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Faculty of Engineering

Department of Electrical and Electronic Engineering

Sensors & Measurements

Graduation Project
EE- 400

Student: Muhammad Rizwan (991226)

Supervisor: Assist. Prof. Dr Kadri Bürüncük

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ABSTRACT

The classes of sensors that perform the control and measurement of temperature are known as thermal sensors. Resistance-temperature detectors, thermistors and Thermocouples are used to develop a voltage which is proportional to the change in temperature. Bimetallic strip converts temperature into a physical motion of metal elements. Gas and vapor-pressure temperature sensors convert temperature into gas pressure, which then is converted to an electrical signal or is used directly in pneumatic system.

Position, location, and displacement sensors include the Potentiometric, capacitive and LVDTs to convert the displacement linearly into voltage. Strain-gauges convert strain into a change of resistance. Accelerometers are used to measure the acceleration of objects because of rectilinear motion, vibration and shock. For gas pressure less than 1 atm, purely electrical techniques are used. Flow sensors are very important in the manufacturing world. Fluid flow through pipes or channels is typically measured by converting the flow information into pressure by restriction or obstruction in the flow system.

In the world of optical sensors there are four photo-detectors: photoconductive, photovoltaic, photo-emissive and photodiode. Each has its special characteristics relative to spectral sensitivity, detectable power and response time. Applications of optical techniques are particularly useful where contact measurement is difficult. Optical encoders play an important role in our industrial life to measure the motion of objects with Incremental encoders and exact position with Absolute encoders.

CONTENTS

1. INTRODUCTION

The component of an instrument that converts an input signal into a quantity that is measured by another part of the instrument and changed into a useful signal for an information-gathering system is called sensor.

There are multiple ways of sensing and estimating just about every physical attribute of the earth, atmosphere, and aircraft. Physical sensors that provide the raw data vary in quality, reliability, and the extent to which their values must be filtered and combined with others to obtain useful estimates.

The second chapter is about thermal sensors. The objective of this chapter stress the understanding required for application of measurement and instrumentation sensors. We shall be able to know about temperature and thermal energy, design the application of an RTD temperature sensor to specific problems in temperature measurements, design the application of thermistor to specific temperature measurement problems, design the application of thermocouples to specific temperature measurement problems, explanation of a bimetal strip for temperature measurement, operation of a gas thermometer and vapor pressure thermometer.

Third chapter is about mechanical sensors. This chapter describes the various types of mechanical sensors. We shall be able to know the definition of relationship among acceleration, velocity and position, design the application of an LVDT to a displacement measurement problem, types of accelerometer and the characteristics of each type, design of a system of strain measurements using metal foil strain gauges, definition of two types of pressure measurements with electrical signal output and system of flow measurements using differential pressure measurement.

The Fourth chapter is about optical sensors. This chapter describes the EM radiation in terms of frequency and spectrum, comparison of photoconductive, photovoltaic and photo-emissive type photo-detectors, incandescent and laser light sources by the characteristics of their light and design of the application of optical techniques to process-control measurement application.

2. THERMAL SENSORS

2.1 Definition

Process control is a term used to describe any condition, by which a physical quantity is regulated. There is no more widespread evidence of such control than that associated with temperature and other thermal phenomena. In our natural surrounding, some of the most remarkable techniques of temperature regulation are found in the bodily functions of living creatures. On the artificial side, humans have been vitally concerned with temperature control since the first fire waves struck for warmth. Industrial temperature regulation has always been of paramount important and becomes even more so the advance of technology. In this chapter we shall be concerned first with developing an understanding of the principles of the thermal energy and temperature and then with developing a working knowledge of the various thermal sensors employed for temperature measurements.

2.2 Temperature

If we are to measure the thermal energy, we must have some sort of units by which to classify the measurement. The original units used were "hot" and "cold". These were satisfactory for their time but are inadequate for modern use. The proper unit for energy measurement is the Joules of the sample in the SI system, but this would depend on the size of the material so it would indicate the total thermal energy.

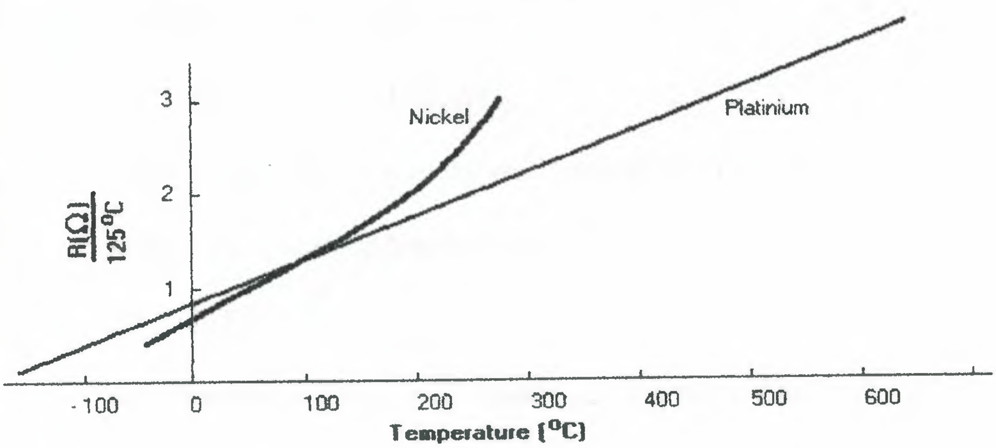


Figure 2.1: Metal resistance increases almost linearly with temperature but the slope is very small.

2.3 Resistance versus Temperature Approximation

An approximation of the resistance versus temperature curves of figure 2.1 shows that the curves are very nearly linear, that is, a straight line. In fact, when only short temperature spans are considered, the linearity is even evident. This fact is employed to develop approximate analytical equation for the resistance versus temperature of a particular metal.

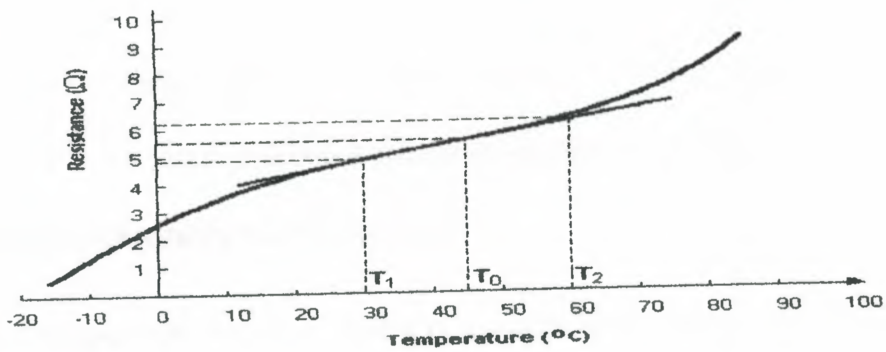


Figure 2.2: Line represents a linear approximation of resistance versus temperature between T_1 and T_2.

Linear Approximation

A linear approximation means that we may develop an equation for a straight line that approximates the resistance versus temperature (R-T) curve over some specified span. In the figure 2.2, we see a typical R-T curve of some material that represent temperature T_1 and T_2 as shown, and T_0 represents the midpoint temperature. The equation of this straight line is the linear approximation to the curve over a span T_1 to T_2 is written as:

$$R(T) = R(T_0)\,[1+\alpha_0\,\Delta T\,] \qquad T_1 < T < T_2$$

Where, $R(T)$ = Approximation of the resistance at temperature T

$R(T_0)$ = Resistance at temperature T_0

$\Delta T = T - T_0$

α_0 = Fractional change in resistance per degree of temperature at T_0

$$\alpha_0 = \frac{1}{R(T)}\,(\text{slope at } T_0)$$

Quadratic Approximation

A quadratic approximation to the R-T curve is more nearly accurate representation of R-T curve over some span of temperature. It includes both a linear term, as before, and a term that varies as the square of the temperature. Such an analytical approximation is usually written as:

$$R(T) = R(T_0)\,[1+\alpha_1\,\Delta T + \alpha_2\,(\Delta T)^2]$$

Where, α_1 = Linear fractional change in resistance with temperature

α_2 = Quadratic fractional change in resistance with temperature

2.4 Resistance-Temperature Detectors

A resistance temperature detector (RTD) is a temperature sensor that is based on the principle, that is, Metal resistance increases with temperature. Metals used in these devices vary from Platinum, which is very repeatable, quite sensitive and very expensive, to Nickel, which is not quite as repeatable, more sensitive and less expensive.

Sensitivity

An estimate of RTD sensitivity can be noted from typical values of α_0. For Platinum, this number is typically on the order of 0.004/ ^{0}C, and for Nickel a typical value is 0.005/ ^{0}C. Thus with platinum, for example, a change of 0.4Ω would be expressed for a 100Ω RTD if the temperature is changed by 1 ^{0}C. Usually a specification will provide the calibrated information either as a graph of resistance versus temperature or as a table of values from which the sensitivity can be determined.

Response Time

In general, RTD has a response time of 0.5 to 5 seconds or more. The slowness of response is due principally to the slowness of thermal conductivity in bringing the devices into thermal equilibrium with its environment. Generally, time constants are specified either for a "free air" condition (or its equivalent) or an "oil bath" condition (or its equivalent). In the

former case, there is poor thermal contact and hence slow response, and in the latter, good thermal contact and fast response. These numbers yield a range of response times depending on the application.

Construction

An RTD, of course, is simply a length of wire whose resistance is to be monitored as a function of temperature. The construction is typically such that the wire is wound on a form (in a coil) to achieve small size and improve thermal conductivity to decrease response time. In many cases, the coil is protected from the environment by the sheath or protective tube that inevitably increases response time but may be necessary in the hostile environments. A loosely applied standard sets the resistance at multiples of 100Ω for the temperature of 0 ^{0}C.

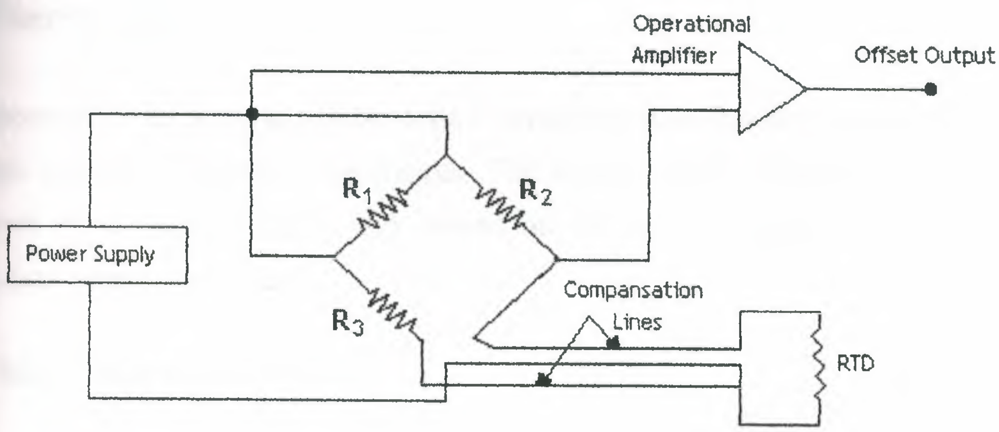


Figure 2.3: Note the compensation lines in this typical RTD signal conditioning circuit.

Signal Conditioning

In view of the very small fractional changes of resistance with temperature (0.4%), the RTD is generally used in a bridge circuit. Figure 2.3 illustrates the essential features of such a system. The compensation line in the R_3 leg of the bridge is required when lead lengths are so long that thermal gradients along the RTD leg may cause changes in line resistance. These changes show up as false information, suggesting changes in RTD resistance. By

using the compensation line, the same resistance changes also appear on the R_3 side of the bridge and cause no net shift in the bridge null.

Dissipation Constant

Because the RTD is a resistance, there is an I^2R power dissipated by the device itself that causes a slight heating effect, self-heating. This may also cause an erroneous reading or even upset the environment in delicate measurement conditions. Thus the current though the RTD must be kept sufficiently low and constant to avoid self-heating. Typically, dissipation constant is provided in RTD specifications. This number relates the power required to raise the RTD temperature by one degree of temperature. Thus, 25mW / ^{0}C dissipation constant shows that if I^2R power losses in the RTD equal to 25mW, then the RTD will be heated by 1^{0}C.

2.5 Thermistors

The thermistor represents to another class of temperature sensors that measures temperature through changes of material resistances. The characteristics of these devices are very different from those of RTDs and depend on the peculiar behavior of semiconductor resistances versus temperature.

2.5.1 Thermistor Characteristics

A thermistor is a temperature sensor that has been developed from the principles of semiconductor resistance change with temperature. The particular semiconductor material used varies widely to accommodate temperature ranges, sensitivity, resistance ranges and other factors. The devises are usually mass produced for a particular configuration and tables or graphs of resistance versus temperature are provided for calibration.

