow to become essentially level in their containers (or other physical boundaries) because of gravity whereas most bulk solids pile at an angle of repose to a peak. The substance to be measured can be inside a container or can be in its natural form (e.g., a river or a lake). The level measurement can be either continuous or point values. Continuous level sensors measure level within a specified range and determine the exact amount of substance in a certain place, while point-level sensors only indicate whether the substance is above or below the sensing point. Generally the latter detect levels that are excessively high or low.

There are various types of point and continuous level sensors. Some of them are listed and explained below.

2.4.1 Gauge Glass Type Level Detector:

A very simple means by which liquid level is measured in a vessel is by the gauge glass method, shown in Figure 2.13. In the gauge glass method, a transparent tube is attached to the bottom and top (top connection not needed in a tank open to atmosphere) of the tank that is

monitored. The height of the liquid in the tube will be equal to the height of water in the tank.

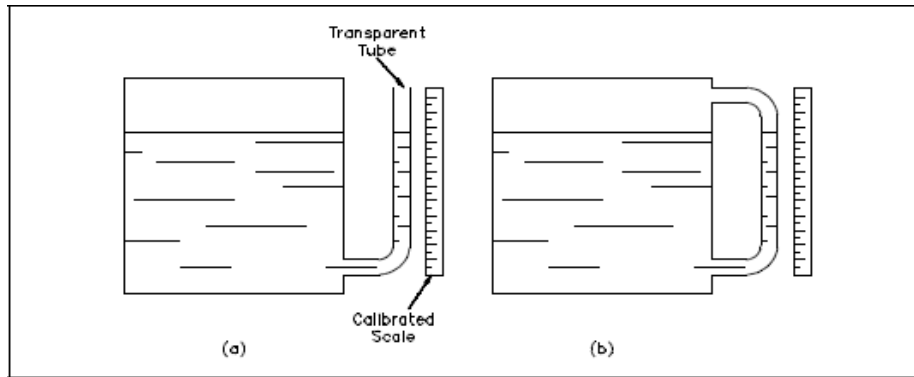


Figure 2.13: Transparent tube level detector

Figure 12.13 (a) shows a gauge glass which is used for vessels where the liquid is at ambient temperature and pressure conditions. Figure 12.13 (b) shows a gauge glass which is used for vessels where the liquid is at an elevated pressure or a partial vacuum. Notice that the gauge glasses in Figure 12.13 effectively form a "U" tube manometer where the liquid seeks its own level due to the pressure of the liquid in the vessel.

Gauge glasses made from tubular glass or plastic are used for service up to 450 psig and 400°F. If it is desired to measure the level of a vessel at higher temperatures and pressures, a different type of gauge glass is used. The type of gauge glass utilized in this instance has a body made of metal with a heavy glass or quartz section for visual observation of the liquid level. The glass section is usually flat to provide strength and safety. Figure 12.14 illustrates a typical transparent gauge glass construction.

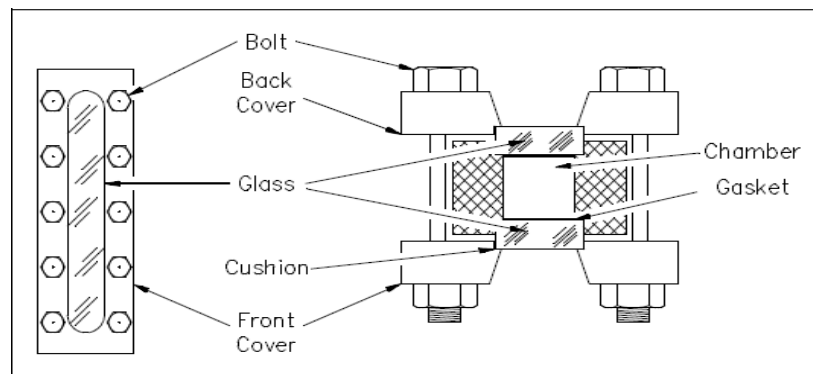


Figure 2.13: Transparent tube level detector construction

Another type of gauge glass is the refraction type (Figure 12.14). This type is especially useful in areas of reduced lighting; lights are usually attached to the gauge glass. Operation is based on the principle that the bending of light, or refraction, will be different as light passes through

various media. Light is bent, or refracted, to a greater extent in water than in steam. For the portion of the chamber that contains steam, the light rays travel relatively straight, and the red lens is illuminated. For the portion of the chamber that contains water, the light rays are bent, causing the green lens to be illuminated. The portion of the gauge containing water appears green; the portion of the gauge from that level upward appears red.

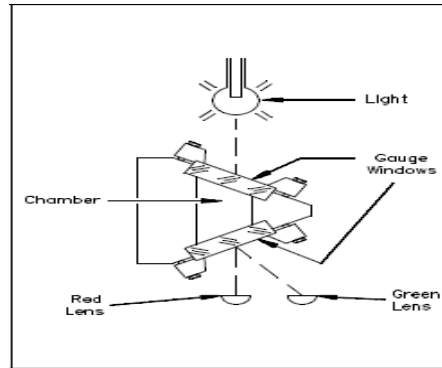


Figure 2.14: Refraction gauge glass level detector.

2.4.2 Ball Float Type Level Detector:

The ball float method is a direct reading liquid level mechanism. The most practical design for the float is a hollow metal ball or sphere. However, there are no restrictions to the size, shape, or material used. The design consists of a ball float attached to a rod, which in turn is connected to a rotating shaft which indicates level on a calibrated scale (Figure 12.5). The operation of the ball float is simple. The ball floats on top of the liquid in the tank. If the liquid level changes, the float will follow and change the position of the pointer attached to the rotating shaft.

The travel of the ball float is limited by its design to be within ± 30 degrees from the horizontal plane which results in optimum response and performance. The actual level range is determined by the length of the connecting arm. The stuffing box is incorporated to form a water-tight seal around the shaft to prevent leakage from the vessel.

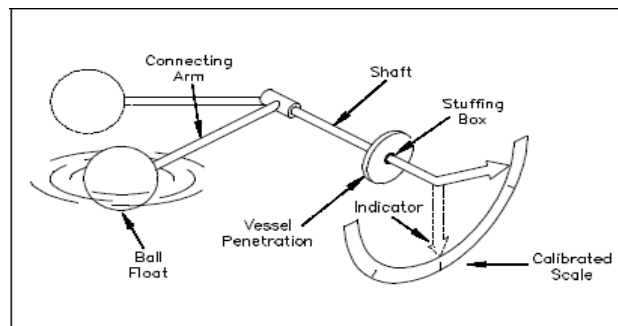


Figure 2.15: Ball Float level detector.

2.4.3 Chain Float Type Level Detector:

This type of float gauge has a float ranging in size up to 12 inches in diameter and is used where small level limitations imposed by ball floats must be exceeded. The range of level measured will be limited only by the size of the vessel. The operation of the chain float is similar to the ball float except in the method of positioning the pointer and in its connection to the position indication. The float is connected to a rotating element by a chain with a weight attached to the other end to provide a means of keeping the chain taut during changes in level. Figure 12.16 shows this.

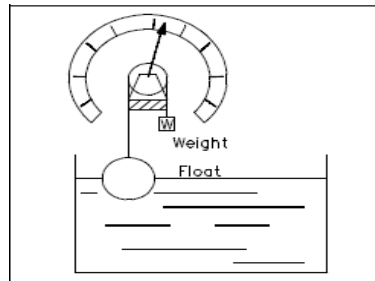


Figure 2.16: Chain Float level detector.

2.4.4 Magnetic Bond Method Level Detector:

The magnetic bond method was developed to overcome the problems of cages and stuffing boxes. The magnetic bond mechanism consists of a magnetic float which rises and falls with changes in level. The float travels outside of a non-magnetic tube which houses an inner magnet connected to a level indicator. When the float rises and falls, the outer magnet will attract the inner magnet, causing the inner magnet to follow the level within the vessel (Figure 2.7).

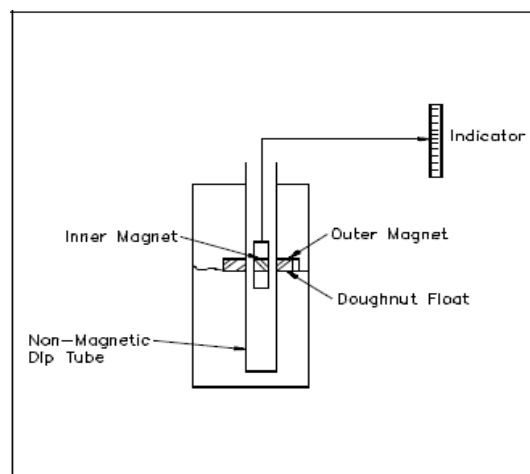


Figure 2.17: Magnetic Bond level detector.

2.4.5: Conductive Probe Method Level Detector:

Figure 2.18 illustrates a conductivity probe level detection system. It consists of one or more level detectors, an operating relay, and a controller. When the liquid makes contact with any of

the electrodes, an electric current will flow between the electrode and ground. The current energizes a relay which causes the relay contacts to open or close depending on the state of the process involved. The relay in turn will actuate an alarm, a pump, a control valve, or all three. A typical system has three probes: a low level probe, a high level probe, and a high level alarm probe.

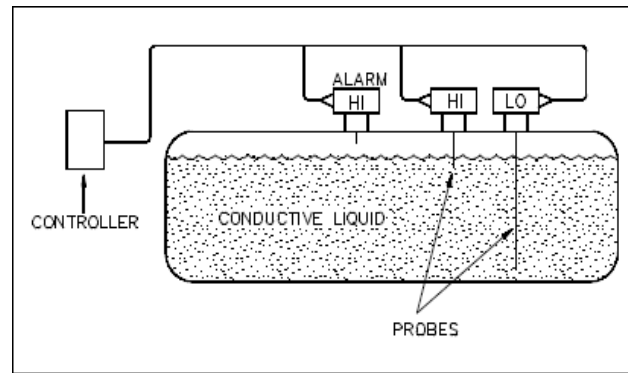


Figure 2.18: Conductivity probe level detector.

2.4.5 : Differential Pressure Method Level Detector:

The differential pressure (ΔP) detector method of liquid level measurement uses a ΔP detector connected to the bottom of the tank being monitored. The higher pressure, caused by the fluid in the tank, is compared to a lower reference pressure (usually atmospheric). This comparison takes place in the ΔP detector. Figure 12.9 illustrates a typical differential pressure detector attached to an open tank.

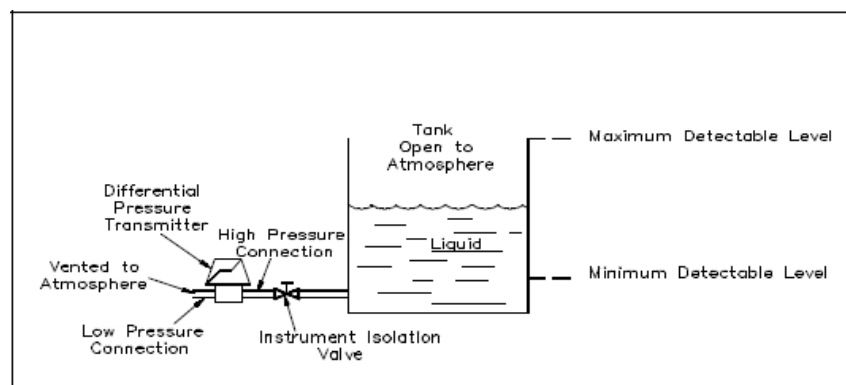


Figure 2.19: Open Tank Differential Pressure level detector.

The tank is open to the atmosphere; therefore, it is necessary to use only the high pressure (HP) connection on the ΔP transmitter. The low pressure (LP) side is vented to the atmosphere; therefore, the pressure differential is the hydrostatic head, or weight, of the liquid in the tank. The maximum level that can be measured by the ΔP transmitter is determined by the maximum height of liquid above the transmitter. The minimum level that can be measured is determined

by the point where the transmitter is connected to the tank.

Not all tanks or vessels are open to the atmosphere. Many are totally enclosed to prevent vapors or steam from escaping, or to allow pressurizing the contents of the tank. When measuring the level in a tank that is pressurized or the level that can become pressurized by vapor pressure from the liquid, both the high pressure and low pressure sides of the ΔP transmitter must be connected (Figure 12.20).

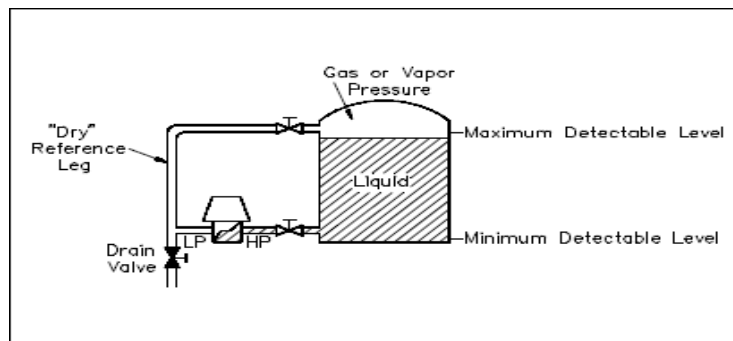


Figure 2.20 Closed Tank Differential Pressure Dry Reference level detector.

The high pressure connection is connected to the tank at or below the lower range value to be measured. The low pressure side is connected to a "reference leg" that is connected at or above the upper range value to be measured. The reference leg is pressurized by the gas or vapor pressure, but no liquid is permitted to remain in the reference leg. The reference leg must be maintained dry so that there is no liquid head pressure on the low pressure side of the transmitter. The high pressure side is exposed to the hydrostatic head of the liquid plus the gas or vapor pressure exerted on the liquid's surface. The gas or vapor pressure is equally applied to the low and high pressure sides. Therefore, the output of the ΔP transmitter is directly proportional to the hydrostatic head pressure, that is, the level in the tank.

Where the tank contains a condensable fluid, such as steam, a slightly different arrangement is used. In applications with condensable fluids, condensation is greatly increased in the reference leg. To compensate for this effect, the reference leg is filled with the same fluid as the tank. The liquid in the reference leg applies a hydrostatic head to the high pressure side of the transmitter, and the value of this level is constant as long as the reference leg is maintained full. If this pressure remains constant, any change in DP is due to a change on the low pressure side of the transmitter (Figure 12.21).