Sensitivity

The sensitivity of the thermistor is a significant factor in the application. Changes in resistance of 10% per ^{0}C are not uncommon. Thus, a thermistor with a nominal resistance of 10 KΩ at some temperature may change by 1 KΩ for a 1^{0}C change in temperature.

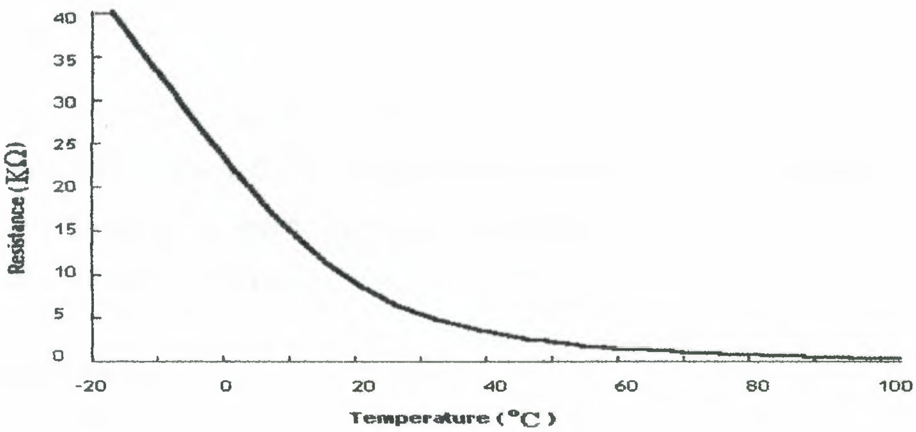


Figure 2.4: Thermistor resistance versus temperature is highly nonlinear and usually has a negative slope.

Construction

Because the thermistor is a bulk semiconductor, it can be fabricated in many forms. Thus, common forms include discs, beads and rods, varying in size from a bead of 1mm to a disc of several centimeters in diameter and several centimeters thick. By variation of doping and use of different semiconductor material, a manufacturer can provide a wide range of resistance values at any particular temperature.

Range

The temperature range of thermistor depends on the material used to construct the sensor. In general, there are three range limitation effects:

1. Melting or deterioration of the semiconductor
2. Deterioration of encapsulation material
3. Insensitivity at higher temperatures

The semiconductor material melts or deteriorates as the temperature is raised. This condition generally limits the upper temperature to less than 300 ^{0}C. At the low end, the principle limitation is that the thermistor resistance becomes very high, into the MΩ's, making practical applications difficult. For thermistor shown in figure 2.4, if extended, the lower limit is about -80^{0}C, where its resistance has risen to over 3MΩ! Generally the lower limit is -50^{0}C to -100^{0}C.

Response Time

The response time of the thermistor depends principally on the quantity of material present and the environment. Thus, for the smallest bead thermistor in an oil bath (good thermal contact), a response of ½ second is typical. The same thermistor in still air will respond with typical response of 10seconds.

Signal Conditioning

Because a thermistor exhibits such a large change in resistance with temperature, there are many circuit applications. In many cases, however, a bridge circuit is used because the nonlinear features of the thermistors make it difficult as an actual measurement device. Because these devices are resistances, care must be taken to ensure that power dissipation in the thermistor does not exceed limits specified or even interfere with the environment for which the temperature is being measured. Dissipation constants are quoted for thermistors as the power in milli-watts required to raise a thermistor's temperature 1^0C above its environment.

2.6 Thermocouples

In previous section we have considered the change in material resistance as a function of temperature. Such a resistance change is considered a variable parameter property in the sense that the measurement of resistance, and thereby temperature, requires external power resources. There exists another dependence of electrical behavior of materials on temperature that forms the basis of a large percentage of all temperature measurements. This effect is characterized by a voltage-generating sensor in which an electromotive force (emf) is produced that is proportional to temperature. Such an emf is found to be almost linear with temperature and very repeatable for constant materials. Devices that measure temperature on the basis of this thermoelectric principle are called thermocouples (TCs).

2.6.1 Thermoelectric Effect

The basic theory of the thermocouple effect is found from a consideration of the electrical

and thermal transport properties of different metals. In particular, when a temperature differential is maintained across a given metal, the vibration of atoms and motion of electrons is affected so that a difference in potential exists across the material. This potential difference is related to the fact that electrons in the hotter end of material have more thermal energy than those in the cooler end, and thus tend to drift toward the cooler end. This drift varies for different metals at the same temperature because of differences in their thermal conductivities. If a circuit is closed by connecting the ends through another conductor, a current is found to flow on the closed loop.

The proper description of such an effect is to say that an emf has been established in the circuit that is causing the current to flow. In figure 2.5a, we see a pictorial representation of this effect where two different metals A and B are used to close the loop with the connecting junctions at temperature T_1 and T_2.

We could not close the loop with the same metal because the potential differences across each leg would be the same, and thus no net emf would be present. The emf produced is proportional to the difference in temperature between the two junctions. Theoretical treatments of this problem involve the thermal activities of the two metals.

Seebeck Effect

Using solid state theory, the aforementioned situation may be analyzed to show that its emf can be given by integration over temperature

$$\varepsilon = \int_{T_2}^{T_1} (Q_A - Q_B)dt$$

Where, ε = emf produced in volts

T_1, T_2 = junction temperature in K

Q_A, Q_B = thermal transport constants of the two metals

This equation, which describes the Seebeck effect, shows that the emf produced is proportional to the difference in temperature and, further, to the difference in the metallic thermal transport constants.

Thus, if the metals are the same, the emf is zero, and if the temperature is also same, the emf is also zero. In practice it is found that the two constants Q_A *and* Q_B are nearly independent of temperature and that an approximate linear relationship exits as

$$\varepsilon = \alpha\,(T_2 - T_1)$$

Where α is a constant in volts/K

However, the small but finite temperature dependence of Q_A *and* Q_B is necessary for accurate consideration.

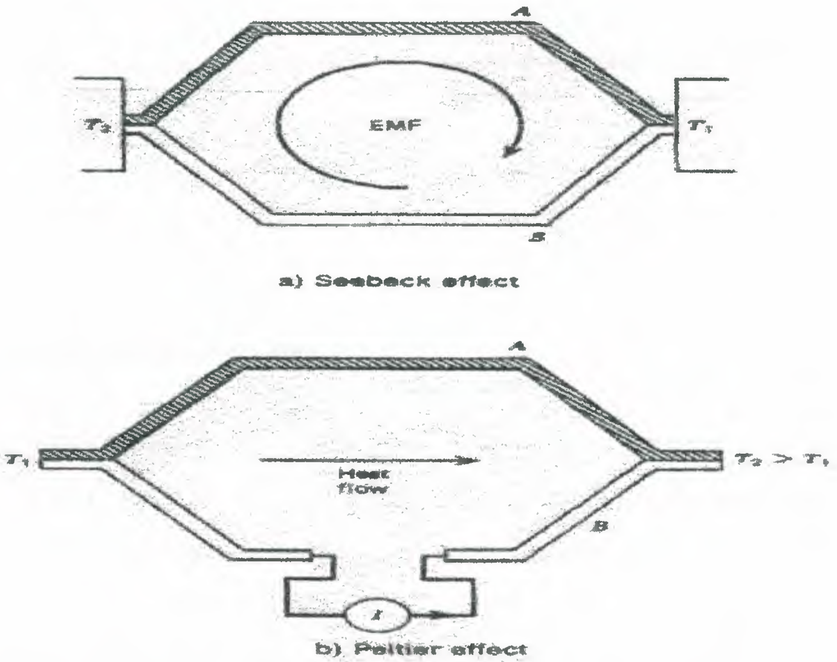


Figure 2. 5: The seebeck and peltier effects refer to the relation between emf and temperature in a two wire system.

Peltier Effect

An interesting and sometimes useful extension of the same thermoelectric properties occurs when the reverse of Seebeck effect is considered. In this case, we construct a closed loop of two different metals, A and B, as before. However, an external voltage is applied to the system to cause a current to flow in the circuit as shown in figure 2.5b. Because of the

different electro-thermal transport properties of the metals, it is found that one of the junctions will be heated and the other cooled; that is, the device is a refrigerator! This process is referred to as the Peltier effect. Some practical applications of such device, such as cooling small electronic parts, have been employed.

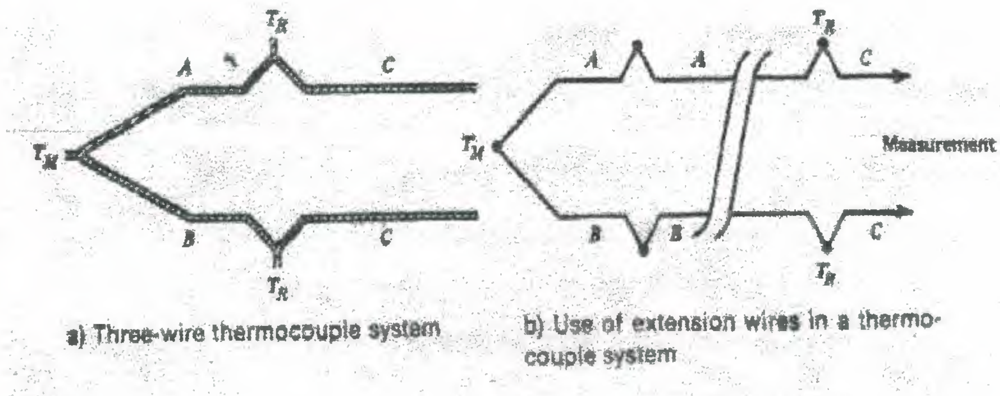


Figure 2.6: Practical measurements with a thermocouple system often employ extension wires to move the reference to a more secure location.

2.6.2 Thermocouple Characteristics

To use the Seebeck effect as the basis of a temperature sensor, we need to establish a definite relationship between the measured emf of the thermocouple and the unknown temperature. We see first that one temperature must already be known because the Seebeck voltage is proportional to the difference between the junction temperatures. Furthermore, every connection of different metals made in the thermocouple loop for measuring devices, extension leads, and so on will contribute an emf, depending on the difference in metals and various junction temperatures. To provide an output it is definite with respect to the temperature to be measured, an arrangement such as that shown in figure 2.6a is used. This shows that the measurement junction T_M is exposed to the environment whose temperature is to be measured. This junction is form of metals A and B as shown.

Two other junctions then are formed to a common metal C, which then connects to the measurement apparatus. The reference junctions are held at a common, known temperature T_R, the reference junction temperature. When an emf is measured, such problem as voltage

drops across resistive elements in the loop must be considered. In this arrangement, an open circuit voltage is measured (at high impedance) that is then a function of only the temperature difference ($T_M - T_R$) and the type of metal A and B. The voltage produced has a magnitude of the temperature difference and a polarity depend on the absolute magnitude of the temperature difference and a polarity dependant on which temperature is larger, reference or measurement junction. Thus, it is not necessary that the measurement junction have a higher temperature than the reference junctions, but both magnitude and sign of measured voltage must be noted.

To use the thermocouple to measure a temperature, the reference temperature must be known and the reference junctions must be held at the same temperature. The temperature must be constant, or at least not very much. In most industrial environments this would be difficult to achieve if the measurement junction and reference junction were close. It is possible to move the reference junction to a remote location without upsetting the measurement process by the use of extension wires, as shown in figure 2.6b. A junction is formed with the measurement system, but to wires of the same type as the thermocouple. These wires may be stranded and of different gauges, but they must be of the same type of metal as the thermocouple. The extension wires now can be run a significant distance to the actual reference junction.

2.6.3 Thermocouple Sensors

The use of a thermocouple for a temperature sensor has evolved from an elementary process with crudely prepared thermocouple constituents into a precise and exacting technique.

Sensitivity

Typically the range of the thermocouple voltages is less than 100mV. The actual sensitivity strongly depends on the type of the signal conditioning employed and on the TC itself.

Construction

A thermocouple by itself is, of course, simply a welded or even a twisted junction between

two metals, and in many cases that is the construction. There are cases, however, where the TC is sheathed in a protective covering or even sealed in the glass to protect the unit from a hostile environment. The size of the TC wire is determined by the application and can range from 0.02mm micro-wire in refined biological measurements of temperature.

Response

Thermocouple time response is simply related to the size of the wire and any protective material used with the sensor. The time response equates to how long it takes the TC system to reach thermal equilibrium with the environment.

Large industrial TCs using thick wire or encased in stainless steel sheathing may have time constants as high as 10to 20 seconds. On the other hand, a TC made from very small gauge wire can have a time constant as small as 10 to 20ms. Often the time constant is specified under conditions of good thermal contact and poor thermal contact as well, so that you can account for the environment.