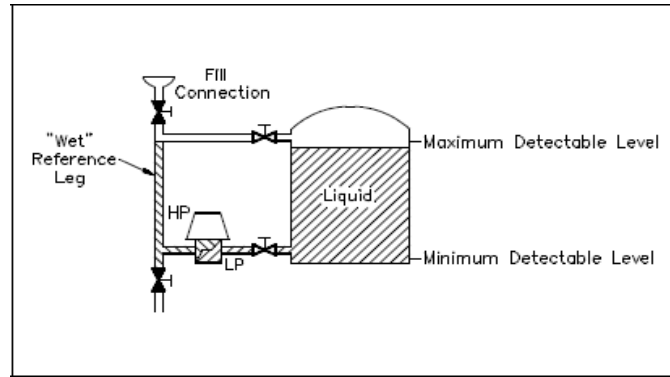


Figure 2.21 Closed Tank Differential Pressure Wet Reference level detector.

The filled reference leg applies a hydrostatic pressure to the high pressure side of the transmitter, which is equal to the maximum level to be measured. The DP transmitter is exposed to equal pressure on the high and low pressure sides when the liquid level is at its maximum; therefore, the differential pressure is zero. As the tank level goes down, the pressure applied to the low pressure side goes down also, and the differential pressure increases. As a result, the differential pressure and the transmitter output are inversely proportional to the tank level.

Environmental Concerns:

Density of the fluid whose level is to be measured can have a large effect on level detection instrumentation. It primarily affects level sensing instruments which utilize a wet reference leg. In these instruments, it is possible for the reference leg temperature to be different from the temperature of the fluid whose level is to be measured. An example of this is the level detection instrumentation for a boiler steam drum. The water in the reference leg is at a lower temperature than the water in the steam drum. Therefore, it is denser, and must be compensated for to ensure the indicated steam drum level is accurately indicated.

Ambient temperature variations will affect the accuracy and reliability of level detection instrumentation. Variations in ambient temperature can directly affect the resistance of components in the instrumentation circuitry, and, therefore, affect the calibration of electric/electronic equipment. The effects of temperature variations are reduced by the design of the circuitry and by maintaining the level detection instrumentation in the proper environment. The presence of humidity will also affect most electrical equipment, especially electronic equipment. High humidity causes moisture to collect on the equipment. This moisture can

cause short circuits, grounds, and corrosion, which, in turn, may damage components. The effects due to humidity are controlled by maintaining the equipment in the proper environment.

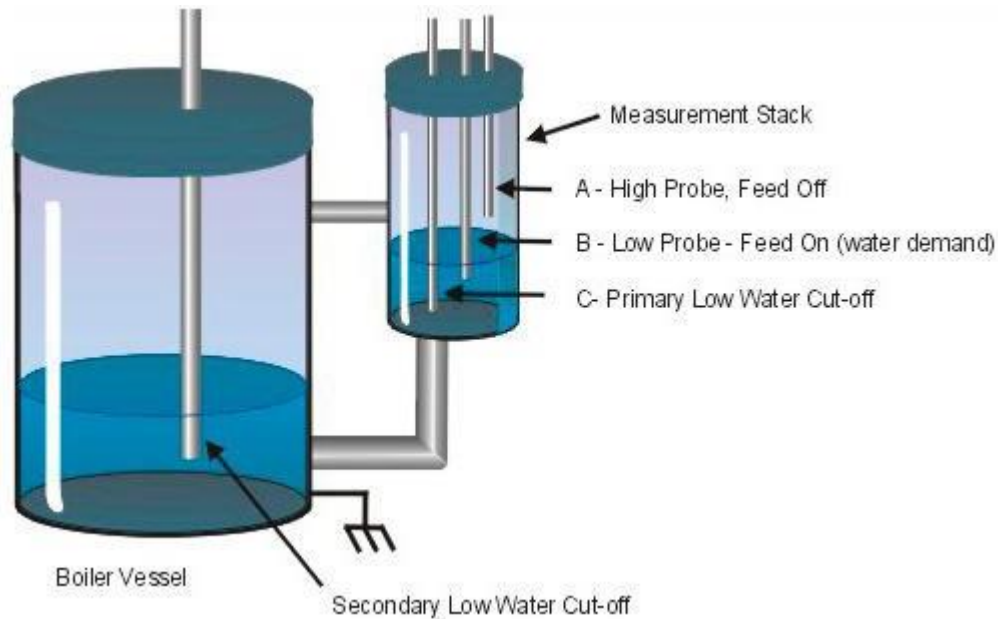
2.4.6 Applications of Level Sensors

1. Fuel Level Sensor in Generator, Car, etc:

The Fuel Level Sensor used here could be a float-type liquid level sensor that is used to measure the fuel level in a storage tank. The sensor can be connected to RJ-45 Intelligent Sensor ports enabling the system to continuously monitor the amount of fuel remaining in your storage tank. By setting the proper alerts in the software, it can be configured to detect fuel leaks or fuel theft. A sensor of this type is ideal for remote sites that depend on generator power. The low level alerts can be customized to your requirements. For example, it can be configured to send normal notifications when the fuel level reaches $\frac{3}{4}$ and $\frac{1}{2}$ tank, and send critical alerts when fuel level drops down to $\frac{1}{4}$ and $\frac{1}{8}$ of a tank. A level sensor can also be used to detect fuel theft or leakage by detecting a drop in fuel level while the engine is off or if the fuel level drops too quickly when the engine's running.

2. Water Level Sensor in Boilers:

The typical steam boiler has at least two or more independent Low Water Cutoff circuits, and the system comprises a water feeder (water make-up) circuit responsible for replenishing water as it is converted to steam. There are both mechanical and electrical means supporting feeder circuits. Shown below is an electrical version using conductivity sensing probes, one of the liquid level sensors we have.

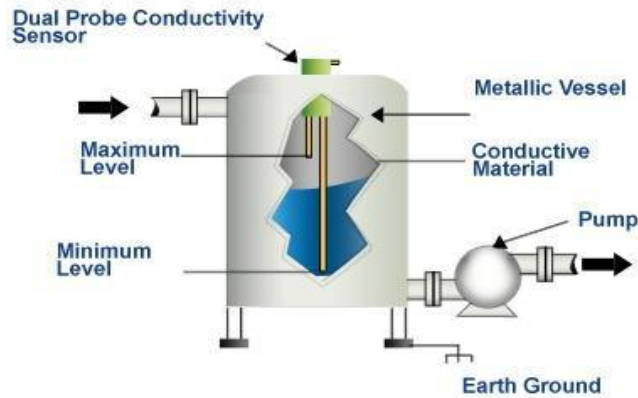


3. Water Level Control in Elevated Tanker:

In this arrangement, two dual-tip probes are employed which are helpful in indicating the highest and lowest levels of fluid. As soon as the level of the liquid approaches the upper probe, a switch gets deactivated to stop the pump motor. Whereas when the level drops below and approaches the lower probe, the switch gets activated and makes the pump motor on.



On the other side of the elevated tank, the level sensors can be used to detect if the water reservoir has enough water to be pumped to the elevated tank. In this case, as soon as the level of the liquid approaches the upper probe, a switch gets operated to activate the discharge pump whereas when the level drops below and approaches the lower probe, the switch gets deactivated and the pump gets stopped. The arrangement is shown below.



The conductive probes operate by means of differences in the electrical resistance between the reference electrode and the level control electrode. These sensors tend to detect the electrical resistance when the level electrodes get submerged in the process fluid. An electrically conductive tank wall can be used as the reference electrode. If the tank is made of plastic, concrete, or any other nonconductive material, an additional electrode is required.

2.5 Flow Sensor

A flow sensor is a device for sensing the rate of fluid flow. Typically a flow sensor is the sensing element used in a flow meter, or flow logger, to record the flow of fluids. As is true for all sensors, absolute accuracy of a measurement requires functionality for calibration. There are various kinds of flow sensors and flow meters, including some that have a vane that is pushed by the fluid, and can drive a rotary potentiometer, or similar devices. Other flow sensors are based on sensors which measure the transfer of heat caused by the moving medium. This principle is common for micro sensors to measure flow. Flow meters are related to devices called velocimeters that measure velocity of fluids flowing through them. Here below listed are some of the commonly used flow sensors.

2.5.1 Head Flow Meter:

Head flow meters operate on the principle of placing a restriction in the line to cause a differential pressure head. The differential pressure, which is caused by the head, is measured and converted to a flow measurement. Industrial applications of head flow meters incorporate a pneumatic or electrical transmitting system for remote readout of flow rate. Generally, the indicating instrument extracts the square root of the differential pressure and displays the flow rate on a linear indicator.

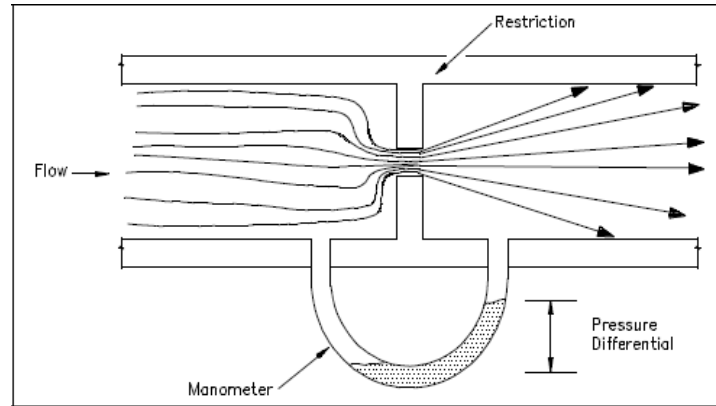


Figure 2.22 Head Flow Meter

There are two elements in Head Flow Meter a head flow meter; the primary element is the restriction in the line, and the secondary element is the differential pressure measuring device. Figure 2.22 shows the basic operating characteristics of a head flow meter. The flow path restriction, such as an orifice, causes a differential pressure across the orifice. This pressure differential is measured by a mercury manometer or a differential pressure detector. From this measurement, flow rate is determined from known physical laws.

2.5.2 Orifice Plate:

The orifice plate is the simplest of the flow path restrictions used in flow detection, as well as the most economical. Orifice plates are flat plates 1/16 to 1/4 inch thick. They are normally mounted between a pair of flanges and are installed in a straight run of smooth pipe to avoid disturbance of flow patterns from fittings and valves. Three kinds of orifice plates are used: concentric, eccentric, and segmental as shown in Figure 2.23.

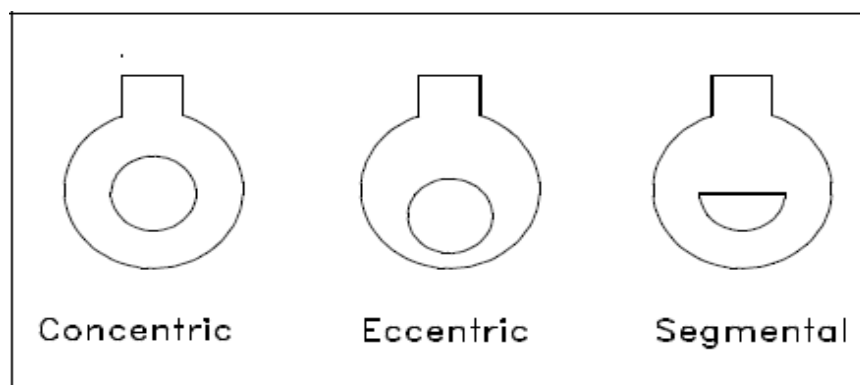


Figure 2.23 Orifice Plates

The concentric orifice plate is the most common of the three types. As shown, the orifice is equidistant (concentric) to the inside diameter of the pipe. Flow through a sharp-edged orifice plate is characterized by a change in velocity. As the fluid passes through the orifice, the fluid

converges, and the velocity of the fluid increases to a maximum value. At this point, the pressure is at a minimum value. As the fluid diverges to fill the entire pipe area, the velocity decreases back to the original value. The pressure increases to about 60% to 80% of the original input value. The pressure loss is irrecoverable; therefore, the output pressure will always be less than the input pressure. The pressures on both sides of the orifice are measured, resulting in a differential pressure which is proportional to the flow rate.

Segmental and eccentric orifice plates are functionally identical to the concentric orifice. The circular section of the segmental orifice is concentric with the pipe. The segmental portion of the orifice eliminates damming of foreign materials on the upstream side of the orifice when mounted in a horizontal pipe. Depending on the type of fluid, the segmental section is placed on either the top or bottom of the horizontal pipe to increase the accuracy of the measurement. Eccentric orifice plates shift the edge of the orifice to the inside of the pipe wall. This design also prevents upstream damming and is used in the same way as the segmental orifice plate.

2.5.3 Venturi Tube:

The venturi tube, illustrated in Figure 3, is the most accurate flow-sensing element when properly calibrated. The venturi tube has a converging conical inlet, a cylindrical throat, and a diverging recovery cone. It has no projections into the fluid, no sharp corners, and no sudden changes in contour.

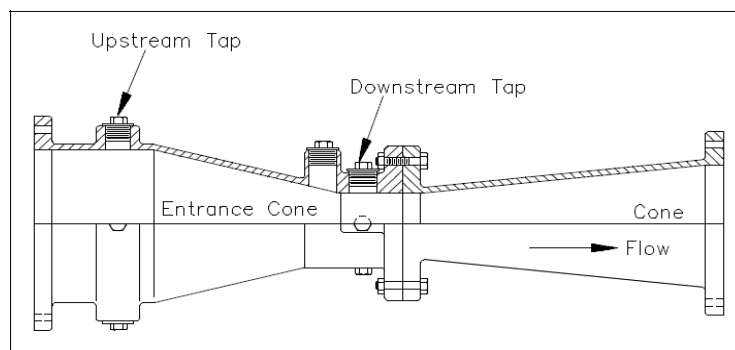


Figure 2.24: Venturi Tube

The inlet section decreases the area of the fluid stream, causing the velocity to increase and the pressure to decrease. The low pressure is measured in the center of the cylindrical throat since the pressure will be at its lowest value, and neither the pressure nor the velocity is changing. The recovery cone allows for the recovery of pressure such that total pressure loss is only 10% to 25%. The high pressure is measured upstream of the entrance cone.

2.5.4 Rotating disc:

The most common type of displacement flow meter is the rotating disk, or wobble plate meter.

A typical rotating disk is shown in Figure 2.25.

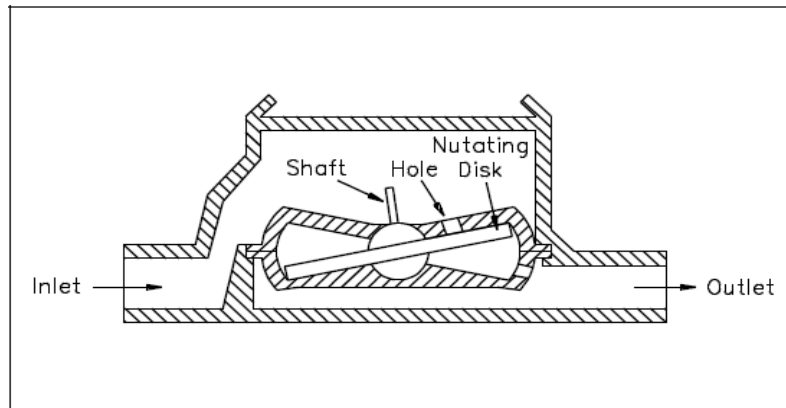


Figure 2.24: Rotating Disc

This type of flow meter is normally used for water service, such as raw water supply and evaporator feed. The movable element is a circular disk which is attached to a central ball. A shaft is fastened to the ball and held in an inclined position by a cam or roller. The disk is mounted in a chamber which has spherical side walls and conical top and bottom surfaces. The fluid enters an opening in the spherical wall on one side of the partition and leaves through the other side. As the fluid flows through the chamber, the disk wobbles, or executes a rotating motion. Since the volume of fluid required to make the disc complete one revolution is known, the total flow through a rotating disc can be calculated by multiplying the number of disc rotations by the known volume of fluid.

To measure this flow, the motion of the shaft generates a cone with the point, or apex, down. The top of the shaft operates a revolution counter, through a crank and set of gears, which is calibrated to indicate total system flow. A variety of accessories, such as automatic count resetting devices, can be added to the fundamental mechanism, which performs functions in addition to measuring the flow.

2.5.5 Electromagnetic Flow meter:

The electromagnetic flow meter is similar in principle to the generator. The rotor of the generator is replaced by a pipe placed between the poles of a magnet so that the flow of the fluid in the pipe is normal to the magnetic field. As the fluid flows through this magnetic field, an electromotive force is induced in it that will be mutually normal (perpendicular) to both the magnetic field and the motion of the fluid. This electromotive force may be measured with the aid of electrodes attached to the pipe and connected to a galvanometer or an equivalent. For a given magnetic field, the induced voltage will be proportional to the average velocity of the fluid. However, the fluid should have some degree of electrical conductivity.

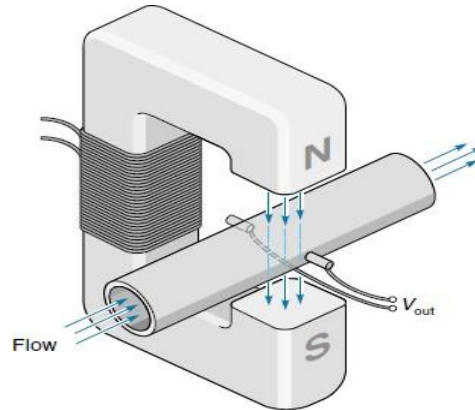


Figure 2.24: Electromagnetic Flow meter

Functional Use of Flow sensors:

The flow of liquids and gases carries energy through the piping system. In many situations, it is very important to know whether there is flow and the rate at which the flow is occurring. An example of flow that is important to a facility operator is equipment cooling flow. The flow of coolant is essential in removing the heat generated by the system, thereby preventing damage to the equipment. Typically, flow indication is used in protection systems and control systems that help maintain system temperature. Like the other sensors, Flow sensors are used to provide the three basic functions: indication, alarm, and control.

Environmental Concerns:

The effect of density is most important when the flow sensing instrumentation is measuring gas flows, such as steam. Since the density of a gas is directly affected by temperature and pressure, any changes in either of these parameters will have a direct effect on the measured flow. Therefore, any changes in fluid temperature or pressure must be compensated for to achieve an accurate measurement of flow.

Ambient temperature variations will affect the accuracy and reliability of flow sensing instrumentation. Variations in ambient temperature can directly affect the resistance of components in the instrumentation circuitry, and, therefore, affect the calibration of electric/electronic equipment. The effects of temperature variations are reduced by the design of the circuitry and by maintaining the flow sensing instrumentation in the proper environment.

The presence of humidity will also affect most electrical equipment, especially electronic equipment. High humidity causes moisture to collect on the equipment. This moisture can cause short circuits, grounds, and corrosion, which, in turn, may damage components. The effects due to humidity are controlled by maintaining the equipment in the proper

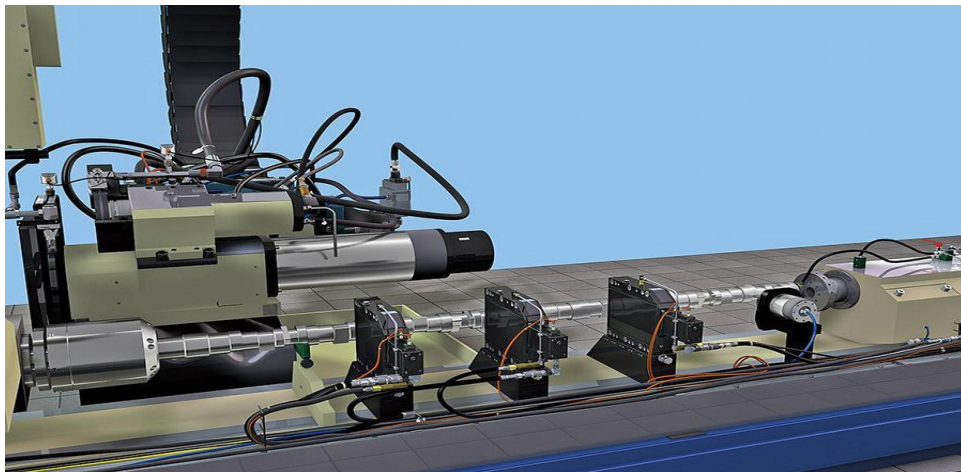
environment.

2.5.6 Applications of Flow Sensors:

Flow sensors are among the most important sensors used in industries, medical centers, gas stations, etc. Though flow sensors are used in various areas, the followings are few of the applications of flow sensors.

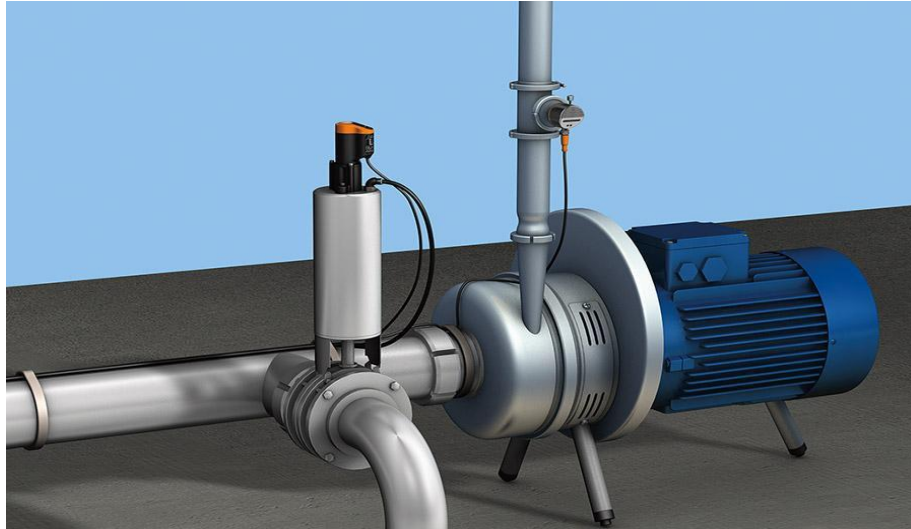
2.5.6.1 Coolant Monitoring on a Cam Shaft Grinding Machine:

Grinding is an important step in the production of cam shafts. The surface quality achieved here is decisive for the quality of the shafts. To assure a consistently high precision during the grinding process, coolant emulsion must be permanently supplied. In the supply pipe of the plant, the flow of the emulsion is monitored using flow sensor. If the coolant supply is interrupted, the grinding process is stopped. Due to the permanent monitoring of the emulsion, the high processing quality of the cam shafts is ensured and the uptime of the grinding disks is increased. The figure below shows this.



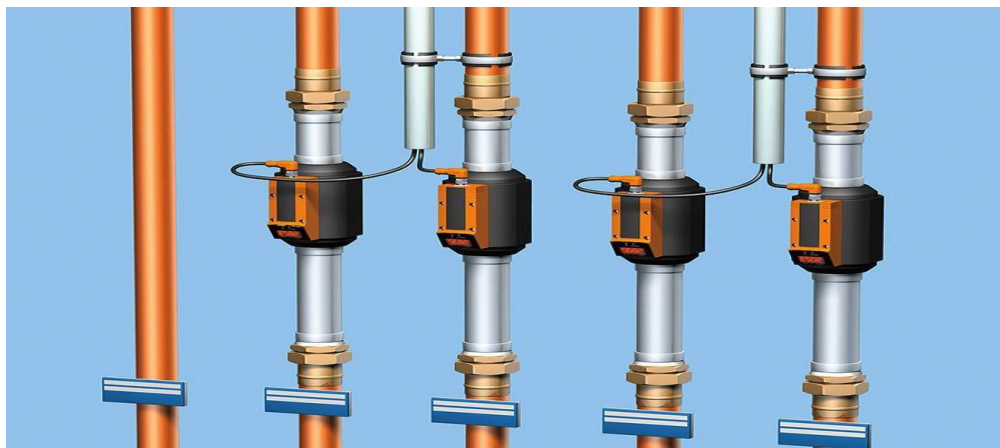
2.5.6.2 Run Dry Protection on Pump:

During conveyance of liquid foods such as dairy products or beverages the product flow has to be monitored. An interruption of the product flow can cause considerable damage and downtime to the pump. Hence; flow sensor senses is there is enough amount of fluid flowing in the system. If there is not enough flow in the system to be pumped, the sensor sends control signal to stop the pump from operating. Hence; dry running and thus damage to the pump are effectively prevented. The figure below shows this.



2.5.6.3 Compressed Air Leak Cost Analysis:

Compressed air is one of the most expensive types of energy. It is therefore important to make economical use of this resource and to be able to allocate the compressed air consumption to the respective production units. To measure the consumption in different sections of a plant, several compressed air meters "efector metris" were used. These sensors precisely detect the compressed air consumption and even detect very small leaks. In addition to the current consumption, quantities per day and total quantities can also be allocated to the different production units. Furthermore, leaks are detected and can be repaired. This reduces energy costs. The figure below shows this.



2.6 Position Sensors

2.6.1 Proximity sensors:

2.6.1.1 Limit Switches:

A limit switch is a mechanical/electrical device which can be used to determine the physical position of equipment. For example, an extension on a valve shaft mechanically trips a limit switch as it moves from open to shut or shut to open. The limit switch gives ON/OFF output that corresponds to valve position. Normally, limit switches are used to provide full open or full shut indications as illustrated in Figure 2.25.

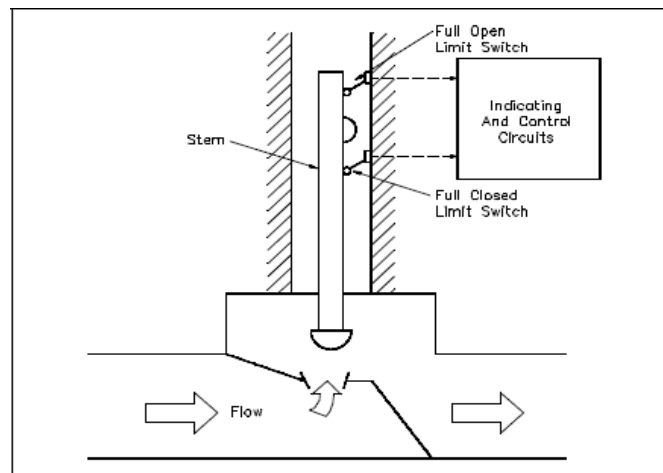


Figure 2.25: Limit Switch

Many limit switches are the push-button variety. When the valve extension comes in contact with the limit switch, the switch depresses to complete, or turn on, the electrical circuit. As the valve extension moves away from the limit switches, spring pressure opens the switch, turning off the circuit.

Another example is in an automatic garage-door opener, all the controller needs to know is if the door is all the way open or all the way closed. Limit switches can detect these two conditions.

Switches are fine for many applications, but they have at least two drawbacks: (1) Being a mechanical device, they eventually wear out, and (2) they require a certain amount of physical force to actuate. Limit switch failures are normally mechanical in nature. If the proper indication or control function is not achieved, the limit switch is probably faulty. In this case, local position indication should be used to verify equipment position.

Two other types of proximity sensors, which use either optics or magnetic to determine if an object is near, do not have these problems. The price we pay for these improved characteristics is that they require some support electronics.

2.6.1.2 Optical Proximity Sensors:

Optical proximity sensors, sometimes called *interrupters*, use a light source and a photo sensor that are mounted in such a way that the object to be detected cuts the light path. Figure 2.26 illustrates an application of using photo detectors. Here, a photo detector counts the number of cans on an assembly line.

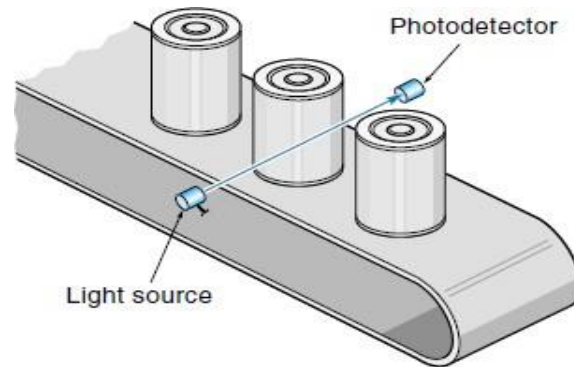


Figure 2.26: Counting Cans on a Conveyor Belt

The light source may be modulated to give the beam a unique 'signature' so that the detector can distinguish between the beam and stray light.

Four types of photo detectors are in general use: photo resistors, photodiodes, photo transistors, and photovoltaic cells.