Signal Conditioning

The key element in the use of thermocouples is that the output voltage is very small, typically less than 50mV. This means that considerable amplification will be necessary for practical application; in addition the small signal levels make the devices susceptible to electrical noise. In most cases the thermocouple is used with a high gain differential amplifier.

Noise

Perhaps the biggest obstacle to the use of the thermocouple for temperature measurement in Industry is their susceptibility to electrical noise. First, the voltages generated are less than 50mV, and often are 2 or 3mV, and in the industrial environment it is common to have hundreds of mill volts of electrical noise generated by large electrical machines in any electrical system. Second, a thermocouple constitutes an excellent antenna for pickup of noise from electromagnetic radiation in the radio, TV and microwave bands. In short, a

bare thermocouple may have many times more noise than temperature signal at a given time.

To use thermocouples effectively in industry, a number of noise reduction techniques are employed. The following three are the most popular:

The extension or lead wires from the thermocouple to the reference junction or measurement system are twisted ad them wrapped with a grounded foil sheath.

The measurement junction itself is grounded at the point of measurement. The grounding is typically to the inside of the stainless steel sheath that covers the actual thermocouple.

An instrumentation amplifier that has excellent common mode rejection is employed for measurement.

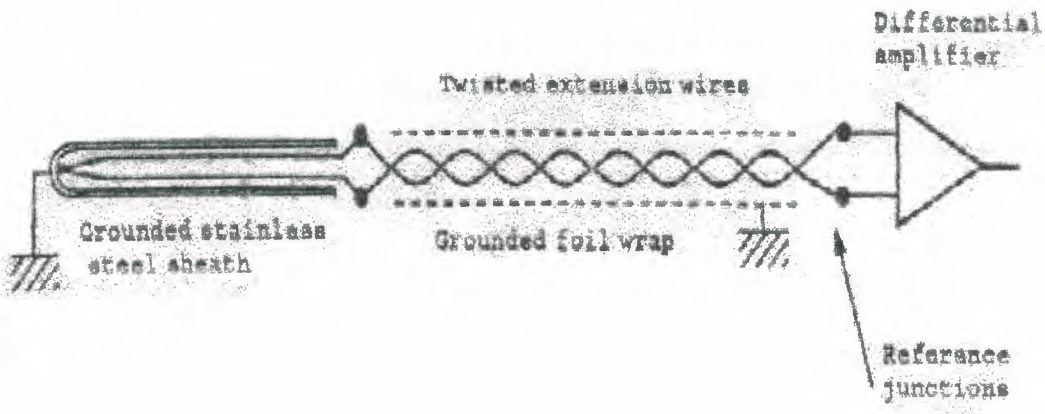


Figure 2.7: Since TC voltages are small, great care must be taken to protect against electrical noise such as by shielding, twisting, and differential amplification.

Figure 2.7 shows a typical arrangement for measurement with a thermocouple. Note that the junction itself is grounded through the stainless steel sheath. The differential amplifier must have very good common mode rejection to aid in the noise rejection process.

The advantages of grounding the measurement junction is that the noise voltage will be distributed equally on each wire of TC. Then the differential amplifier will, at least partially, cancel this noise because the voltage on these lines is subtracted.

Twisting is done to decouple the wires from induced voltages from varying electric and magnetic fields that permeate our environment. In principle, equal voltages are induced in each loop of the twisted wires but of opposite phase, so they cancel.

2.7 Bimetallic Strips

This type of the temperature sensor has the characteristics of being relatively inaccurate, having hysteresis, having relatively slow response time, and being low in cost. Such devices are use in numerous applications, particularly where an ON/OFF cycle rather than smooth or continuous control is described.

2.7.1 Thermal Expansion

We have seen that greater thermal energy causes the molecules of the solids to execute the greater amplitude and higher frequency vibrations about their average positions. It is natural to expect that an expansion of volume of a solid would accompany this effect, as the molecules tend to occupy more volume on the average with their vibrations. This effect varies in degree from material to material because of many factors, including molecular size and weight, lattice structure and others.

If we have a rod of length L_o at temperature T_o and the temperature is raised to a new value T, then the rod will be found to have new length L, given by:

$$L = L_0 [1 + \gamma \Delta T]$$

Where, γ is the linear thermal expansion coefficient appropriate to the material of which the rod is made.

2.7.2 Bimetallic Sensor

The thermal sensor exploiting the effect discussed previously occurs when two materials with grossly different thermal expansion coefficients are bounded together. Thus, when heated, the different expansion rates cause the assembly curve shown in figure 2.8. This effect can be used to close the switch contact or to actuate an ON/OFF mechanism when

the temperature increases to some appropriate set point. This effect also is used for temperature indicators, by means of assemblages, to convert the curvature into dial rotation.

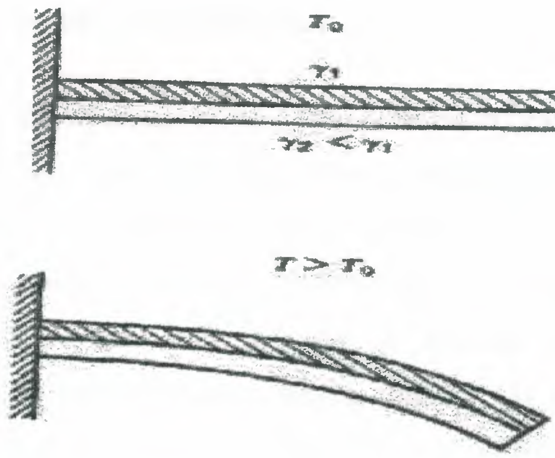


Figure 2.8: A bimetallic strip will curve when exposed to a temperature change because of differential thermal expansion coefficients. Metal thickness has been exaggerated in this figure.

2.8 Gas Thermometers

The operational principle of the gas thermometer is based on a basic law of gases. In particular, if a gas is kept in a container at constant volume and the pressure and temperature vary, then the ratio of gas pressure and temperature is a constant.

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Where, P_1, T_1 = Absolute pressure and temperature (in K) in state 1

P_2, T_2 = Absolute pressure and temperature (in K) in state 2

Because the gas thermometer converts temperature information directly into pressure signal, it is particularly useful in pneumatic systems. Such transducers are also advantageous because they are not moving parts and no electric stimulation is necessary. For electronic analog or digital process control applications, however, it is necessary system for converting the pressure to electrical signals. This type of sensor is often used with bourdon tubes to produce directly indicating temperature meter and recorders. The gas

most commonly employed is Nitrogen. Time response is slow in relation to the electrical devices because of the greater mass that must be heated.

2.9 Vapor-pressure Thermometers

A vapor pressure thermometer converts temperature information into pressure as does the gas thermometer, but it operates by the different process. If a closed vessel is partially filled with liquid, then the space above the liquid will consist of evaporated vapor of the liquid at a pressure that depends on the temperature. If the temperature is raised, more liquid will vaporize and the pressure will increase. A decrease in temperature will result in condensation of some of the vapor, and the pressure will decrease. Thus, vapor pressure depends on temperature. Different materials have different curves of pressure versus temperature, and there is no simple equation like that for a gas thermometer. Figure 2.9 shows a curve a curve of vapor pressure versus temperature for methyl chloride, which is often employed in these sensors. The pressure available is substantial as the temperature rises. As in case of gas thermometers, the range is not great and response time is slow (20 seconds or more) because the liquid and vessel must be heated.

2.10 Liquid expansion Thermometers

Just as solid experiences an expansion in dimension with temperature, a liquid also shows an expansion in volume with temperature. This effect forms the basis for the traditional liquid-in-glass thermometers that are so common in temperature measurement. The relationship that governs the operation of this device is:

$$V(T) = V(T_0)[1 + \beta \, \Delta T]$$

Where, V(T) = volume at temperature T

$V(T_0)$ = volume at temperature T_0

β = volume thermal expansion constant

In actual practice, the expansion effects of the glass container must be accounted for to obtain high accuracy in temperature indications. This type of temperature sensor is not

commonly used in process control work because further transduction is necessary to convert the indicated temperature into an electrical signal.

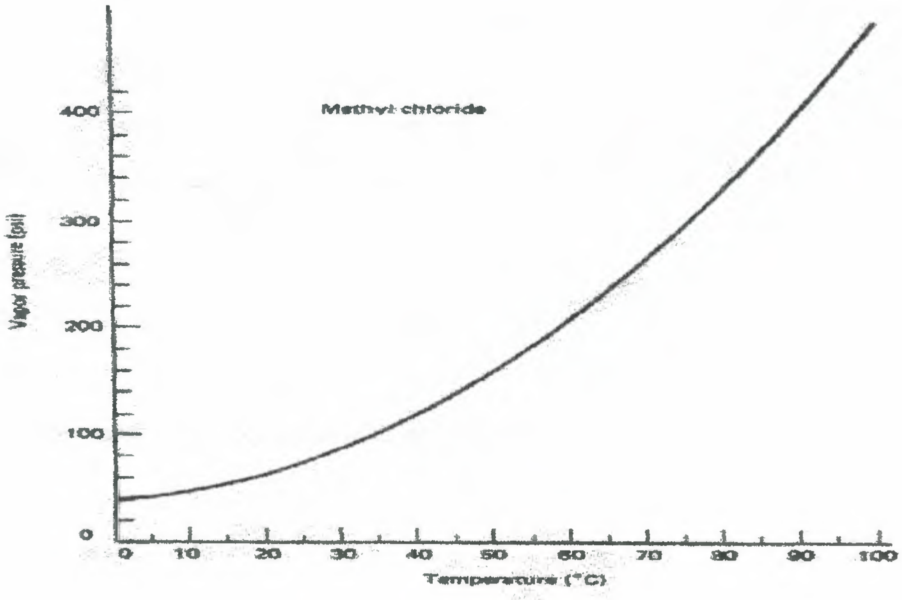


Figure 2.9: Vapor pressure curve for Methyl chloride.

2.11 Solid State Temperature Sensors

Many integrated manufacturers now market solid state temperature sensors for consumer and industrial applications. These devices offer voltages that vary linearly with temperature over a specified range. The operating temperature of these sensors is typically in the range of -50 °C to 150 °C. The time constant in good thermal contact varies in the range of 1 to 5 seconds, whereas in poor thermal contact it may increase to 60 seconds or more.

These sensors are easy to interface to control systems and computers, and are becoming popular for measurement within the somewhat limited range they offer. An important application is to provide automatic reference temperature compensation for thermocoupler. This is provided by connecting the sensors to the reference junction block of the TC and providing signal conditioning so that the reference corrections are automatically provided to the TC output, as shown in figure 2.10.

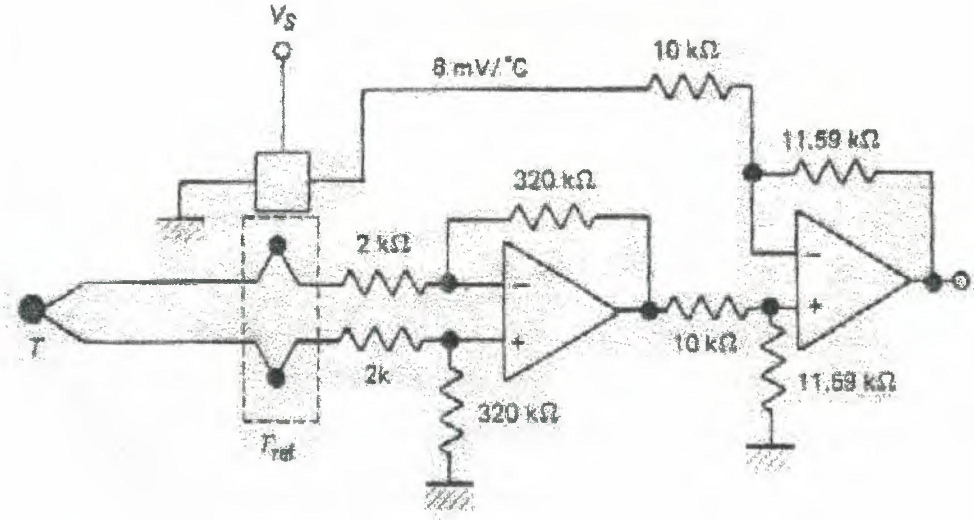


Figure 2.10: It shows the circuit diagram of solid state thermal sensor.

3. MECHANICAL SENSORS

3.1 Introduction

The class of sensors used for the measurement of mechanical phenomena is of special significance because of the extensive use of these devices through out the process control industry. In many instances, an interrelation exists by which a sensor designed to measure some mechanical variable is used to measure another variable. To learn to use the mechanical sensors, it is important to understand the mechanical phenomena themselves and the operating principles and application details of the sensors.