A *photo resistor*, which is made out of a material such as cadmium sulfide (CdS), has the property that its resistance decreases when the light level increases. It is inexpensive and quite sensitive, that is, the resistance can change by a factor of 100 or more when exposed to light and dark. Figure 2.27(a) shows a typical interface circuit—as the light increases, R_{pd} decreases, and so V_{out} increases.

A *photodiode* is a light-sensitive diode. A little window allows light to fall directly on the PN junction where it has the effect of increasing the reverse-leakage current. Figure 2.27(b) shows the photodiode with its interface circuit. Notice that the photodiode is reversed-biased and that the small reverse-leakage current is converted into an amplified voltage by the op-amp.

A *photo transistor* [Figure 2.27(c)] has no base lead. Instead, the light effectively creates a base current by generating electron-hole pairs in the CB junction—the more light, the more the transistor turns on.

The *photovoltaic cell* is different from the photo sensors discussed so far because it actually creates electrical power from light—the more light, the higher the voltage. (A solar cell is a photovoltaic cell.) When used as a sensor, the small voltage output must usually be amplified,

as shown in Figure 2.27(d).

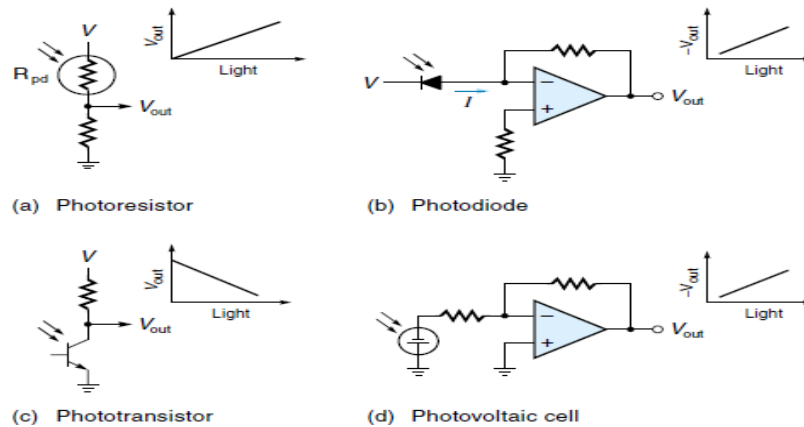


Figure 2.27: Various Types of Photo detectors

Optical sensors enjoy the advantage that neither the light source, the object to be detected, nor the detectors have to be near each other. An example of this is a burglar alarm system. The light source is on one side of the room, the burglar is in the middle, and the detector is on the other side of the room. This property can be important in a case where there are no convenient mounting surfaces near the part to be measured. On the other hand, keeping the lenses clean may be a problem in some industrial situations.

2.6.2 Potentiometer:

A *potentiometer* (pot) can be used to convert rotary or linear displacement to a voltage. Actually, the pot itself gives resistance, but as we will see, this resistance value can easily be converted to a voltage. Figure 2.28(a) illustrates how the pot works. A resistive material, such as conductive plastic, is formed in the shape of a circle (terminating at contacts A and C). This material has a very uniform resistivity so that the ohms-per-inch value along its length is a constant. Connected to the shaft is the **slider**, or **wiper**, which slides along the resistor and taps off a value [contact B in Figure 2.28(a)]. Figure 2.28(b) shows the circuit symbol. The pot just described is the single-turn type, which actually has only about 350° of useful range. A single-turn pot may have 'stops' at each end of its travel. Obviously, such a pot could only be used where the rotation never exceeds 350° . A single-turn pot without stops has a small 'dead zone' when the wiper crosses the end of the resistor.

Figure 2.28(c) illustrates a linear-motion potentiometer. In this case, the wiper can move back-and-forth in a straight line. Linear-motion pots are useful for sensing the position of objects that move in a linear fashion.

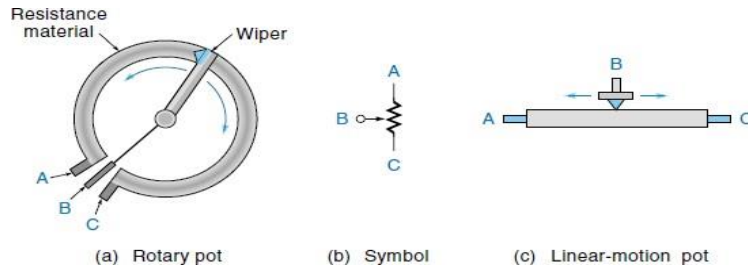


Figure 2.28: Various Types of Potentiometers

2.6.3 Linear Variable Differential Transformers:

The linear variable differential transformer (LVDT) is a high-resolution position sensor that outputs an AC voltage with a magnitude proportional to linear position. It has a relatively short range of about 2 in., but it has the advantage of no sliding contacts. Figure 2.29(a) illustrates that the unit consists of three windings and a movable iron core. The center winding, or *primary*, is connected to an AC reference voltage. The outer two windings, called *secondaries*, are wired to be out of phase with each other and are connected in series.

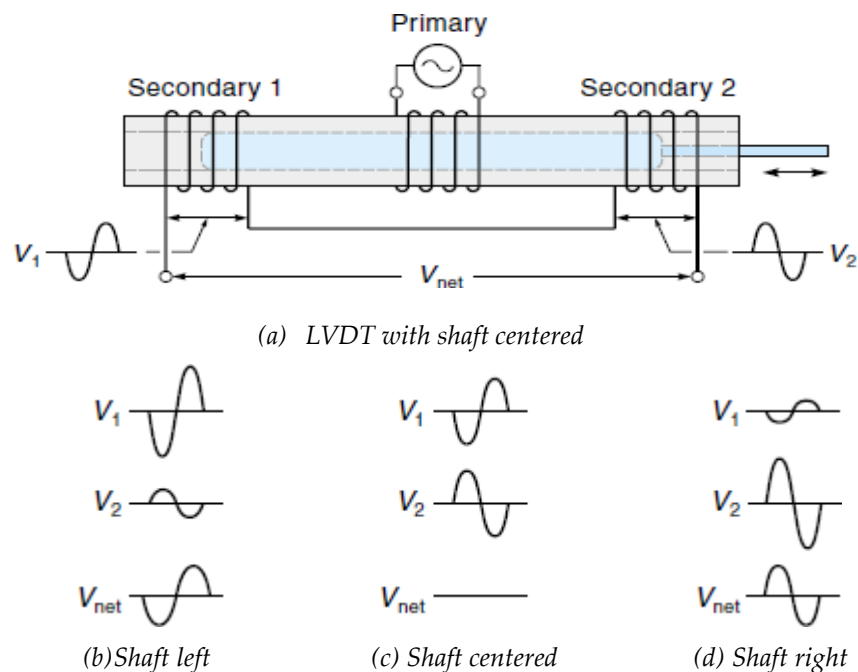


Figure 2.29: Pictorial description of an LVDT

If the iron core is exactly in the center, the voltages induced on the secondaries by the primary will be equal and opposite, giving a net output (V_{net}) of 0 V [as shown in Figure 2.29(c)]. Consider what happens when the core is moved a little to the right. Now there is more

coupling to secondary 2 so its voltage is higher, while secondary 1 is lower. Figure 2.29(d) illustrates the waveforms of this situation. The algebraic sum of the two secondaries is in phase with secondary 2, and the magnitude is proportional to the distance the core is off center. If the core is moved a little left of center, then secondary 1 has the greater voltage, producing a net output that is in phase with secondary 1 [Figure 2.29(b)]. In fact, the only way we can tell from the output which direction the core moved is by the phase. Summarizing, the output of the LVDT is an AC voltage with a magnitude and phase angle. The magnitude represents the distance that the core is off center, and the phase angle represents the direction of the core (left or right.)

The extension valve shaft, or control rod, is made of a metal suitable for acting as the movable core of a transformer. Moving the extension between the primary and secondary windings of a transformer causes the inductance between the two windings to vary, thereby varying the output voltage proportional to the position of the valve or control rod extension. Figure 2.30 illustrates a valve whose position is indicated by an LVDT. If the open and shut position is all that is desired, two small secondary coils could be utilized at each end of the extension's travel.

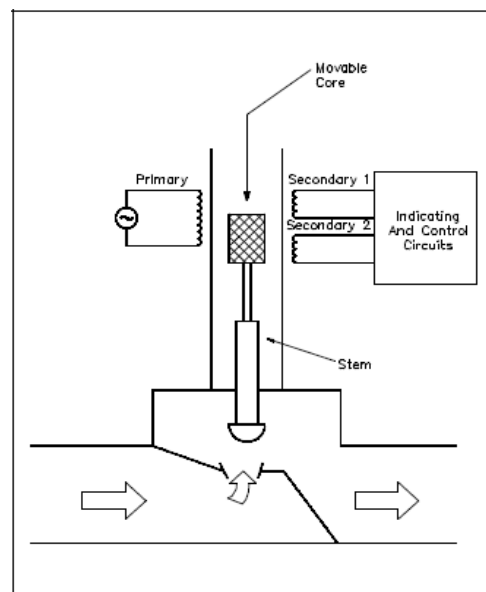


Figure 2.30: Extension valve shaft using an LVDT

LVDTs are extremely reliable. As a rule, failures are limited to rare electrical faults which cause erratic or erroneous indications. An open primary winding will cause the indication to fail to some predetermined value equal to zero differential voltage. This normally corresponds to mid-stroke of the valve. A failure of either secondary winding will cause the output to indicate either full open or full closed.

2.6.4 Optical Rotary Encoders

An *optical rotary encoder* produces angular position data directly in digital form, eliminating any need for the ADC converter. The concept is illustrated in Figure 2.31, which shows a slotted disk attached to a shaft. A light source and photocell arrangement are mounted so that the slots pass the light beam as the disk rotates. The angle of the shaft is deduced from the output of the photocell. There are two types of optical rotary encoders: the absolute encoder and the incremental encoder.

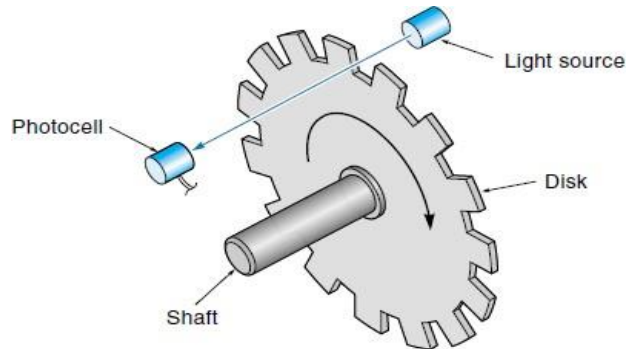


Figure 2.31: An optical rotary encoder.

2.6.4.1 Absolute Optical Encoders:

Absolute optical encoders use a glass disk marked off with a pattern of concentric tracks (Figure 2.32). A separate light beam is sent through each track to individual photo sensors. Each photo sensor contributes 1 bit to the output digital word. The encoder in Figure 2.32 outputs a 4-bit word with the least significant bit (LSB) coming from the outer track. The disk is divided into 16 sectors, so the resolution in this case is $360^\circ/16 = 22.5^\circ$. For better resolution, more tracks would be required. For example, eight tracks (providing 256 states) yield $360^\circ/256 = 1.4^\circ/\text{state}$, and ten tracks (providing 1024 states) yield $360^\circ/1024 = 0.35^\circ/\text{state}$.

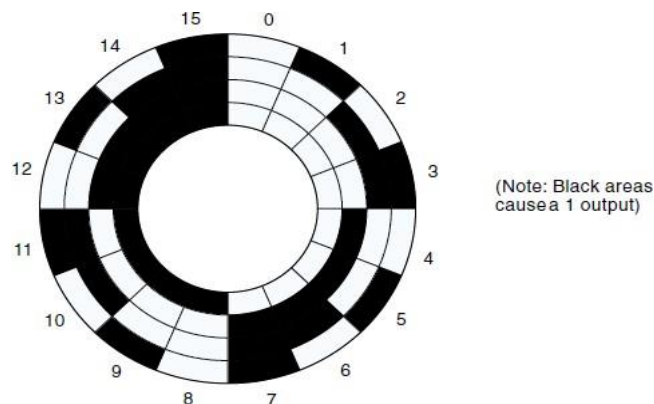


Figure 2.32: An absolute optical encoder using straight binary code.

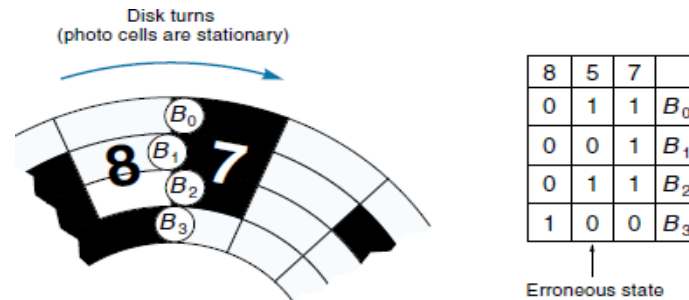


Figure 2.33: An absolute optical encoder showing how an out-of-alignment photocell can cause an erroneous state.
(Note: Dark areas produce a 1, and light areas produce a 0.)

2.6.4.2 Incremental Optical Encoders:

The **incremental optical encoder** (Figure 2.34) has only one track of equally spaced slots. Position is determined by counting the number of slots that pass by a photo sensor, where each slot represents a known angle. This system requires an initial reference point, which may come from a second sensor on an inner track or simply from a mechanical stop or limit switch. In many applications, the shaft being monitored will be cycling back-and-forth, stopping at various angles. To keep track of the position, the controller must know which direction the disk is turning as well as the number of slots passed.

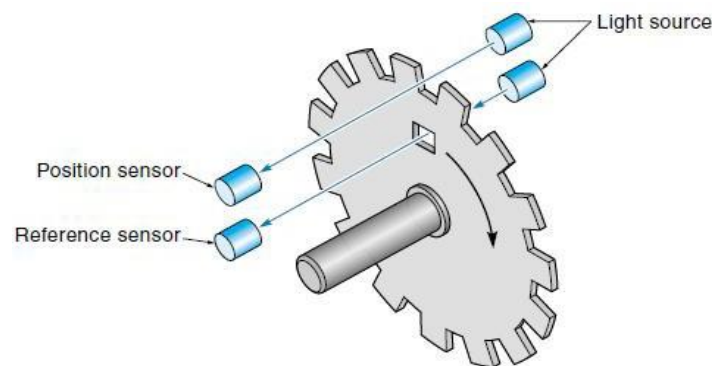


Figure 2.34: An incremental optical encoder.