3.2 Displacement, Location or Position Sensors

The measurement of displacement, position or location is an important topic in the process industries. Examples of industrial requirements to measure these variables are many and varied and the required sensors are also of greatly varied designs. To give a few examples of measurement needs:

1. Location and position of objects on a conveyer system
2. Orientation of steel plates in a rolling mill
3. Liquid or solid level measurements
4. Location and position of work piece in automatic milling operation
5. Conversion of pressure to a physical displacement

3.2.1 Potentiometric

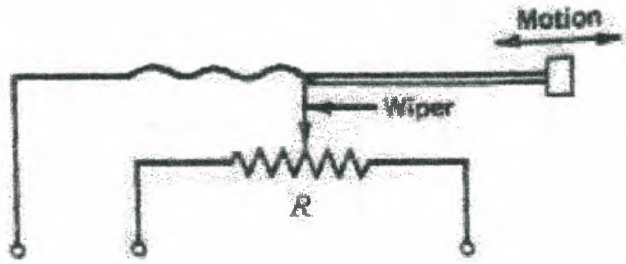


Figure 3.1: Potentiometric displacement sensor.

The simplest type of displacement sensor involves the action of displacement in moving the wiper of a potentiometer. This device then converts linear or angular motion into a changing resistance that may be converted directly to voltage and/or current signals. Such potentiometric device often suffer from the obvious problems of mechanical wear, friction in wiper action, limited resolution in wire-wound units and high electronic noise.

3.2.2 Capacitive and Inductive

The second class of sensors for displacement measurement involves changes in capacity and inductance.

Capacitive

The basic operation of a capacitive sensor can be seen from the familiar equation for a parallel-plate capacitor.

$$C = K\varepsilon_o \frac{A}{d}$$

Where, K= The dielectric constant

ε_o= Permittivity = 8.85 pF/m

A= Plate common area

d= Plate separation

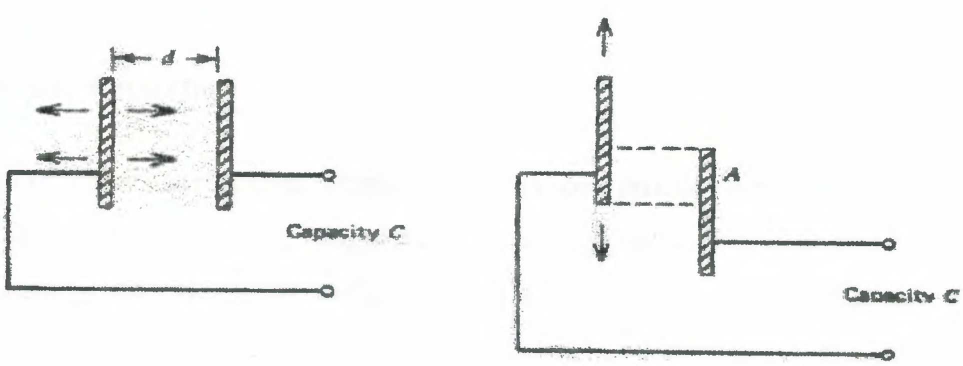


Figure 3.2: Capacity varies with distance between plates and common area. Both are used in sensors.

There are three ways to change the capacity:

- Variation of distance between the plates (d)
- Variation of shared area of the plates (A)
- Variation of the dielectric constant (K)

Inductive

If a permeable core is inserted into an inductor as shown in figure 3.3, the net inductance is increased. Every new position of the core produces a different inductance. In this fashion, the inductor and movable core assembly may be used as a displacement sensor. An AC bridge or other active electronic circuit sensitive to inductance then may be employed for signal conditioning.

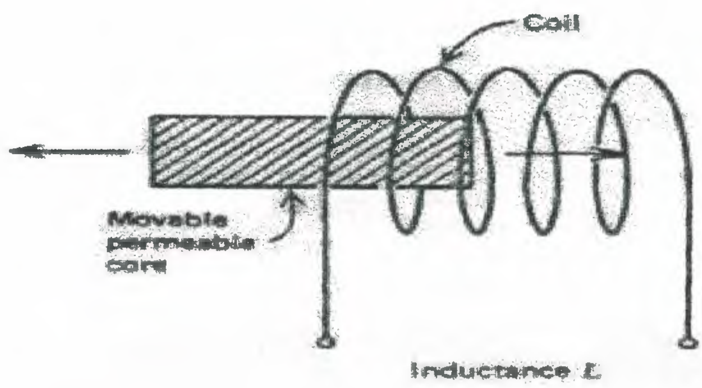


Figure 3.3: The variable reluctance displacement sensor changes the inductance in coil in response to core motion.

3.2.3 Variable Reluctance

The class of variable-reluctance displacement sensors differs from the inductive in that moving core is used to vary the magnetic flux coupling between two or more coils, rather than changing am individual inductance. Such devices find application in many circumstances for the measure of both translational and angular displacements. Many configurations of these devices exist, but the most common and extensively used is called a linear variable differential transformer (LVDT).

3.2.3.1 LVDT

The LVDT is an important and common sensor for displacement in the industrial environment. Figure 3.4 shows that an LVDT consists of three coils of wire wounded on a hollow form. A core of permeable material can slide freely through the centre of the form. Flux formed by the primary, which is excited by some AC source as shown. Flux formed by the primary is linked to the two secondary coils, inducing an AC voltage in each coil.

When the core is centrally located in assembly, the voltage induces in each primary is equal. If the core moves to one slide or the other, a larger AC voltage will be induced in one coil and a smaller AC voltage in the other because of changes in the flux linkage associated with the core as shown in figure 3.4.

When the core centrally located, the net voltage is zero. When the core is moved to one side, the net voltage amplitude will increase. In addition, there is a change in phase with respect to the source when the core is moved to one side or the other.

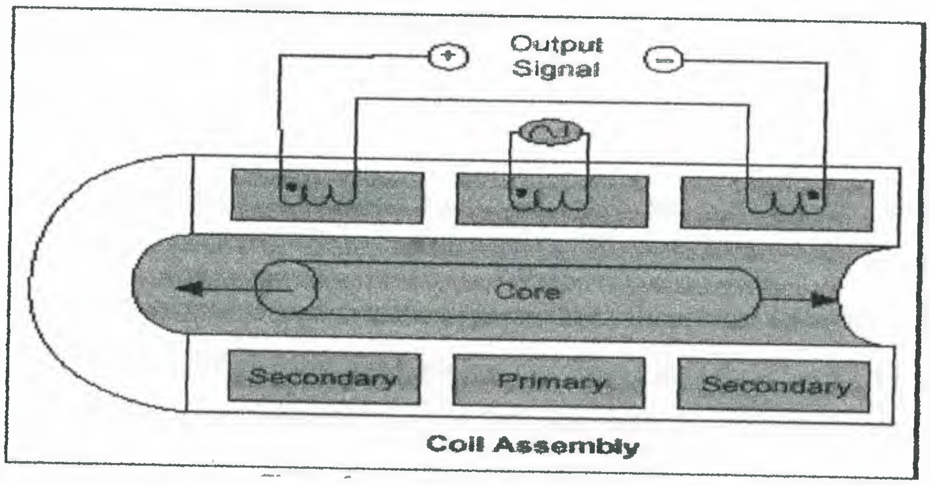


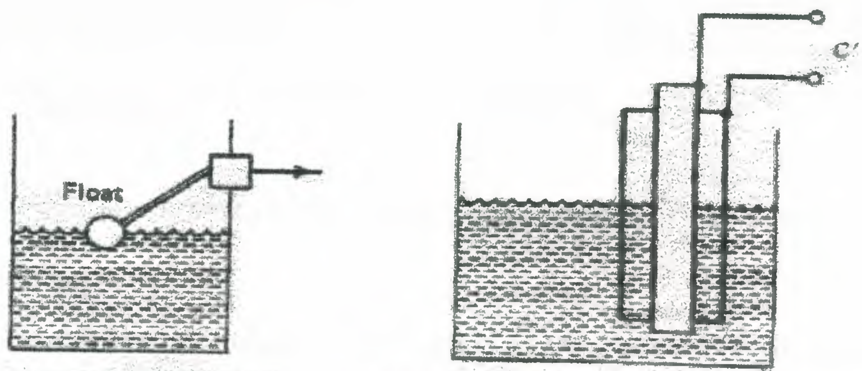
Figure 3.4: The LVDT has a movable core with three coils.

3.2.4 Level Sensors

The measurement of solid or liquid level calls for a special class of displacement sensor. The level measured is most commonly associated with material in a tank or hopper. A great variety of measurement techniques exists, as the following representative examples show.

Mechanical

One of the most common techniques for level measurement, particularly for liquids, is a float that is allowed to ride up and down with level changes. This float, as shown in figure 3.5a, is connected by linkage to a secondary displacement measuring system such as potentiometric device or an LVDT core.



a) Level measurement by a float and linkage

b) Level measurement by a concentric cylindrical capacitor

Figure 3.5: There are many level measurement techniques.

Electrical

They are several purely electrical methods of measuring level. For example, one may use the inherent conductivity of a liquid or solid to vary the resistance seen by the probes inserted into the material. Another common technique is illustrated in figure 3.5b. In this case, two concentric cylinders are contained in a liquid tank. The level of the liquid partially occupies the space between the parallel, one with the dielectric constant of air (≈ 1) and the other with that of the liquid. Thus, variation of liquid level causes variation of the electrical capacity measured between the cylinders.

Ultrasonic

The use of the ultrasonic reflection to measure level is favored because it is a non-sensitive technique; that is, it does not involve placing anything in the material. Figure 3.6 shows the external and internal techniques.

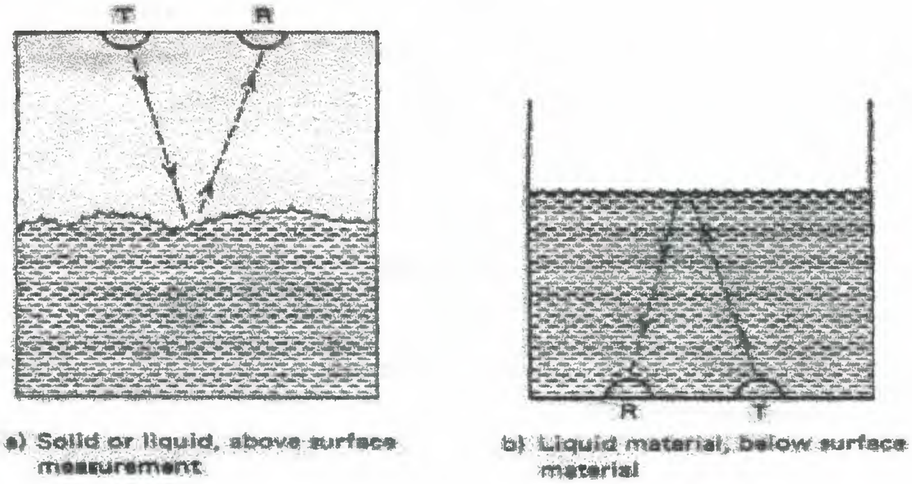


Figure 3.6: Ultrasonic measurement needs no physical contact with material, just a transmitter T and receiver R.

Obviously, the external technique is better suited to solid material level material. In both cases the measurement depends on the length of time taken for reflections of an ultrasonic pulse from the surface of the material. Ultrasonic techniques based on reflection time also have become popular for ranging measurements.

Pressure

For liquid measurement, it is also possible to make a no contact measurement of level if the density of the liquid is known. This method based on the well-known relationship between pressure at the bottom of a tank and the height and density of the liquid.

3.3 Strain Sensors

Although not obvious at first, the measurement of strain in solid objects is common in process control. The reason it is not obvious that strain sensors are used as a secondary step in sensors to measure many other process variables, including flow, pressure, weight and acceleration. Strain measurements have been used to measure pressures from over a million pounds per square inch to those within living biological systems. We shall first review the concept of strain and how it is related to the forces that produce it and then discuss the sensors used to measure strain.

3.3.1 Strain and Stress

Strain is the result of the application of force to solid objects. The forces are defined in a special way described by general term, stress.

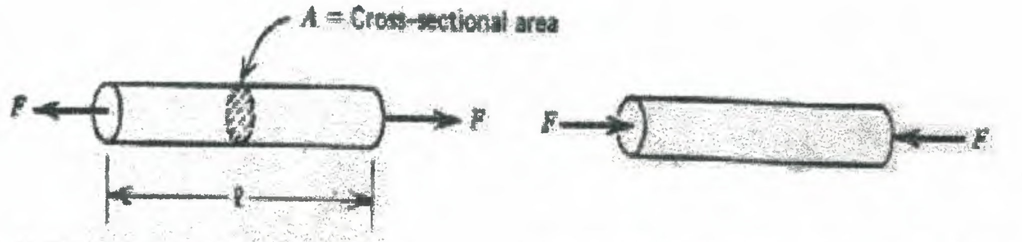


Figure 3.7: Tensile and Compressional stress can be defined in terms of forces applied to a uniform rod.

A special case exists for the relation between force applied to a solid object and the resulting deformation of that object is called strain. Solids are assemblages of atoms in which the atomic spacing has been adjusted to render the solid in equilibrium with all external forces acting on the solid. This spacing determines the physical dimensions of the solid. If the applied forces are changed, the object atoms rearrange themselves again to come into equilibrium with the mew set of forces. This rearrangement results in a change in physical dimensions that is referred to as a deformation of the solid.

The study of this phenomenon has evolved into an exact technology. The effect of applied force is referred to as a stress and the resulting deformation as a strain. To facilitate a proper analytical treatment of the object, stress and the resulting are carefully defined to emphasize the physical properties of the material being stressed and the specific type of stress applied. We delineate here the three most common types of stress-strain relationships.

Tensile stress Strain

In figure 3.7, the nature of a tensile force is shown as a force applied to a sample of material so as to elongate or pull apart sample. In this case, the stress is defined as:

$$Tensile\ stress = \frac{F}{A}$$

Where, F= Applied force in N

A= Cross-sectional area of the sample in m^2

We see that the units of stress are N/m^2 in SI units and they are like a pressure.

The strain in this case is defined as the fractional change in the length of the sample and Strain is unitless quantity.

$$Tensile\ stress = \frac{\Delta L}{L}$$

Compressional stress Strain

The only differences between Compressional and tensile stress are the direction of applied force and the polarity of the change in length. Thus, in a Compressional stress, the force pressed in on a sample, as shown in figure 3.7b.

Shear stress Strain

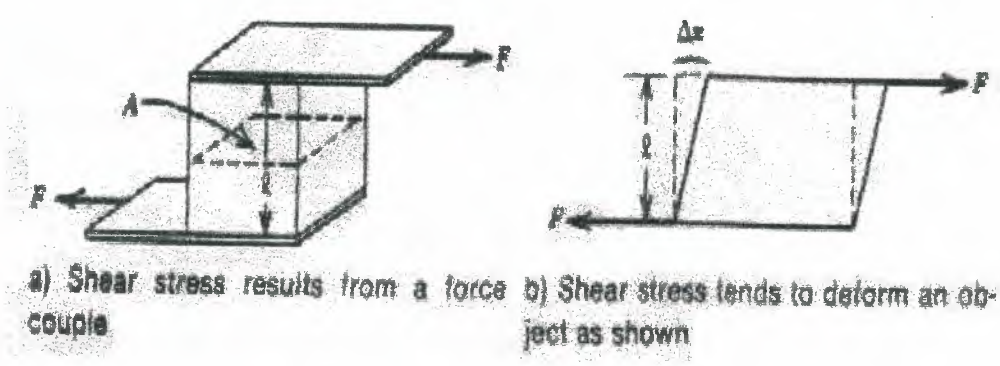


Figure 3.8: Shear stress is defined in terms of a couple that tends to deform a joining member.

Figure 3.8, shows the nature of shear stress. In this case, the force is applied as a couple (that is, not along the same line), tending to shear off the solid object that separates the force arms. In this case the stress is again the same as that of previous sections.

3.3.2 Strain gauge Principle

Metal resistance of a sample is given as:

$$R_o = \rho \frac{L_o}{A_o}$$

Where, R_o= Sample resistance in Ω

ρ = Sample resistivity in Ω-m

L_o= Length in m

A_o= Cross sectional area in m^2

Suppose the sample is now stressed by the application of a force F as shown in figure 3.7a. Then we know that the material elongates by some amount ΔL so that the new length is L= L+ ΔL. It is also true that in such a stress-strain condition, although the sample lengths, its volume will remain nearly constant. Because the volume unstressed V= L_o A_o, it follows that if the volume remains constant and the length increases, then the area must decrease by some amount ΔA:

$$V = L_o A_o = (L_o + \Delta L)(Ao - \Delta A)$$

Because both length and area have changed, we find that the resistance of the sample will have also changed:

$$R = \rho \frac{L_o + \Delta L}{A_o - \Delta A}$$

By combining these two equations, we shall find:

$$R \cong \rho \frac{L_o}{A_o}\left(1 + 2\frac{\Delta L}{L_o}\right)$$

For which we conclude that the change in resistance is:

$$R \cong 2R_o \frac{\Delta L}{L_o}$$

This is the final equation that underlies the use of metal strain gauges because it shows that the strain ΔL/L converts directly into a resistance change.

Measurement Principle

The basic technique of strain gauge (SG) measurement involves attaching (gluing) a metal wire or foil to the element whose strain is to be measured. As stress is applied and the element deforms, the SG material experiences the same deformation, if it is securely attached. Because the strain is a fractional change in length, the change in SG resistance reflects the strain of both the gauge and the element to which it is secured.

Temperature Effects

If not for temperature compensation effects, the aforementioned method of SG measurement would be useless. To see this, we need only note that the metals used in SG construction have linear temperature coefficients of $\alpha \cong 0.004/^{o}C$, typically for most metals. Temperature changes of 1°C are not uncommon in measurement conditions in the industrial environment.

3.3.3 Metal Strain Gauges (SGs)

Metal SGs are devices that operate on the principles discussed earlier. The following items are important to understanding SG applications.

Gauge Factor

Relation between strain and resistance change is approximately true. Impurities in the metal, the type of metal, and other factors lead to slight corrections. An SG specifications always indicates the correct relation through statement of a gauge factor (GF), which is defined as:

$$\text{GF}=\frac{\Delta R/R}{Strain}$$

Where, $\Delta R/R$ = Fractional change in gauge resistance because of strain

NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical and Electronic Engineering

Sensors & Measurements

Graduation Project

EE- 400

Student: Muhammad Rizwan (991226)

Supervisor: Assist. Prof. Dr Kadri Bürüncük

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ABSTRACT

The classes of sensors that perform the control and measurement of temperature are known as thermal sensors. Resistance-temperature detectors, thermistors and Thermocouples are used to develop a voltage which is proportional to the change in temperature. Bimetallic strip converts temperature into a physical motion of metal elements. Gas and vapor-pressure temperature sensors convert temperature into gas pressure, which then is converted to an electrical signal or is used directly in pneumatic system.

Position, location, and displacement sensors include the Potentiometric, capacitive and LVDTs to convert the displacement linearly into voltage. Strain-gauges convert strain into a change of resistance. Accelerometers are used to measure the acceleration of objects because of rectilinear motion, vibration and shock. For gas pressure less than 1 atm, purely electrical techniques are used. Flow sensors are very important in the manufacturing world. Fluid flow through pipes or channels is typically measured by converting the flow information into pressure by restriction or obstruction in the flow system.

In the world of optical sensors there are four photo-detectors: photoconductive, photovoltaic, photo-emissive and photodiode. Each has its special characteristics relative to spectral sensitivity, detectable power and response time. Applications of optical techniques are particularly useful where contact measurement is difficult. Optical encoders play an important role in our industrial life to measure the motion of objects with Incremental encoders and exact position with Absolute encoders.

CONTENTS

1. INTRODUCTION

The component of an instrument that converts an input signal into a quantity that is measured by another part of the instrument and changed into a useful signal for an information-gathering system is called sensor.

There are multiple ways of sensing and estimating just about every physical attribute of the earth, atmosphere, and aircraft. Physical sensors that provide the raw data vary in quality, reliability, and the extent to which their values must be filtered and combined with others to obtain useful estimates.

The second chapter is about thermal sensors. The objective of this chapter stress the understanding required for application of measurement and instrumentation sensors. We shall be able to know about temperature and thermal energy, design the application of an RTD temperature sensor to specific problems in temperature measurements, design the application of thermistor to specific temperature measurement problems, design the application of thermocouples to specific temperature measurement problems, explanation of a bimetal strip for temperature measurement, operation of a gas thermometer and vapor pressure thermometer.

Third chapter is about mechanical sensors. This chapter describes the various types of mechanical sensors. We shall be able to know the definition of relationship among acceleration, velocity and position, design the application of an LVDT to a displacement measurement problem, types of accelerometer and the characteristics of each type, design of a system of strain measurements using metal foil strain gauges, definition of two types of pressure measurements with electrical signal output and system of flow measurements using differential pressure measurement.

The Fourth chapter is about optical sensors. This chapter describes the EM radiation in terms of frequency and spectrum, comparison of photoconductive, photovoltaic and photo-emissive type photo-detectors, incandescent and laser light sources by the characteristics of their light and design of the application of optical techniques to process-control measurement application.

2. THERMAL SENSORS

2.1 Definition

Process control is a term used to describe any condition, by which a physical quantity is regulated. There is no more widespread evidence of such control than that associated with temperature and other thermal phenomena. In our natural surrounding, some of the most remarkable techniques of temperature regulation are found in the bodily functions of living creatures. On the artificial side, humans have been vitally concerned with temperature control since the first fire waves struck for warmth. Industrial temperature regulation has always been of paramount important and becomes even more so the advance of technology. In this chapter we shall be concerned first with developing an understanding of the principles of the thermal energy and temperature and then with developing a working knowledge of the various thermal sensors employed for temperature measurements.

2.2 Temperature

If we are to measure the thermal energy, we must have some sort of units by which to classify the measurement. The original units used were “hot” and “cold”. These were satisfactory for their time but are inadequate for modern use. The proper unit for energy measurement is the Joules of the sample in the SI system, but this would depend on the size of the material so it would indicate the total thermal energy.

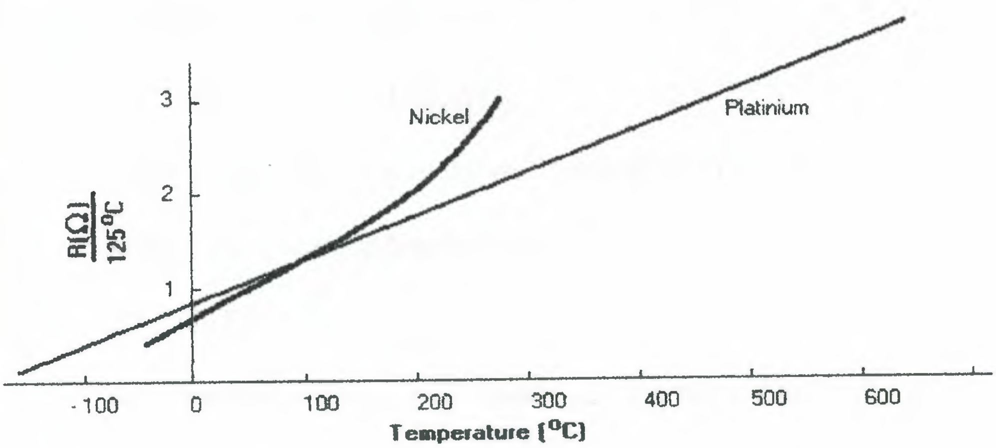

Figure 2.1: Metal resistance increases almost linearly with temperature but the slope is very small.

2.3 Resistance versus Temperature Approximation

An approximation of the resistance versus temperature curves of figure 2.1 shows that the curves are very nearly linear, that is, a straight line. In fact, when only short temperature spans are considered, the linearity is even evident. This fact is employed to develop approximate analytical equation for the resistance versus temperature of a particular metal.

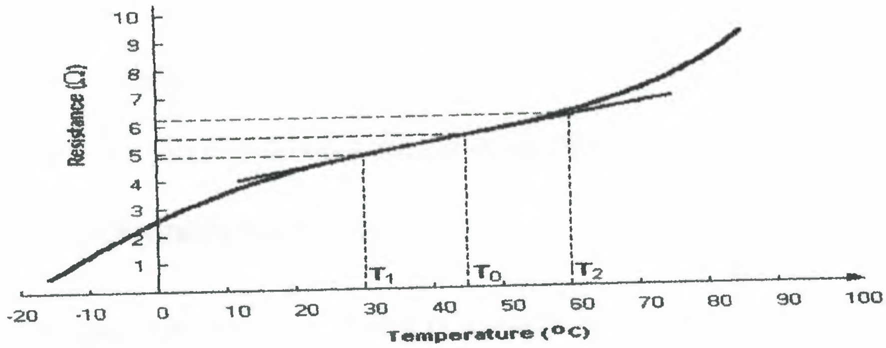

Figure 2.2: Line represents a linear approximation of resistance versus temperature between T_1 and T_2.