A single photo sensor cannot convey which direction the disk is rotating; however, a clever system using two sensors can. As Figure 2.35(a) illustrates, the two sensors, V_1 and V_2 , are located slightly apart from each other on the same track. For this example, V_1 is initially off (well, almost you can see it is half-covered up), and V_2 is on. Now imagine that the disk starts to rotate CCW. The first thing that happens is that V_1 comes completely on (while V_2 remains on). After more rotation, V_2 goes off, and slightly later V_1 goes off again. Figure 2.35(b) shows the waveform for V_1 and V_2 . Now consider what happens when the disk is rotated in the CW direction [starting again from the position shown in Figure 2.35 (a)]. This time V_1 goes off

immediately, and V_2 stays on for half a slot and then goes off. Later V_1 comes on, followed by V_2 coming on. Figure 2.35(c) shows the waveforms generated by V_1 and V_2 . Compare the two sets of waveforms notice that *in the CCW case V_2 leads V_1 by 90° , whereas for the CW case V_1 is leading V_2 by 90°* . This difference in phase determines which direction the disk is turning.

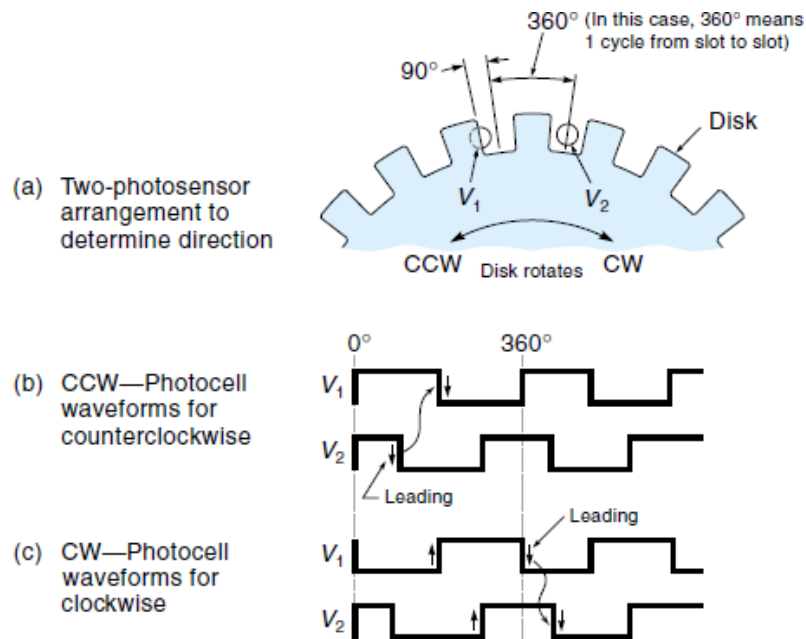
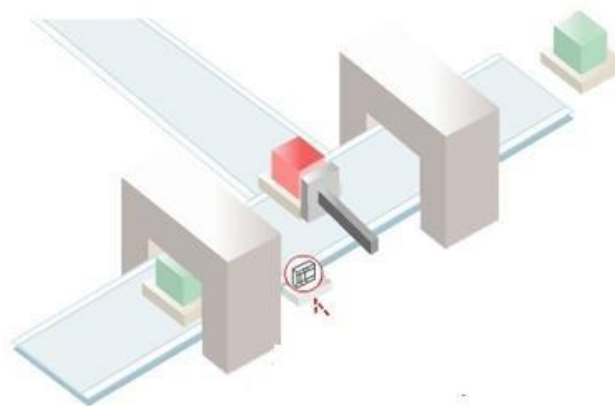


Figure 2.35: An incremental optical encoder direction of rotation determination.

2.6.5 Applications of Position Sensors

2.6.5.1 Production Line Conveyor Shift Unit:

Proximity switch is used as a conveyor shift unit. A sensor detects when a product has arrived, and then sends signals to stoppers and the Conveyor Shifting Unit to shift the product to another conveyor. This is depicted in the figure shown below.



2.6.5.2 Overhead Crane Collision Avoidance:

At an iron fabrication plant, two overhead cranes operate on one runway; at times, the manufacturing process requires the cranes to operate in overlapping areas of the bay. If an operator becomes distracted or is concentrating on the load being transported, a collision with the opposing crane is possible. This is depicted in the figure shown below.



A complete system using non-contacting proximity sensors for the purpose of material handling system collision avoidance could be used. The addition of these sensors to the cranes provides the operator with an audible warning when one crane comes within 40 ft of the opposing crane. The warning alerts the operator that the cranes are in close proximity. If the operator continues movement toward the opposing crane, the braking system will activate at 10 ft.

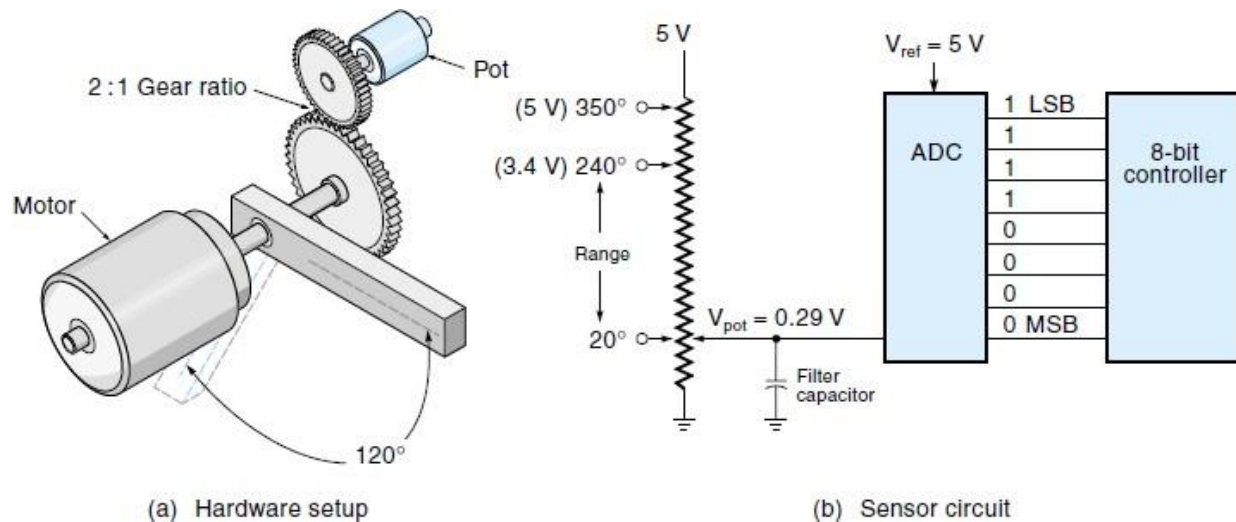
2.6.5.3 Pot sensor position system for robot arm:

Servo motors are closed-loop systems, and they are inherently useful in arm systems where precise position control of the joints is necessary. But what about when using other types of motors, including DC gear motors and stepper motors? DC and stepper motors have no inherent feedback system of their own, so if you're building an autonomously operated arm, you'll need to add one of the feedback techniques. These turn an open-loop DC or stepper motor system into a closed-loop system. A straightforward method of providing position feedback is to attach the shaft of a potentiometer to the shoulder or elbow joint or motor. As the joint turns, it moves the pot, which in turn changes its resistance. This resistance change indicates the precise position of the joint.

The potentiometer may provide a relative measurement of the position of the arm, but the information is in analog form, as a resistance or voltage, neither of which can be directly interpreted by a computer. The most common and generally most useful—way to connect the

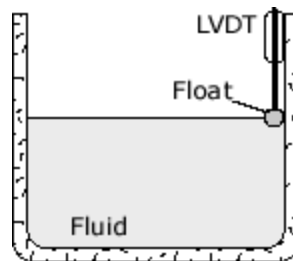
pot to a control circuit is to use the component as a voltage divider. As the pot turns (or slides), its output is a continuously variable voltage from 0 to the positive supply voltage (usually 5 volts). The wiper of the pot is connected to the input of an analog-to-digital converter (ADC), which translates voltage levels into bytes. Many modern microcontrollers have built-in ADCs, saving you the trouble of wiring up a separate analog-to-digital converter chip.

The situation is depicted in the figure shown below.



2.6.5.4 Fluid level measurement:

Although the LVDT is a displacement sensor, many other physical quantities can be sensed by converting displacement to the desired quantity via thoughtful arrangements. One application is fluid level position sensing in hydraulic cylinders. This is shown in the figure below.



Chapter Three

Signal Conditioning and Processing Elements

3.1 Introduction

In electronics, *signal conditioning* means manipulating an analog signal in such a way that it meets the requirements of the next stage for further processing. Specifically here in instrumentation, signal conditioning elements convert the output of sensing elements into a form suitable for further processing. This form is usually a d.c. voltage, a d.c. current or a variable frequency a.c. voltage. Signal conditioning can include *amplification, filtering, converting, range matching, isolation* and any other processes required to make sensor output suitable for processing after conditioning.

3.2 Deflection Bridges

Deflection bridges are used to convert the output of resistive, capacitive and inductive sensors into a voltage signal. Figure 3.1 shows a general deflection bridge network. E_{Th} is the open-circuit output voltage of the bridge, i.e. when current i in $BD = 0$.

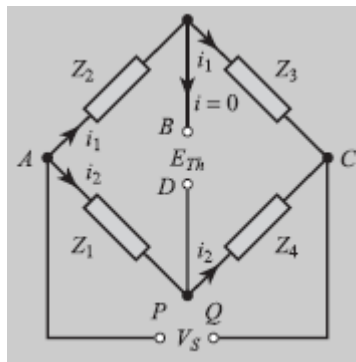


Figure 3.1: Electrical Circuit of Deflection Bridge

Using Kirchoff's laws:

$$V_S = i_1 Z_2 + i_1 Z_3 \quad \text{i.e.} \quad i_1 = \frac{V_S}{Z_2 + Z_3}$$

$$V_S = i_2 Z_1 + i_2 Z_4 \quad \text{i.e.} \quad i_2 = \frac{V_S}{Z_1 + Z_4}$$

Assuming Q is at earth potential, then:

$$\text{Potential at } B = V_S - i_1 Z_2$$

$$\text{Potential at } D = V_S - i_2 Z_1$$

E_{Th} is equal to the potential difference between B and D, i.e.

$$E_{Th} = (V_S - i_1 Z_2) - (V_S - i_2 Z_1)$$

$$= i_2 Z_1 - i_1 Z_2$$

Substituting i_1 and i_2 , we get

$$E_{Th} = V_S \left(\frac{Z_1}{Z_1 + Z_4} - \frac{Z_2}{Z_2 + Z_3} \right)$$

Let us now apply Thevenin equivalent circuit manipulation to find the Thevenin impedance.

The circuit can be redrawn as figure 3.2.

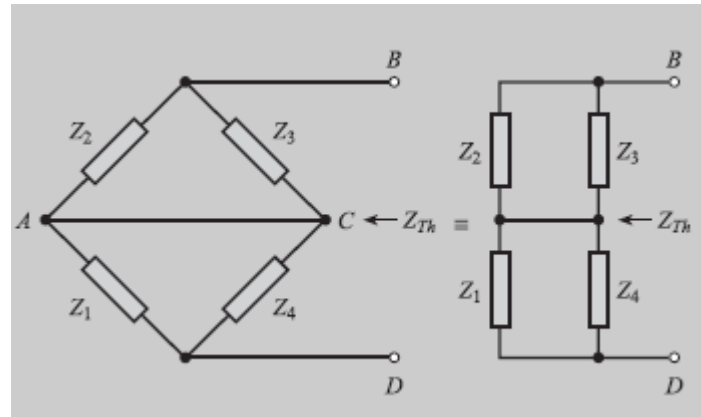


Figure 3.2: Thevenin Equivalent Circuit of Deflection Bridge

Z_{Th} is the impedance, looking back into the circuit, between the output terminals BD , when the supply voltage V_S is replaced by its internal impedance. Assuming the internal impedance of the supply is zero, and then this is equivalent to a short circuit across AC (see Figure 3.2). We see that Z_{Th} is equal to the parallel combination of Z_2 and Z_3 in series with the parallel combination of Z_1 and Z_4 , i.e.

$$Z_{Th} = \frac{Z_2 Z_3}{Z_2 + Z_3} + \frac{Z_1 Z_4}{Z_1 + Z_4}$$

If a load, e.g. a voltmeter or amplifier, of impedance Z_L is connected across the output terminals BD , then the current through the load is $i = E_{Th} / (Z_{Th} + Z_L)$. The corresponding voltage across the load is $V_L = E_{Th} Z_L / (Z_{Th} + Z_L)$. Thus in the limit that $|Z_L| \gg |Z_{Th}|$, $V_L \rightarrow E_{Th}$.

In a resistive or Wheatstone bridge all four impedances Z_1 to Z_4 are pure resistances R_1 to R_4 .

$$E_{Th} = V_S \left(\frac{R_1}{R_1 + R_4} - \frac{R_2}{R_2 + R_3} \right)$$

We first consider the case when only one of the resistances is a sensing element. Here R_1 depends on the input measured variable I , i.e. $R_1 = R_I$, and R_2 , R_3 and R_4 are fixed resistors. This gives

$$E_{Th} = V_S \left(\frac{1}{1 + R_4/R_I} - \frac{1}{1 + R_3/R_2} \right)$$

From which we see that to design a single element bridge we need to specify the three parameters V_S , R_4 and R_3/R_2 . The individual values of R_2 and R_3 are not critical; it is their ratio which is crucial to the design. The three parameters can be specified by considering the range and linearity of the output voltage and electrical power limitations for the sensor. Thus if I_{MIN} and I_{MAX} are minimum and maximum values of the measured variable, and R_{MIN} and R_{MAX} are the corresponding sensor resistances, then in order for the bridge output voltage to have a range from V_{MIN} to V_{MAX} the following conditions must be obeyed:

$$V_{MIN} = V_S \left(\frac{1}{1 + R_4/R_{I_{MIN}}} - \frac{1}{1 + R_3/R_2} \right)$$

$$V_{MAX} = V_S \left(\frac{1}{1 + R_4/R_{I_{MAX}}} - \frac{1}{1 + R_3/R_2} \right)$$

Often we require $V_{MIN} = 0$, i.e. the bridge to be balanced when $I = I_{MIN}$; in this case the above equation reduces to:

$$\frac{R_4}{R_{I_{MIN}}} = \frac{R_3}{R_2}$$

A third condition is required to complete the design. One important consideration is the need to limit the electrical power $i^2 R_I$ in the sensor to a level which enables it to be dissipated as heat flow to the surrounding fluid; otherwise the temperature of the sensor rises above that of the surrounding fluid, thereby affecting the sensor resistance. Thus if \hat{w} watts is the maximum power dissipation, we require:

$$V_S^2 \frac{R_I}{(R_I + R_4)^2} \leq \hat{w}$$

for $I_{MIN} \leq I \leq I_{MAX}$.