Linear Approximation

A linear approximation means that we may develop an equation for a straight line that approximates the resistance versus temperature (R-T) curve over some specified span. In the figure 2.2, we see a typical R-T curve of some material that represent temperature T_1 and T_2 as shown, and T_0 represents the midpoint temperature. The equation of this straight line is the linear approximation to the curve over a span T_1 to T_2 is written as:

$$R(T) = R(T_0)\,[1+\alpha_0\,\Delta T\,] \qquad T_1 < T < T_2$$

Where, $R(T)$ = Approximation of the resistance at temperature T

$R(T_0)$ = Resistance at temperature T_0

$\Delta T = T - T_0$

α_0 = Fractional change in resistance per degree of temperature at T_0

$$\alpha_0 = \frac{1}{R(T)}\,(\text{slope at } T_0)$$

Quadratic Approximation

A quadratic approximation to the R-T curve is more nearly accurate representation of R-T curve over some span of temperature. It includes both a linear term, as before, and a term that varies as the square of the temperature. Such an analytical approximation is usually written as:

$$R(T) = R(T_0)\,[1+\alpha_1\,\Delta T + \alpha_2\,(\Delta T)^2]$$

Where, α_1 = Linear fractional change in resistance with temperature

α_2 = Quadratic fractional change in resistance with temperature

2.4 Resistance-Temperature Detectors

A resistance temperature detector (RTD) is a temperature sensor that is based on the principle, that is, Metal resistance increases with temperature. Metals used in these devices vary from Platinum, which is very repeatable, quite sensitive and very expensive, to Nickel, which is not quite as repeatable, more sensitive and less expensive.

Sensitivity

An estimate of RTD sensitivity can be noted from typical values of α_0. For Platinum, this number is typically on the order of 0.004/ ^{0}C, and for Nickel a typical value is 0.005/ ^{0}C. Thus with platinum, for example, a change of 0.4Ω would be expressed for a 100Ω RTD if the temperature is changed by 1 ^{0}C. Usually a specification will provide the calibrated information either as a graph of resistance versus temperature or as a table of values from which the sensitivity can be determined.

Response Time

In general, RTD has a response time of 0.5 to 5 seconds or more. The slowness of response is due principally to the slowness of thermal conductivity in bringing the devices into thermal equilibrium with its environment. Generally, time constants are specified either for a "free air" condition (or its equivalent) or an "oil bath" condition (or its equivalent). In the

former case, there is poor thermal contact and hence slow response, and in the latter, good thermal contact and fast response. These numbers yield a range of response times depending on the application.

Construction

An RTD, of course, is simply a length of wire whose resistance is to be monitored as a function of temperature. The construction is typically such that the wire is wound on a form (in a coil) to achieve small size and improve thermal conductivity to decrease response time. In many cases, the coil is protected from the environment by the sheath or protective tube that inevitably increases response time but may be necessary in the hostile environments. A loosely applied standard sets the resistance at multiples of 100Ω for the temperature of 0 ^{0}C.

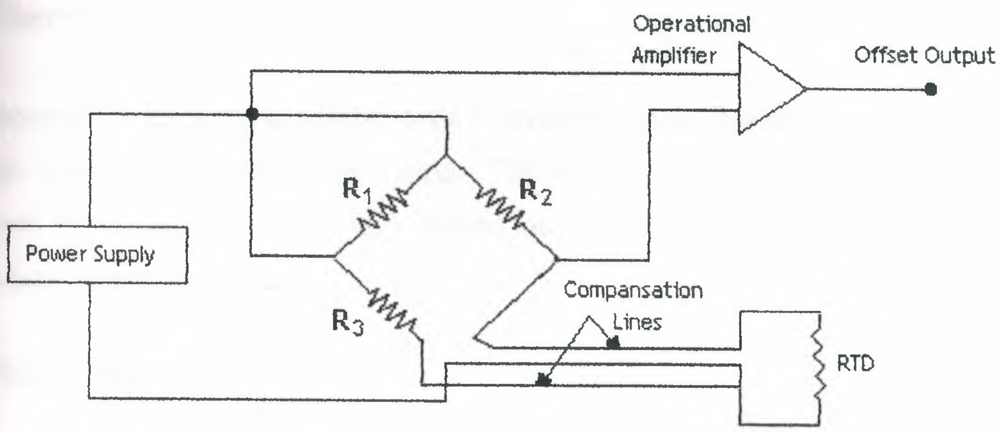

Figure 2.3: Note the compensation lines in this typical RTD signal conditioning circuit.

Signal Conditioning

In view of the very small fractional changes of resistance with temperature (0.4%), the RTD is generally used in a bridge circuit. Figure 2.3 illustrates the essential features of such a system. The compensation line in the R_3 leg of the bridge is required when lead lengths are so long that thermal gradients along the RTD leg may cause changes in line resistance. These changes show up as false information, suggesting changes in RTD resistance. By

using the compensation line, the same resistance changes also appear on the R_3 side of the bridge and cause no net shift in the bridge null.

Dissipation Constant

Because the RTD is a resistance, there is an I^2R power dissipated by the device itself that causes a slight heating effect, self-heating. This may also cause an erroneous reading or even upset the environment in delicate measurement conditions. Thus the current though the RTD must be kept sufficiently low and constant to avoid self-heating. Typically, dissipation constant is provided in RTD specifications. This number relates the power required to raise the RTD temperature by one degree of temperature. Thus, 25mW / ^{0}C dissipation constant shows that if I^2R power losses in the RTD equal to 25mW, then the RTD will be heated by 1^{0}C.

2.5 Thermistors

The thermistor represents to another class of temperature sensors that measures temperature through changes of material resistances. The characteristics of these devices are very different from those of RTDs and depend on the peculiar behavior of semiconductor resistances versus temperature.

2.5.1 Thermistor Characteristics

A thermistor is a temperature sensor that has been developed from the principles of semiconductor resistance change with temperature. The particular semiconductor material used varies widely to accommodate temperature ranges, sensitivity, resistance ranges and other factors. The devises are usually mass produced for a particular configuration and tables or graphs of resistance versus temperature are provided for calibration.

Sensitivity

The sensitivity of the thermistor is a significant factor in the application. Changes in resistance of 10% per ^{0}C are not uncommon. Thus, a thermistor with a nominal resistance of 10 KΩ at some temperature may change by 1 KΩ for a 1^{0}C change in temperature.

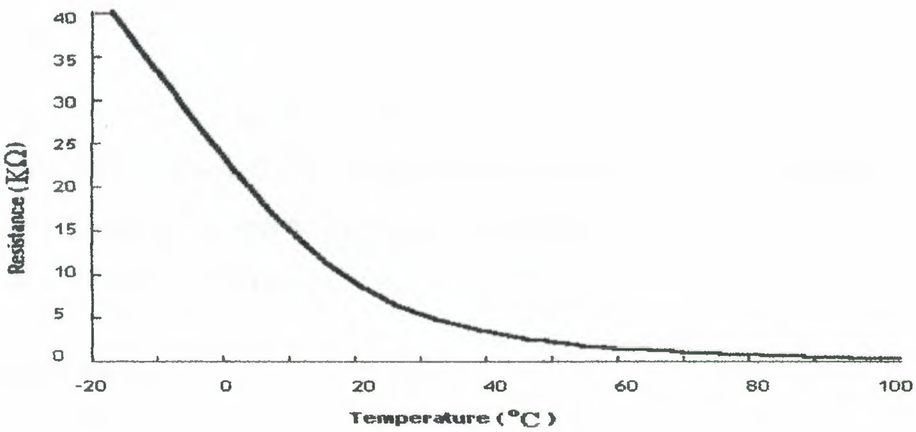

Figure 2.4: Thermistor resistance versus temperature is highly nonlinear and usually has a negative slope.

Construction

Because the thermistor is a bulk semiconductor, it can be fabricated in many forms. Thus, common forms include discs, beads and rods, varying in size from a bead of 1mm to a disc of several centimeters in diameter and several centimeters thick. By variation of doping and use of different semiconductor material, a manufacturer can provide a wide range of resistance values at any particular temperature.

Range

The temperature range of thermistor depends on the material used to construct the sensor. In general, there are three range limitation effects:

1. Melting or deterioration of the semiconductor
2. Deterioration of encapsulation material
3. Insensitivity at higher temperatures

The semiconductor material melts or deteriorates as the temperature is raised. This condition generally limits the upper temperature to less than 300 ^{0}C. At the low end, the principle limitation is that the thermistor resistance becomes very high, into the MΩ's, making practical applications difficult. For thermistor shown in figure 2.4, if extended, the lower limit is about -80^{0}C, where its resistance has risen to over 3MΩ! Generally the lower limit is -50^{0}C to -100^{0}C.

Response Time

The response time of the thermistor depends principally on the quantity of material present and the environment. Thus, for the smallest bead thermistor in an oil bath (good thermal contact), a response of ½ second is typical. The same thermistor in still air will respond with typical response of 10seconds.

Signal Conditioning

Because a thermistor exhibits such a large change in resistance with temperature, there are many circuit applications. In many cases, however, a bridge circuit is used because the nonlinear features of the thermistors make it difficult as an actual measurement device. Because these devices are resistances, care must be taken to ensure that power dissipation in the thermistor does not exceed limits specified or even interfere with the environment for which the temperature is being measured. Dissipation constants are quoted for thermistors as the power in milli-watts required to raise a thermistor's temperature 1^0C above its environment.

2.6 Thermocouples

In previous section we have considered the change in material resistance as a function of temperature. Such a resistance change is considered a variable parameter property in the sense that the measurement of resistance, and thereby temperature, requires external power resources. There exists another dependence of electrical behavior of materials on temperature that forms the basis of a large percentage of all temperature measurements. This effect is characterized by a voltage-generating sensor in which an electromotive force (emf) is produced that is proportional to temperature. Such an emf is found to be almost linear with temperature and very repeatable for constant materials. Devices that measure temperature on the basis of this thermoelectric principle are called thermocouples (TCs).

2.6.1 Thermoelectric Effect

The basic theory of the thermocouple effect is found from a consideration of the electrical

and thermal transport properties of different metals. In particular, when a temperature differential is maintained across a given metal, the vibration of atoms and motion of electrons is affected so that a difference in potential exists across the material. This potential difference is related to the fact that electrons in the hotter end of material have more thermal energy than those in the cooler end, and thus tend to drift toward the cooler end. This drift varies for different metals at the same temperature because of differences in their thermal conductivities. If a circuit is closed by connecting the ends through another conductor, a current is found to flow on the closed loop.

The proper description of such an effect is to say that an emf has been established in the circuit that is causing the current to flow. In figure 2.5a, we see a pictorial representation of this effect where two different metals A and B are used to close the loop with the connecting junctions at temperature T_1 and T_2.

We could not close the loop with the same metal because the potential differences across each leg would be the same, and thus no net emf would be present. The emf produced is proportional to the difference in temperature between the two junctions. Theoretical treatments of this problem involve the thermal activities of the two metals.

Seebeck Effect

Using solid state theory, the aforementioned situation may be analyzed to show that its emf can be given by integration over temperature

$$\varepsilon = \int_{T_2}^{T_1} (Q_A - Q_B)dt$$

Where, ε = emf produced in volts

T_1, T_2 = junction temperature in K

Q_A, Q_B = thermal transport constants of the two metals

This equation, which describes the Seebeck effect, shows that the emf produced is proportional to the difference in temperature and, further, to the difference in the metallic thermal transport constants.

Thus, if the metals are the same, the emf is zero, and if the temperature is also same, the emf is also zero. In practice it is found that the two constants Q_A *and* Q_B are nearly independent of temperature and that an approximate linear relationship exits as

$$\varepsilon = \alpha\,(T_2 - T_1)$$

Where α is a constant in volts/K

However, the small but finite temperature dependence of Q_A *and* Q_B is necessary for accurate consideration.

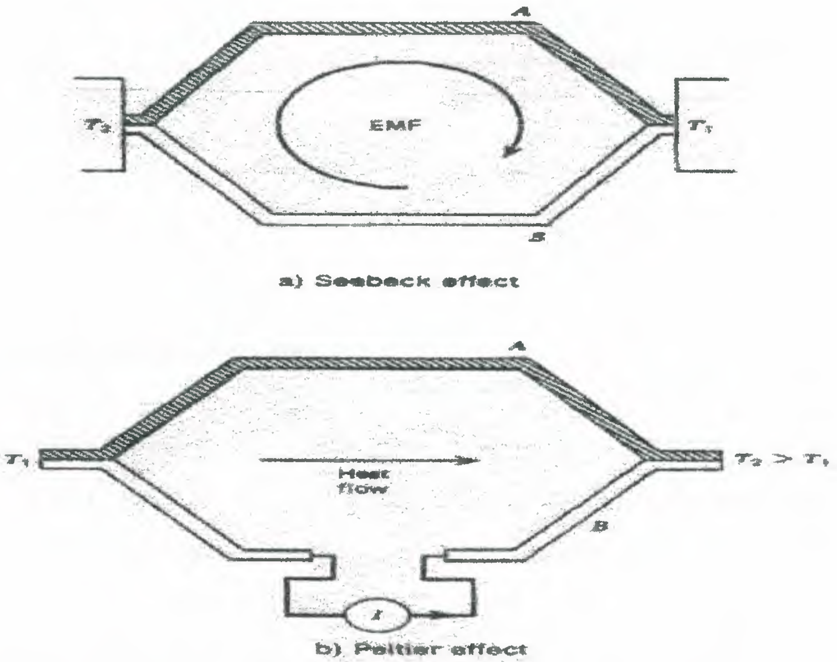

Figure 2. 5: The seebeck and peltier effects refer to the relation between emf and temperature in a two wire system.