3.3 Amplifiers

Amplifiers are necessary in order to amplify low-level signals, e.g. thermocouple or strain gauge bridge output voltages, to a level which enables them to be further processed.

3.3.1 The ideal operational amplifier and its applications:

The operational amplifier can be regarded as the basic building block for modern amplifiers. It is a high gain, integrated circuit amplifier designed to amplify signals from d.c. up to many kHz. It is not normally used by itself but with external feedback networks to produce precise

transfer characteristics which depend almost entirely on the feedback network. Usually there are two input terminals and one output terminal, the voltage at the output terminal being proportional to the difference between the voltages at the input terminals. Figure 3.3 shows the circuit symbol and a simplified equivalent circuit for an operational amplifier. Table 3.1 summarizes the main characteristics of an ideal operational amplifier together with those of a typical practical amplifier OPA27.

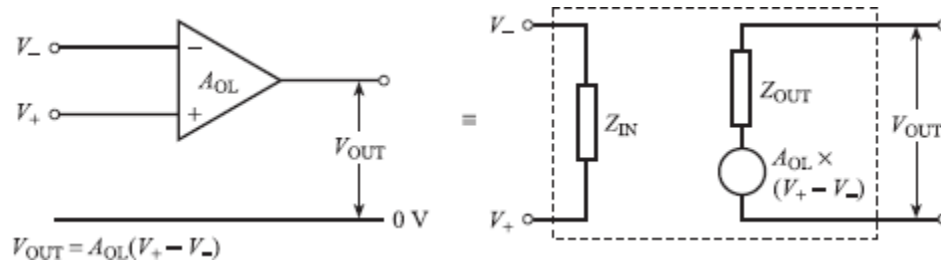


Figure 3.3: Circuit symbol and simplified equivalent circuit for operational amplifier.

Table 3.1

Parameter	Ideal op-amp	OPA27 ^[1]
D.C. open-loop gain A_{OL}	∞	120 dB (10^6)
Input impedance Z_{IN}	∞	6 M Ω
Output impedance Z_{OUT}	0	70 Ω
Input offset voltage V_{OS}	0	25 μ V
Temp. coeff. of input offset voltage γ	0	0.6 μ V $^{\circ}$ C ⁻¹
Input bias current i_B	0	40 nA
3 dB bandwidth 0 to f_B	0 to ∞	0 to 10 Hz
Common mode rejection ratio, CMMR	∞	114 dB

The transfer characteristics are derived using the following two ideal conditions:

$$i_- = i_+ = 0$$

$$V_- = V_+$$

The first condition results from assuming input impedance $Z_{IN} = \infty$. The second condition results from assuming that $A_{OL} \rightarrow \infty$: since $V_{OUT} = A_{OL}(V_+ - V_-)$ and V_{OUT} is finite, then the differential voltage $(V_+ - V_-) \rightarrow 0$ i.e. $V_+ = V_-$. We now derive the transfer characteristics for sample voltage amplifier circuits.

3.3.1.1 Inverting amplifier:

Figure 3.4 shows a signal source V_{IN} , R_{IN} connected to an inverting amplifier. Since $V_+ = V_- = 0$:

$$i_{IN} = \frac{V_{IN}}{R_{IN}}, \quad i_F = \frac{V_{OUT}}{R_F}$$

Also

$$i_{IN} + i_F = i_L = 0$$

giving

$$\frac{V_{IN}}{R_{IN}} + \frac{V_{OUT}}{R_F} = 0$$

$$V_{OUT} = \frac{-R_F V_{IN}}{R_{IN}}$$

Thus the output voltage V_{OUT} is proportional to the input voltage V_{IN} with gain $-R_F/R_{IN}$. The resistance R is set equal to the resistance of R_{IN} in parallel with R_F , i.e.

$$R = \frac{R_{IN} R_F}{R_{IN} + R_F}$$

This is to balance the d.c. bias currents to inverting and non-inverting inputs.

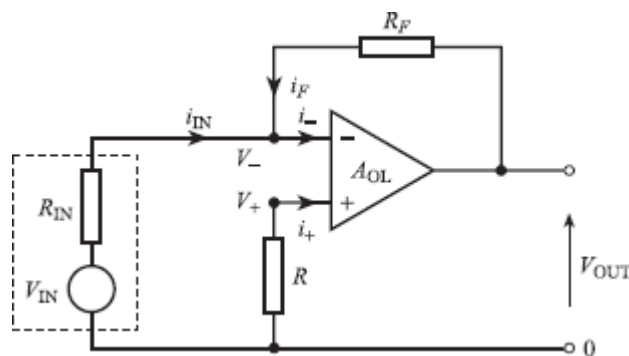


Figure 3.4: Inverting operational amplifier.

3.3.1.2 Non-inverting amplifier:

Figure 3.5 shows a non-inverting amplifier circuit. Since $i_+ = 0$, $V_+ = V_{IN}$; also R_F and R_1 form a potential divider so that:

$$V_- = V_{OUT} \left(\frac{R_1}{R_1 + R_F} \right)$$

Also since $V_+ = V_-$

$$V_{OUT} \left(\frac{R_1}{R_1 + R_F} \right) = V_{IN}$$

$$V_{OUT} = \left(1 + \frac{R_F}{R_1} \right) V_{IN}$$

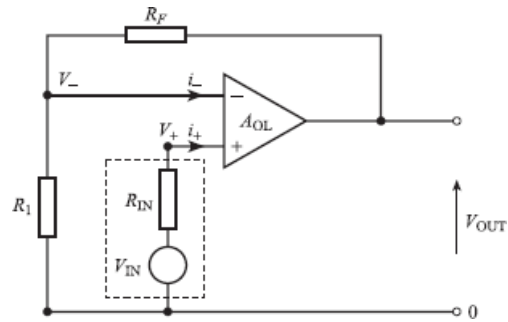


Figure 3.5: Non- Inverting operational amplifier.

3.3.1.3 Differential amplifier:

Figure 3.6 shows two voltage sources V_1 , R_{IN} and V_2 , R_{IN} connected to a differential amplifier. V_2 , R_{IN} and R_F form a potential divider, so that:

$$V_+ = V_2 \left(\frac{R_F}{R_F + R_{IN}} \right)$$

Also:

$$i_{IN} + i_F = i_- = 0$$

where

$$i_{IN} = \frac{(V_1 - V_-)}{R_{IN}}, \quad i_F = \frac{(V_{OUT} - V_-)}{R_F}$$

giving:

$$\frac{(V_1 - V_-)}{R_{IN}} + \frac{(V_{OUT} - V_-)}{R_F} = 0$$

and

$$V_- = \frac{R_{IN} \cdot V_{OUT}}{(R_F + R_{IN})} + \frac{R_F V_1}{(R_F + R_{IN})}$$

Since $V_- = V_+$

$$\frac{R_{IN} V_{OUT}}{(R_F + R_{IN})} + \frac{R_F V_1}{(R_F + R_{IN})} = \frac{R_F V_2}{(R_F + R_{IN})}$$

giving:

$$V_{OUT} = \frac{R_F}{R_{IN}} (V_2 - V_1)$$

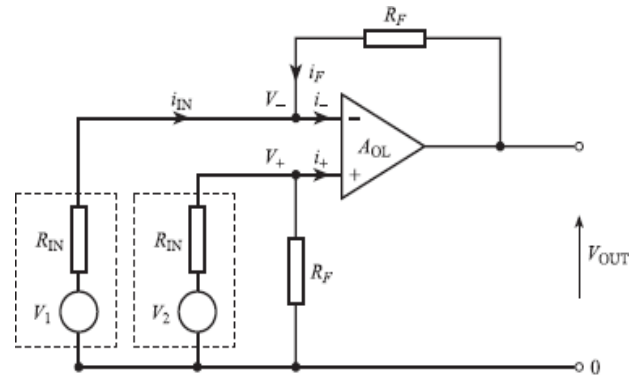


Figure 3.6: Differential amplifier.

Figure 3.7 shows a strain gauge bridge connected to a differential amplifier.

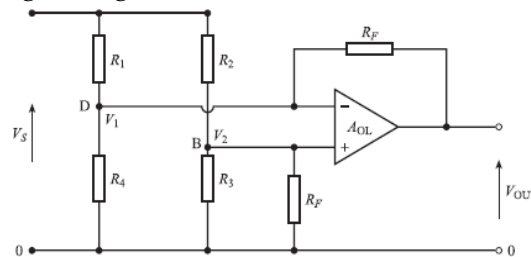


Figure 3.7: Strain Gauge Bridge connected to differential amplifier.

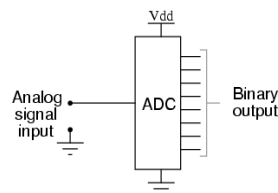
3.4 Signal Processing Elements

These elements take the output of the conditioning element and convert it into a form more suitable for presentation. Examples are:

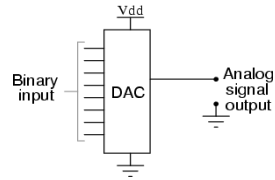
- Analogue-to-digital converter (ADC) which converts a voltage into a digital form for input to a computer
- Computer which calculates the measured value of the variable from the incoming digital data.

3.4.1 Analog to Digital Converters (ADC):

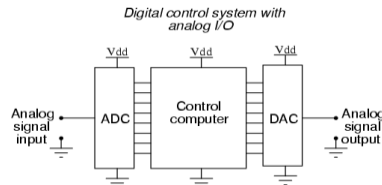
The process of converting analog signal into equivalent digital signal is called A/D conversion. The electronics circuit, which does this process, is called A/D converter. The circuit has only one input with 'n' number of digital outputs. The figure shown below shows this situation.



A DAC, on the other hand, inputs a binary number and outputs an analog voltage or current signal. In block diagram form, it looks like this:



Together, they are often used in digital systems to provide complete interface with analog sensors and output devices for control systems such as those used in automations.



We have a number of Analog to Digital Converters. The commonly used ones are

- Flash ADC
- Digital Ramp ADC
- Successive Approximation ADC

3.4.1.1 Flash ADC:

Flash analog-to-digital converters, also known as parallel ADCs, are the fastest way to convert an analog signal to a digital signal. Flash ADCs are ideal for applications requiring very large bandwidth, but they consume more power than other ADC architectures and are generally limited to 8-bit resolution. It is formed of a series of comparators, each one comparing the input signal to a unique reference voltage. The comparator outputs connect to the inputs of a priority encoder circuit, which then produces a binary output. Figure 3.8 shows a typical flash ADC block diagram.

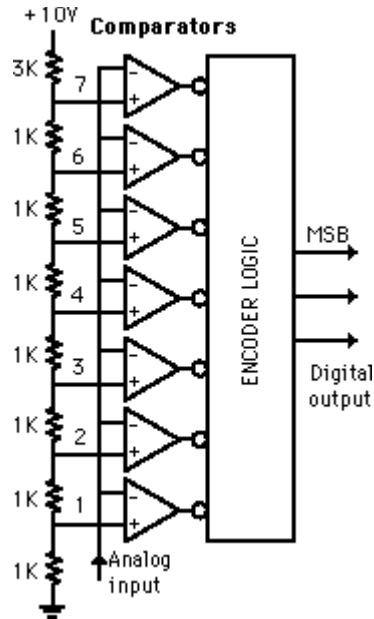


Figure 3.8: Flash ADC architecture

It is the fastest type of ADC available, but requires a comparator for each value of output (63 for 6-bit, 255 for 8-bit, etc.) Such ADCs are available in IC form up to 8-bit and 10-bit flash ADCs (1023 comparators) are planned. The encoder logic executes a truth table to convert the ladder of inputs to the binary number output. The one illustrated in Figure 3.8 is a 3-bit flash ADC with resolution 1 volt.

3.4.1.2 Digital Ramp ADC:

Conversion from analog to digital form inherently involves comparator action where the value of the analog voltage at some point in time is compared with some standard. A common way to do that is to apply the analog voltage to one terminal of a comparator and trigger a binary counter which drives a DAC. The output of the DAC is applied to the other terminal of the comparator. Since the output of the DAC is increasing with the counter, it will trigger the comparator at some point when its voltage exceeds the analog input. The transition of the comparator stops the binary counter, which at that point holds the digital value corresponding to the analog voltage. Figure 3.9 shows a digital ramp ADC.

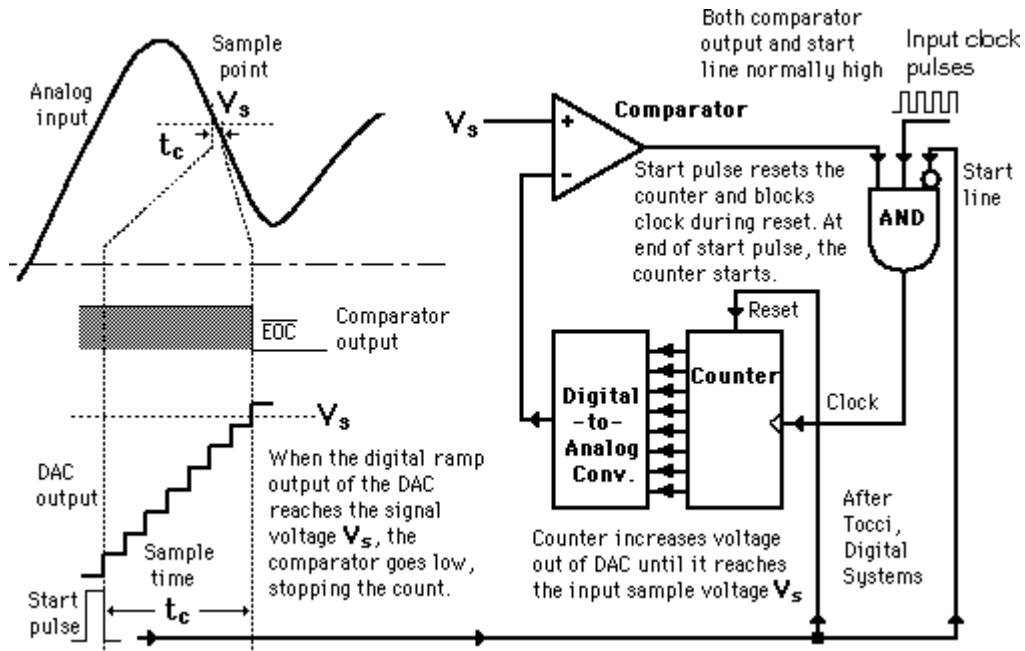


Figure 3.9: Digital Ramp ADC

3.4.1.3 Successive Approximation ADC:

Illustration of 4-bit Successive Approximation ADC with 1 volt step size is shown in Figure 3.10.