Peltier Effect

An interesting and sometimes useful extension of the same thermoelectric properties occurs when the reverse of Seebeck effect is considered. In this case, we construct a closed loop of two different metals, A and B, as before. However, an external voltage is applied to the system to cause a current to flow in the circuit as shown in figure 2.5b. Because of the

different electro-thermal transport properties of the metals, it is found that one of the junctions will be heated and the other cooled; that is, the device is a refrigerator! This process is referred to as the Peltier effect. Some practical applications of such device, such as cooling small electronic parts, have been employed.

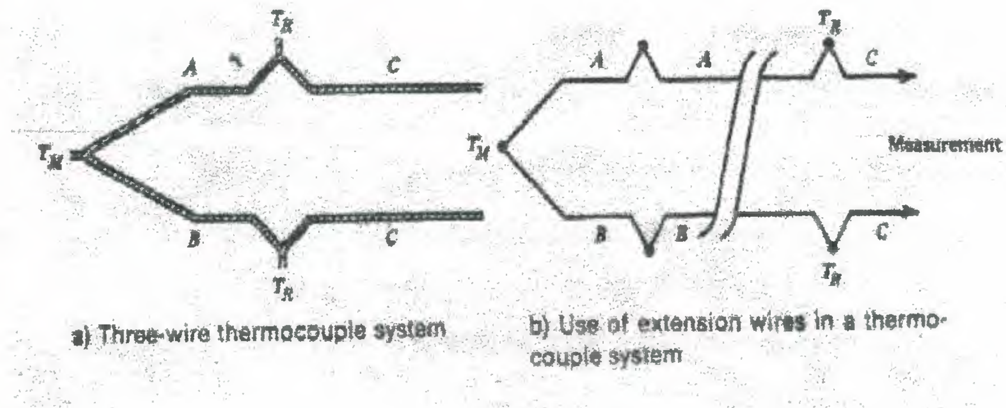

Figure 2.6: Practical measurements with a thermocouple system often employ extension wires to move the reference to a more secure location.

2.6.2 Thermocouple Characteristics

To use the Seebeck effect as the basis of a temperature sensor, we need to establish a definite relationship between the measured emf of the thermocouple and the unknown temperature. We see first that one temperature must already be known because the Seebeck voltage is proportional to the difference between the junction temperatures. Furthermore, every connection of different metals made in the thermocouple loop for measuring devices, extension leads, and so on will contribute an emf, depending on the difference in metals and various junction temperatures. To provide an output it is definite with respect to the temperature to be measured, an arrangement such as that shown in figure 2.6a is used. This shows that the measurement junction T_M is exposed to the environment whose temperature is to be measured. This junction is form of metals A and B as shown.

Two other junctions then are formed to a common metal C, which then connects to the measurement apparatus. The reference junctions are held at a common, known temperature T_R, the reference junction temperature. When an emf is measured, such problem as voltage

drops across resistive elements in the loop must be considered. In this arrangement, an open circuit voltage is measured (at high impedance) that is then a function of only the temperature difference ($T_M - T_R$) and the type of metal A and B. The voltage produced has a magnitude of the temperature difference and a polarity depend on the absolute magnitude of the temperature difference and a polarity dependant on which temperature is larger, reference or measurement junction. Thus, it is not necessary that the measurement junction have a higher temperature than the reference junctions, but both magnitude and sign of measured voltage must be noted.

To use the thermocouple to measure a temperature, the reference temperature must be known and the reference junctions must be held at the same temperature. The temperature must be constant, or at least not very much. In most industrial environments this would be difficult to achieve if the measurement junction and reference junction were close. It is possible to move the reference junction to a remote location without upsetting the measurement process by the use of extension wires, as shown in figure 2.6b. A junction is formed with the measurement system, but to wires of the same type as the thermocouple. These wires may be stranded and of different gauges, but they must be of the same type of metal as the thermocouple. The extension wires now can be run a significant distance to the actual reference junction.

2.6.3 Thermocouple Sensors

The use of a thermocouple for a temperature sensor has evolved from an elementary process with crudely prepared thermocouple constituents into a precise and exacting technique.

Sensitivity

Typically the range of the thermocouple voltages is less than 100mV. The actual sensitivity strongly depends on the type of the signal conditioning employed and on the TC itself.

Construction

A thermocouple by itself is, of course, simply a welded or even a twisted junction between

two metals, and in many cases that is the construction. There are cases, however, where the TC is sheathed in a protective covering or even sealed in the glass to protect the unit from a hostile environment. The size of the TC wire is determined by the application and can range from 0.02mm micro-wire in refined biological measurements of temperature.

Response

Thermocouple time response is simply related to the size of the wire and any protective material used with the sensor. The time response equates to how long it takes the TC system to reach thermal equilibrium with the environment.

Large industrial TCs using thick wire or encased in stainless steel sheathing may have time constants as high as 10to 20 seconds. On the other hand, a TC made from very small gauge wire can have a time constant as small as 10 to 20ms. Often the time constant is specified under conditions of good thermal contact and poor thermal contact as well, so that you can account for the environment.

Signal Conditioning

The key element in the use of thermocouples is that the output voltage is very small, typically less than 50mV. This means that considerable amplification will be necessary for practical application; in addition the small signal levels make the devices susceptible to electrical noise. In most cases the thermocouple is used with a high gain differential amplifier.

Noise

Perhaps the biggest obstacle to the use of the thermocouple for temperature measurement in Industry is their susceptibility to electrical noise. First, the voltages generated are less than 50mV, and often are 2 or 3mV, and in the industrial environment it is common to have hundreds of mill volts of electrical noise generated by large electrical machines in any electrical system. Second, a thermocouple constitutes an excellent antenna for pickup of noise from electromagnetic radiation in the radio, TV and microwave bands. In short, a

bare thermocouple may have many times more noise than temperature signal at a given time.

To use thermocouples effectively in industry, a number of noise reduction techniques are employed. The following three are the most popular:

The extension or lead wires from the thermocouple to the reference junction or measurement system are twisted ad them wrapped with a grounded foil sheath.

The measurement junction itself is grounded at the point of measurement. The grounding is typically to the inside of the stainless steel sheath that covers the actual thermocouple.

An instrumentation amplifier that has excellent common mode rejection is employed for measurement.

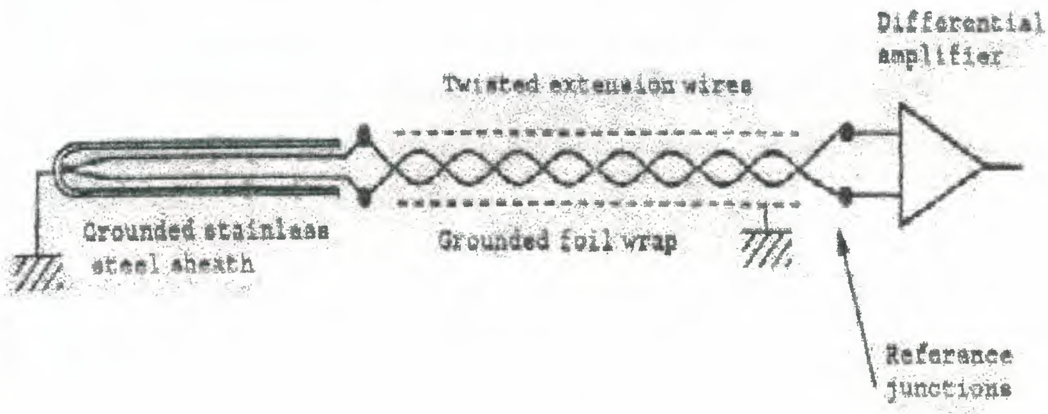

Figure 2.7: Since TC voltages are small, great care must be taken to protect against electrical noise such as by shielding, twisting, and differential amplification.

Figure 2.7 shows a typical arrangement for measurement with a thermocouple. Note that the junction itself is grounded through the stainless steel sheath. The differential amplifier must have very good common mode rejection to aid in the noise rejection process.

The advantages of grounding the measurement junction is that the noise voltage will be distributed equally on each wire of TC. Then the differential amplifier will, at least partially, cancel this noise because the voltage on these lines is subtracted.

Twisting is done to decouple the wires from induced voltages from varying electric and magnetic fields that permeate our environment. In principle, equal voltages are induced in each loop of the twisted wires but of opposite phase, so they cancel.

2.7 Bimetallic Strips

This type of the temperature sensor has the characteristics of being relatively inaccurate, having hysteresis, having relatively slow response time, and being low in cost. Such devices are use in numerous applications, particularly where an ON/OFF cycle rather than smooth or continuous control is described.

2.7.1 Thermal Expansion

We have seen that greater thermal energy causes the molecules of the solids to execute the greater amplitude and higher frequency vibrations about their average positions. It is natural to expect that an expansion of volume of a solid would accompany this effect, as the molecules tend to occupy more volume on the average with their vibrations. This effect varies in degree from material to material because of many factors, including molecular size and weight, lattice structure and others.

If we have a rod of length L_o at temperature T_o and the temperature is raised to a new value T, then the rod will be found to have new length L, given by:

$$L = L_0[1 + \gamma \Delta T]$$

Where, γ is the linear thermal expansion coefficient appropriate to the material of which the rod is made.

2.7.2 Bimetallic Sensor

The thermal sensor exploiting the effect discussed previously occurs when two materials with grossly different thermal expansion coefficients are bounded together. Thus, when heated, the different expansion rates cause the assembly curve shown in figure 2.8. This effect can be used to close the switch contact or to actuate an ON/OFF mechanism when

the temperature increases to some appropriate set point. This effect also is used for temperature indicators, by means of assemblages, to convert the curvature into dial rotation.

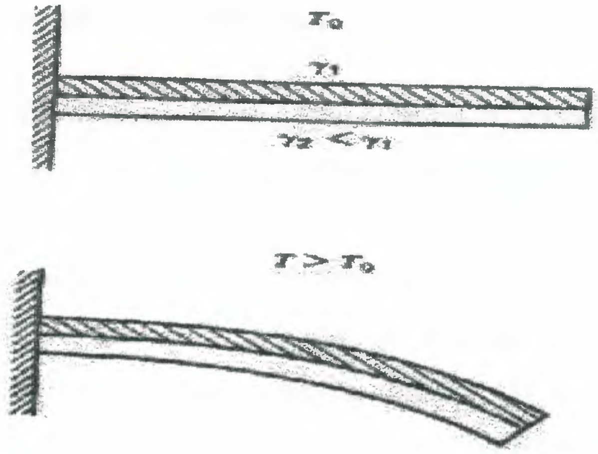

Figure 2.8: A bimetallic strip will curve when exposed to a temperature change because of differential thermal expansion coefficients. Metal thickness has been exaggerated in this figure.

2.8 Gas Thermometers

The operational principle of the gas thermometer is based on a basic law of gases. In particular, if a gas is kept in a container at constant volume and the pressure and temperature vary, then the ratio of gas pressure and temperature is a constant.

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Where, P_1, T_1 = Absolute pressure and temperature (in K) in state 1

P_2, T_2 = Absolute pressure and temperature (in K) in state 2

Because the gas thermometer converts temperature information directly into pressure signal, it is particularly useful in pneumatic systems. Such transducers are also advantageous because they are not moving parts and no electric stimulation is necessary. For electronic analog or digital process control applications, however, it is necessary system for converting the pressure to electrical signals. This type of sensor is often used with bourdon tubes to produce directly indicating temperature meter and recorders. The gas

most commonly employed is Nitrogen. Time response is slow in relation to the electrical devices because of the greater mass that must be heated.

2.9 Vapor-pressure Thermometers

A vapor pressure thermometer converts temperature information into pressure as does the gas thermometer, but it operates by the different process. If a closed vessel is partially filled with liquid, then the space above the liquid will consist of evaporated vapor of the liquid at a pressure that depends on the temperature. If the temperature is raised, more liquid will vaporize and the pressure will increase. A decrease in temperature will result in condensation of some of the vapor, and the pressure will decrease. Thus, vapor pressure depends on temperature. Different materials have different curves of pressure versus temperature, and there is no simple equation like that for a gas thermometer. Figure 2.9 shows a curve a curve of vapor pressure versus temperature for methyl chloride, which is often employed in these sensors. The pressure available is substantial as the temperature rises. As in case of gas thermometers, the range is not great and response time is slow (20 seconds or more) because the liquid and vessel must be heated.