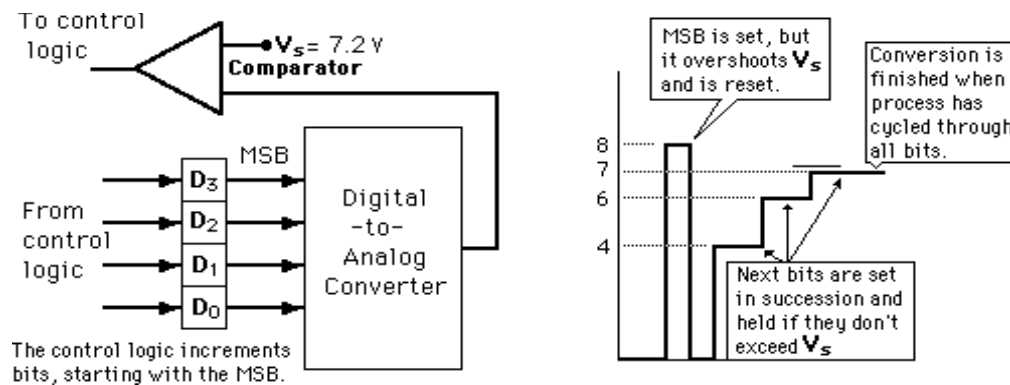


Figure 3.10: Successive Approximation ADC

The successive approximation ADC is much faster than the digital ramp ADC because it uses digital logic to converge on the value closest to the input voltage. A comparator and a DAC are used in the process. The flow chart of the Successive Approximation ADC is shown in Figure 3.11.

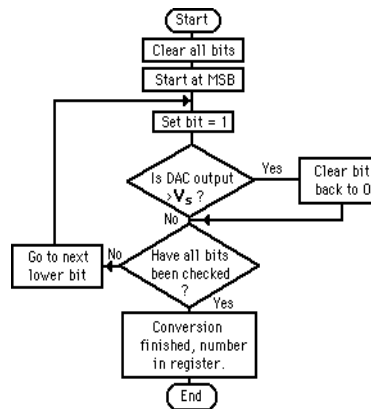


Figure 3.11: Flow chart of Successive Approximation ADC

3.4.2 Microcontroller:

A microcontroller is a microprocessor (=CPU on a chip) with also memory and peripherals on the same die. It is a complete system on one chip. Historically, the 'computer' was first, and then came the microprocessor and the microcontroller appeared only afterwards. A lot of improvements have been made since the invention of microcontroller. To our discussion let us focus on one family of microcontroller called PIC18F4550.

3.4.2.1 Basic Architecture of the PIC18F4550:

The PIC18F4550 is a middle class processor. The processor is available in a 40-pin DIP package and includes quite some extra stuff. The on-board program memory is of the Flash type, hence the F in the family name. Figure 3.12 shows the PIC18F4550 microcontroller.

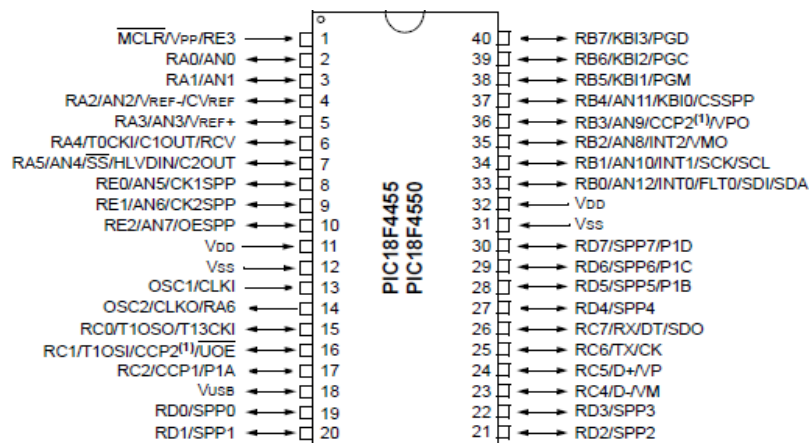


Figure 3.12: 40-pin PIC18F4550 Microcontroller

Parallel Input/output Port:

The PIC18F4550 (40 pin DIL package) has 35 physical input/output lines, grouped in so-called Ports. *PortA* has 7 lines (PA0...PA6) and *PortB* has 8 lines (PB0 ... PB7), same for *PortC* and

PortD and *PortE* has 4 lines. All ports are located in the file registers. These ports are treated as 'normal' memory for the software, but in reality the hardware of the bits of these registers are connections to the outside world. Any line can be either input or output.

Applications of the ports:

Inputs:

- Individual switches
- Switch matrix (keyboard)
- Serial input (bit stream generated by external device)
- Sensors (optionally via an analog-to-digital converter) etc

Outputs

- LED
- Motor control (via power stage)
- Serial output (bit stream intended for external device)
- Actuators (optionally via a digital-to-analog converter) etc

Chapter Four

Data Presentation Elements

4.1 Review and choice of data presentation elements

Figure 4.1 classifies data presentation elements in wide current. It begins by classifying elements into *displays* and *recorders/printers*. If no permanent record of measured variables is required, then displays can be used. A choice must first be made between *analogue pointer-scale indicators* and *digital displays*. With the pointer-scale indicator, the observer must *interpolate* if the pointer lies between two scale marks: thus if the pointer lies between 9 and 10 the observer must decide whether the measured value is say 9.4, 9.5 or 9.6. Thus an observation error of up to ± 0.5 units is possible. This problem is avoided with a two-decade digital display, which presents the number directly as 9.5.

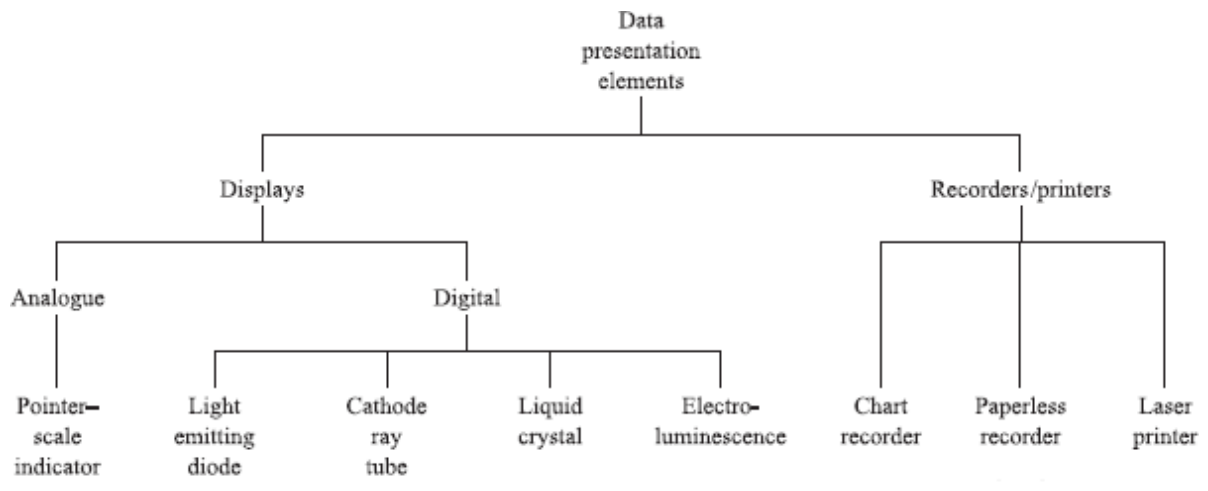
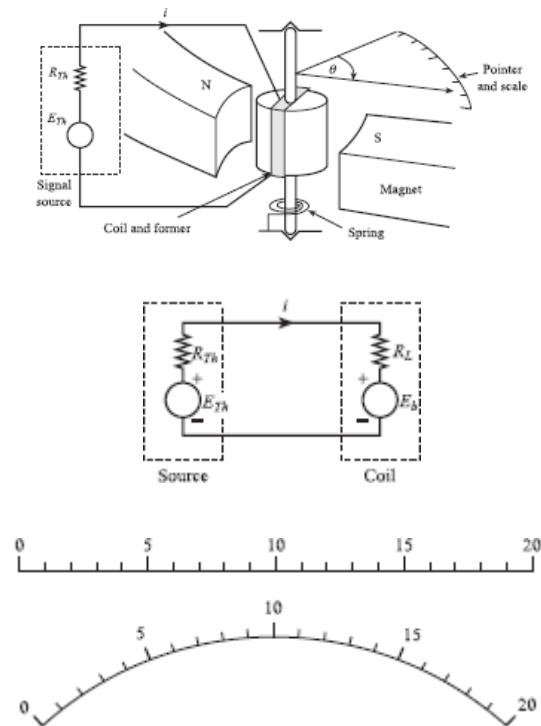


Figure 4.1: Classification of data presentation elements.

4.2 Pointer-scale indicators

These are analogue display devices. The figure depicted below shows simplified diagrams and an equivalent circuit for a moving coil indicator connected to a Thévenin signal source E_{Th} , R_{Th} . The coil is situated in a radial magnetic field of flux density B , so that a current i through the coil produces a deflecting torque.



This deflecting torque is opposed by the spring restoring torque. The difference between these torques is the net torque responsible for the final deflection of the pointer.

4.3 Digital display principles

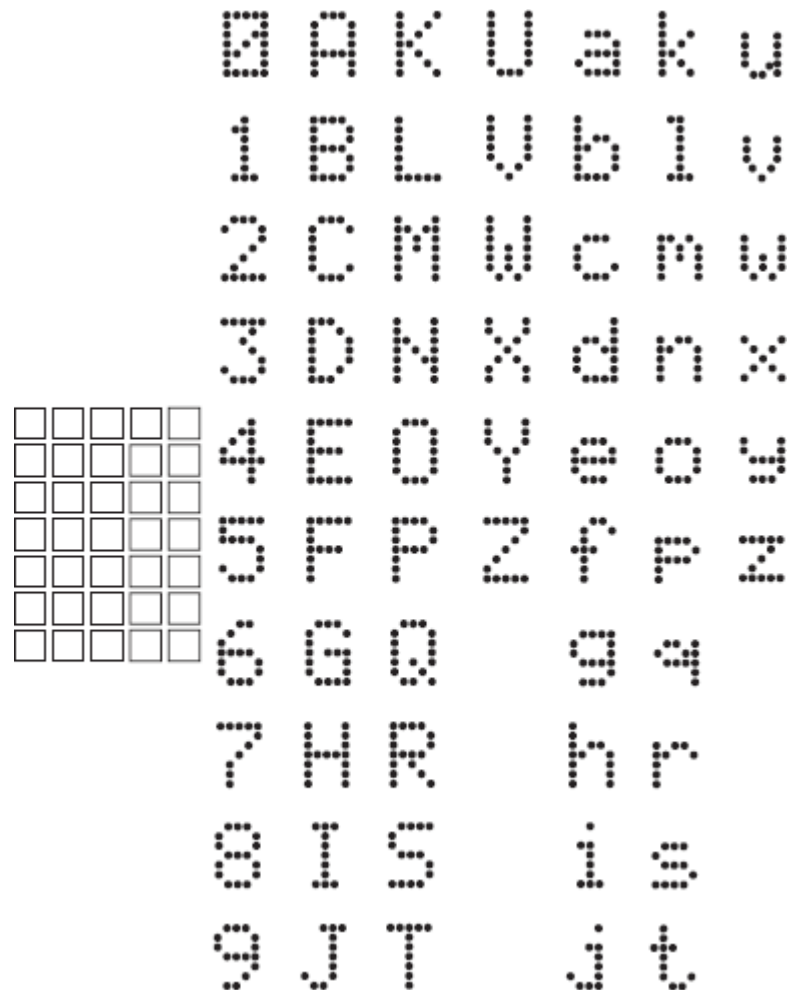
4.3.1 Character displays:

These are used to display the numerals 0 to 9, the letters of the alphabet A to Z in either upper or lower case format, and a few other symbols such as punctuation marks. Displays showing alphabetical and numerical information are often referred to as **alphanumeric**.

Figure 4.2 shows two character formats in widespread use: seven-segment and 7 by 5 dot matrix. Figure 4.2(a) shows seven segments *a* to *g* arranged in a figure-of-eight configuration and the corresponding character set. This is limited to the ten numerals and nine upper case letters. The 7 by 5 dot-matrix format enables a far larger set of typically 192 characters to be obtained; this includes all the numerals, upper and lower case letters (Figure 4.2(b)), together with Greek letters and other symbols. A 9 by 7 dot-matrix format gives a better representation of lower case letters.



(a) Seven Segment Display



(b) 7 by 5 Matrix Display

Figure 4.2: Character Format for Displays

Each character format is an array of segments or dots; these elements are referred to as **pixels**. To display a character each pixel must be separately switched 'on' and 'off' independently of the other pixels. When a pixel is switched on, either it is a source emitting light or it is modulating light from other sources. When a pixel is switched off it is either not emitting light

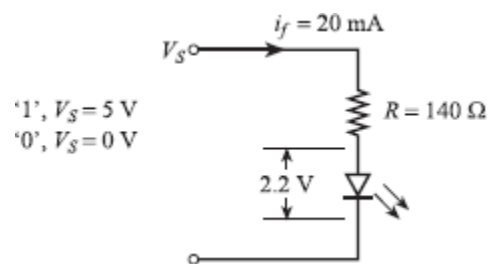
or not modulating light.

4.3 Light Emitting Diode Displays

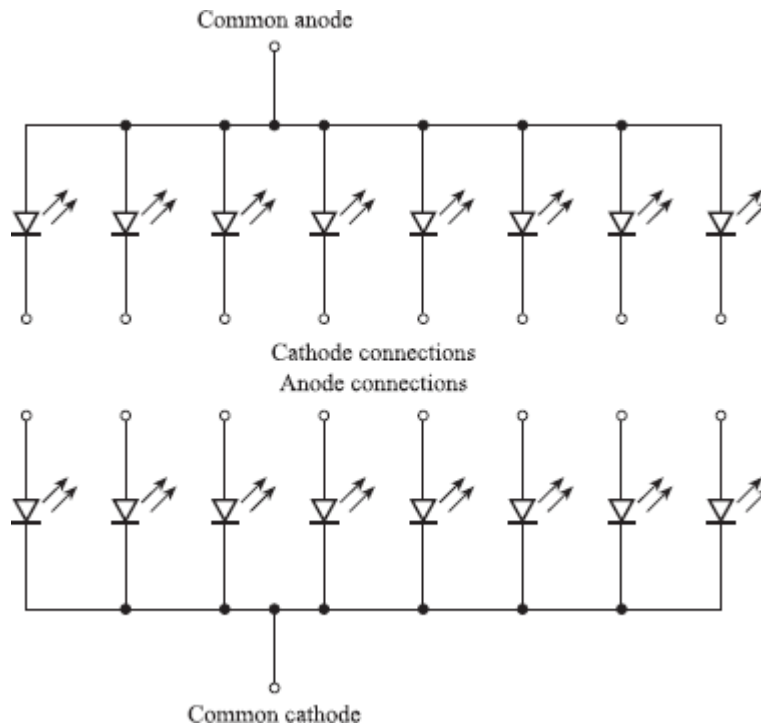
Light-emitting diodes have the special property that when forward biased they emit electromagnetic radiation over a certain band of wavelengths. Two commonly used LED materials are gallium arsenide phosphide (GaAsP), which emits red light, and gallium phosphide (GaP), which emits green or yellow light. In both cases the luminous intensity I_v of the diode light source increases with current.

When switched 'on', a typical GaAsP diode requires a forward current i_F of around 20 mA corresponding to a luminous intensity I_v of 4.0 mcd (millicandela), and a forward voltage V_F of 2.2 V. When used as a display pixel the diode should be switched 'on' by a logic signal in the '1' state, and switched 'off' when the signal is in the '0' state. Figure 4.3(a) shows a simple circuit for achieving this, using a series resistor R of 140 Ω . For a '1' input, $V_S \approx 5$ V, $i_F = (5 - 2.2)/140 = 20$ mA and the diode is 'on'. For a '0' input, $V_S \approx 0$ V, i_F is negligible and the diode is 'off'. Alternatively a 20 mA constant current source may be switched in and out by the logic signal.

A seven-segment LED display device consists of eight individual LEDs, one for each segment and one for the decimal point.



(a) Diode Circuit



(b) Interconnection Methods of LED in LED Displays

Figure 4.3: LED interconnection and circuits

There are two possible methods of interconnection, common anode or common cathode (Figure 4.3(b)).

However; LEDs have high power consumption, which makes them only suitable for small-scale character displays; they are not used in graphic displays.

4.4 Cathode ray tube (CRT) Displays

Cathode ray tubes are used to create large-scale displays. These devices are often referred to as **monitors**. A **visual display unit (VDU)** is a combination of a CRT display and a keyboard. Figure 4.4 shows a basic CRT: electrons are emitted at the cathode and accelerated towards the anode. A third electrode, called a grid or modulator, is placed between cathode and anode: by altering the potential of the modulator the number of electrons in the beam, i.e. the beam current, can be adjusted. The beam then passes through a focusing system followed by X and Y deflection systems: the focusing and deflection systems can be electromagnetic (EM), or electrostatic (ES) as shown in the diagram.

The electron beam is brought to a focus on the inside surface of the screen, which is coated with a large number of **phosphor dots**. These dots form the pixels. Phosphors are semiconductor materials which emit visible radiation in response to the impact of electrons: a spot of light

therefore appears on the screen. In response to a pulse change in beam current, i.e. a sudden increase followed by a sudden decrease, the light emission does not fall instantaneously but there is a gradual reduction called **phosphorescence decay** (Figure 4.4). The corresponding decay time is called the **persistence** of the phosphor; phosphors with a wide range of persistence are available, ranging from less than $1 \mu\text{s}$ (very short) to greater than 1s (very long). In **refresh displays** the phosphors must be 'refreshed' or re-energized every time the phosphorescence decays to a certain level: this is necessary to obtain a stationary pattern on the screen with minimum **flicker**. In the more expensive **storage displays**, the display is retained on the screen and refreshment is not necessary.

A **monochrome** display is obtained with a non-storage CRT and a standard 312-line **raster**. In a raster-type display constant amplitude saw tooth deflection voltages are applied to both X and Y plates (Figure 4.4). The period of the Y voltage, i.e. the time taken for the display to move from the top to the bottom of the screen, is relatively long. A typical period is 20 ms. The period of the X voltage, i.e. the time for each traverse across the screen, is 312 times shorter, i.e. $64 \mu\text{s}$. The resulting motion of the spot on the screen is shown in Figure 4.5. 312 horizontal 'lines' are traced out during the movement of the spot from top to bottom of the screen.

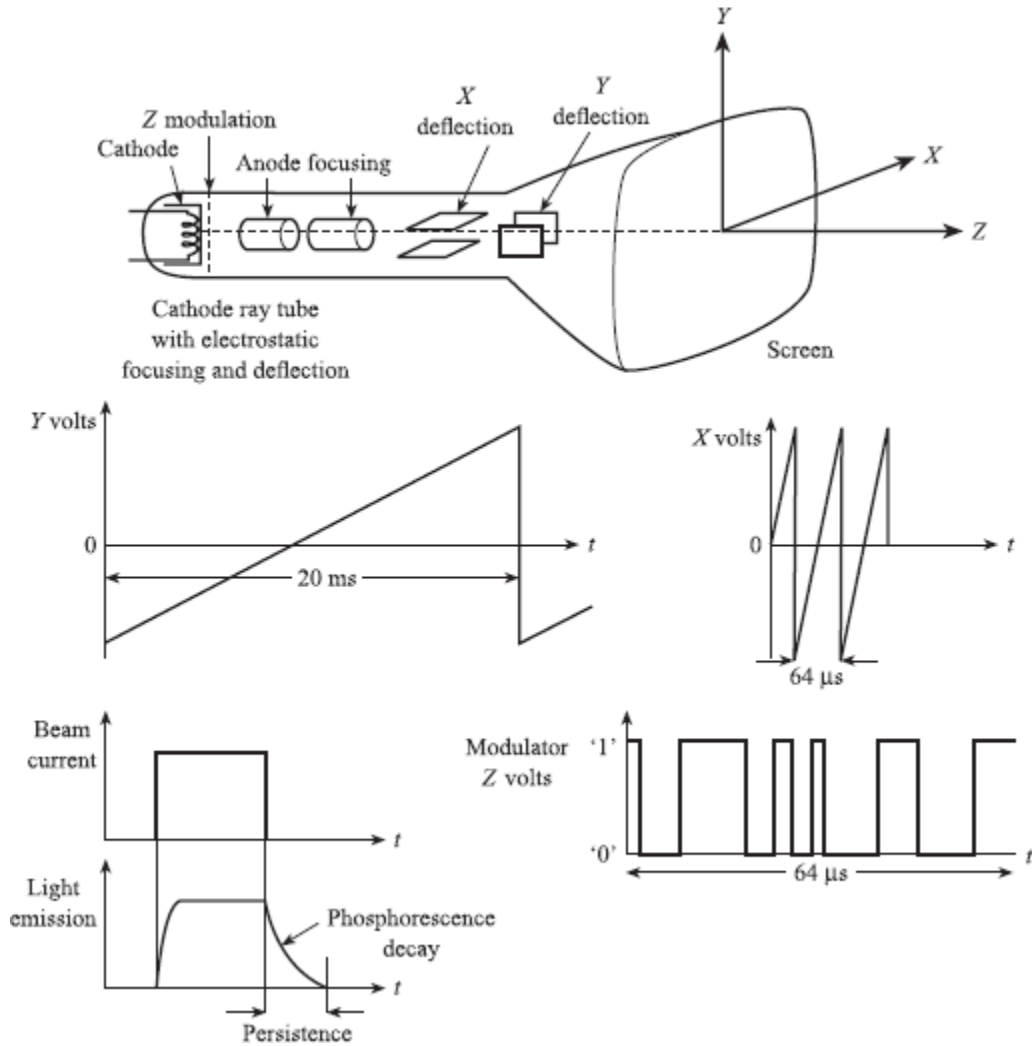


Figure 4.4 Cathode ray construction and waveforms.

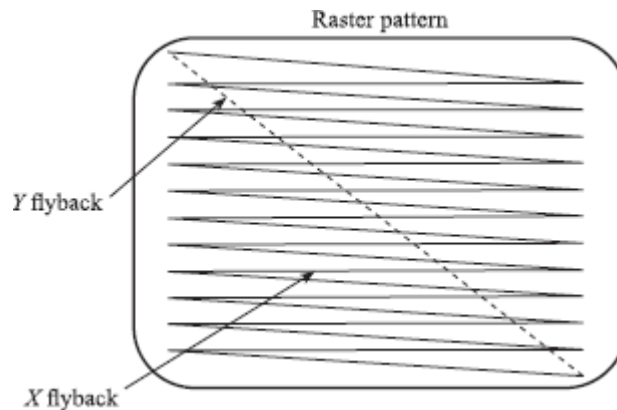


Figure 4.5: Raster display

CRT displays have the disadvantage that they are not 'flat screen' technology and occupy more

volume than comparable liquid crystal displays. They have much higher operating voltages than LCDs. power consumption is also higher in CRT than in LCD displays.

4.5 Liquid crystal displays (LCDs)

Liquid crystal displays (LCDs) do not emit light but use light incident on them from external sources. Consequently LCDs use significantly less power (microwatts) than LEDs (milliwatts). Liquid crystals flow under shear forces as in normal liquids but have some of the properties of solids. In **nematic** liquid crystals individual molecules have a rod-like shape. As the orientation of the molecules changes so there is a corresponding rotation of the plane of **polarization** of the incident light. An applied electric field can alter both the orientation of the molecules and the plane of polarization of the light, thus creating light and dark areas.

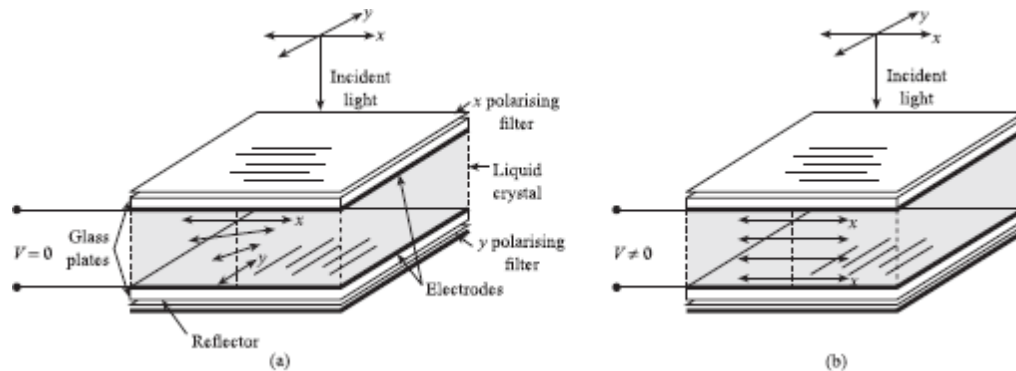


Figure 4.6: Liquid Crystal Displays

Figures 4.6(a) and (b) show the construction of a reflective **monochrome** display using **field effect** or **twisted nematic (TN)** liquid crystal material. The LC material is in contact with a pair of conducting electrodes which are transparent to light; a voltage is applied across these to create an electric field. There are glass plates above and below the electrodes. An x polarizing filter is situated above the upper glass plate; this transmits only x polarized light. Similarly a y polarizing filter below the lower glass plate transmits only y polarized light.

Figure 4.6(a) shows the situation when the applied voltage $V = 0$. The molecules near the top of the LC are lined up along the x -direction. Moving downwards through the liquid, their orientation gradually changes so that the molecules at the bottom are lined up along the y -direction. The light entering the liquid is x polarized; as it moves downwards the direction of polarization rotates so that the light is y polarized on leaving the liquid. The light is therefore able to pass through the y polarizing filter and is reflected back to the observer, the surface appearing pale grey or green.

Figure 4.6(b) shows the situation when the applied voltage V is non-zero. In this case the

molecules remain aligned along the x direction throughout the liquid crystal: this means that the light remains x polarized as it moves downwards. The light cannot therefore pass through the lower y polarizing filter and is absorbed; the surface appears black to an observer.

The basic liquid crystal element shown in Figure 4.6(a) can be used to produce *color displays* by the addition of a matrix of red, green and blue filter elements between the upper electrode and the x polarizing filter.

4.6 Recorders

A record of the time variation of the measured variables would be essential, for example, in the following situations:

(a) High-speed events, e.g. a human heartbeat, which are too fast to be followed by a human observer. Changes in the recorded blood pressure waveform will then show clearly any irregular or abnormal behavior.

(b) The monitoring of a complex process such as a gas compressor which has a number of associated measured variables. If the compressor breaks down, then the exact sequence of events *drop in lubricating oil pressure – rise in bearing temperature – drop in delivery pressure* can be found and the cause of failure established.

(c) Large amounts of data which are to be used in numerical calculations. Examples are the calculations of the yield and efficiency of a chemical reactor from composition, temperature, pressure and flow-rate data, and the value of gas transferred from supplier to customer in a given month.

Chart recorders give a record, on paper, of the time variation of a measured variable; these can be analogue or digital and the record can be either a continuous line or a series of dots. They can record up to six variables but have limited speed of response; they also require regular replacement of paper and pens. A chart recorder could be satisfactorily used in situation (b). *Paperless* recorders use LCD displays and digital archive memory; these typically can record four measured variables and have less maintenance requirements than chart recorders. They also have a fast speed of response and could be satisfactorily used in situation (a). *Laser printers* can print large amounts of data, in character or graphics form, on paper. A laser printer would therefore be ideal in situation (c) where large tables of numerical data need to be printed out for checking and calculation.