2.10 Liquid expansion Thermometers

Just as solid experiences an expansion in dimension with temperature, a liquid also shows an expansion in volume with temperature. This effect forms the basis for the traditional liquid-in-glass thermometers that are so common in temperature measurement. The relationship that governs the operation of this device is:

$$V(T) = V(T_0)[1 + \beta \, \Delta T]$$

Where, V(T) = volume at temperature T

$V(T_0)$ = volume at temperature T_0

β = volume thermal expansion constant

In actual practice, the expansion effects of the glass container must be accounted for to obtain high accuracy in temperature indications. This type of temperature sensor is not

commonly used in process control work because further transduction is necessary to convert the indicated temperature into an electrical signal.

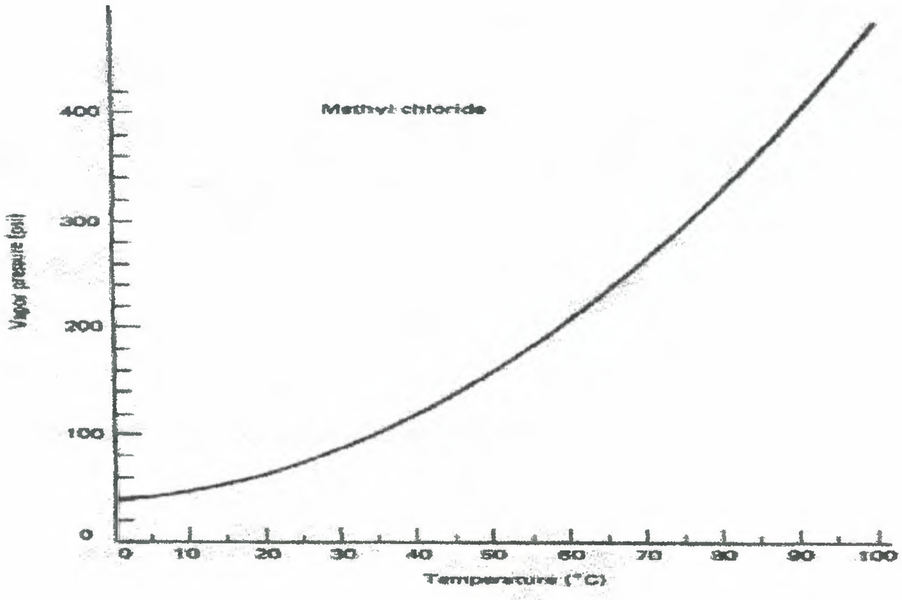

Figure 2.9: Vapor pressure curve for Methyl chloride.

2.11 Solid State Temperature Sensors

Many integrated manufacturers now market solid state temperature sensors for consumer and industrial applications. These devices offer voltages that vary linearly with temperature over a specified range. The operating temperature of these sensors is typically in the range of -50 °C to 150 °C. The time constant in good thermal contact varies in the range of 1 to 5 seconds, whereas in poor thermal contact it may increase to 60 seconds or more.

These sensors are easy to interface to control systems and computers, and are becoming popular for measurement within the somewhat limited range they offer. An important application is to provide automatic reference temperature compensation for thermocoupler. This is provided by connecting the sensors to the reference junction block of the TC and providing signal conditioning so that the reference corrections are automatically provided to the TC output, as shown in figure 2.10.

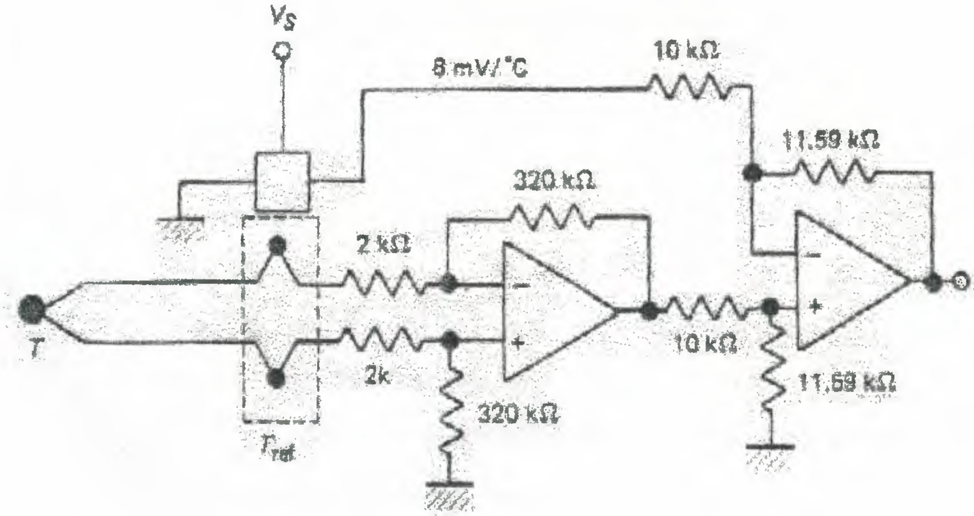

Figure 2.10: It shows the circuit diagram of solid state thermal sensor.

3. MECHANICAL SENSORS

3.1 Introduction

The class of sensors used for the measurement of mechanical phenomena is of special significance because of the extensive use of these devices through out the process control industry. In many instances, an interrelation exists by which a sensor designed to measure some mechanical variable is used to measure another variable. To learn to use the mechanical sensors, it is important to understand the mechanical phenomena themselves and the operating principles and application details of the sensors.

3.2 Displacement, Location or Position Sensors

The measurement of displacement, position or location is an important topic in the process industries. Examples of industrial requirements to measure these variables are many and varied and the required sensors are also of greatly varied designs. To give a few examples of measurement needs:

1. Location and position of objects on a conveyer system
2. Orientation of steel plates in a rolling mill
3. Liquid or solid level measurements
4. Location and position of work piece in automatic milling operation
5. Conversion of pressure to a physical displacement

3.2.1 Potentiometric

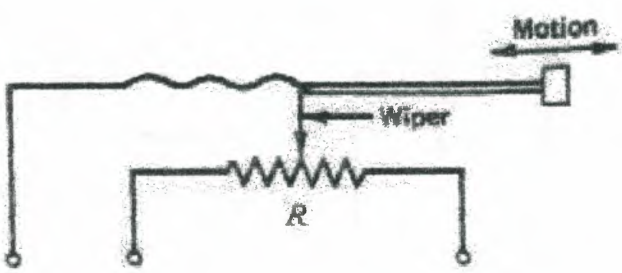

Figure 3.1: Potentiometric displacement sensor.

The simplest type of displacement sensor involves the action of displacement in moving the wiper of a potentiometer. This device then converts linear or angular motion into a changing resistance that may be converted directly to voltage and/or current signals. Such potentiometric device often suffer from the obvious problems of mechanical wear, friction in wiper action, limited resolution in wire-wound units and high electronic noise.

3.2.2 Capacitive and Inductive

The second class of sensors for displacement measurement involves changes in capacity and inductance.

Capacitive

The basic operation of a capacitive sensor can be seen from the familiar equation for a parallel-plate capacitor.

$$C = K\varepsilon_o \frac{A}{d}$$

Where, K= The dielectric constant

ε_o= Permittivity = 8.85 pF/m

A= Plate common area

d= Plate separation

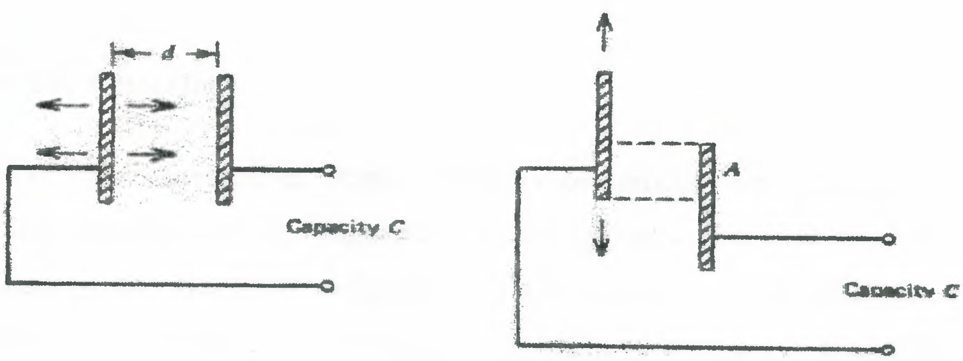

Figure 3.2: Capacity varies with distance between plates and common area. Both are used in sensors.

There are three ways to change the capacity:

- Variation of distance between the plates (d)
- Variation of shared area of the plates (A)
- Variation of the dielectric constant (K)

Inductive

If a permeable core is inserted into an inductor as shown in figure 3.3, the net inductance is increased. Every new position of the core produces a different inductance. In this fashion, the inductor and movable core assembly may be used as a displacement sensor. An AC bridge or other active electronic circuit sensitive to inductance then may be employed for signal conditioning.

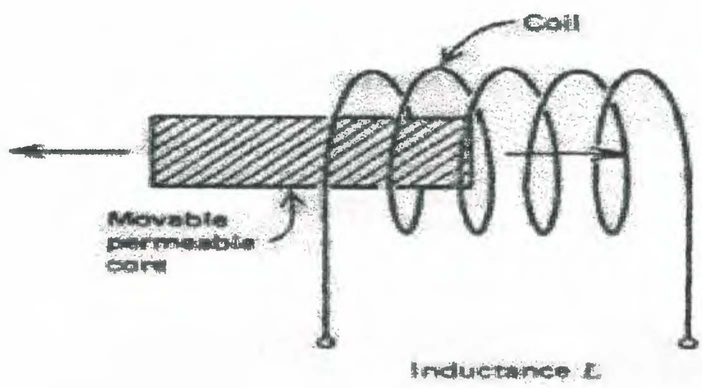

Figure 3.3: The variable reluctance displacement sensor changes the inductance in coil in response to core motion.

3.2.3 Variable Reluctance

The class of variable-reluctance displacement sensors differs from the inductive in that moving core is used to vary the magnetic flux coupling between two or more coils, rather than changing am individual inductance. Such devices find application in many circumstances for the measure of both translational and angular displacements. Many configurations of these devices exist, but the most common and extensively used is called a linear variable differential transformer (LVDT).

3.2.3.1 LVDT

The LVDT is an important and common sensor for displacement in the industrial environment. Figure 3.4 shows that an LVDT consists of three coils of wire wounded on a hollow form. A core of permeable material can slide freely through the centre of the form. Flux formed by the primary, which is excited by some AC source as shown. Flux formed by the primary is linked to the two secondary coils, inducing an AC voltage in each coil.

When the core is centrally located in assembly, the voltage induces in each primary is equal. If the core moves to one slide or the other, a larger AC voltage will be induced in one coil and a smaller AC voltage in the other because of changes in the flux linkage associated with the core as shown in figure 3.4.

When the core centrally located, the net voltage is zero. When the core is moved to one side, the net voltage amplitude will increase. In addition, there is a change in phase with respect to the source when the core is moved to one side or the other.

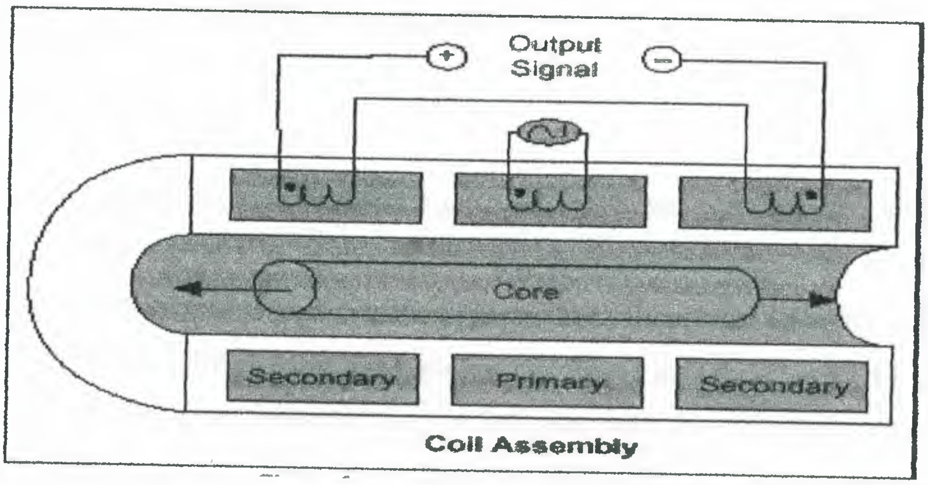

Figure 3.4: The LVDT has a movable core with three coils.

3.2.4 Level Sensors

The measurement of solid or liquid level calls for a special class of displacement sensor. The level measured is most commonly associated with material in a tank or hopper. A great variety of measurement techniques exists, as the following representative examples show.

Mechanical

One of the most common techniques for level measurement, particularly for liquids, is a float that is allowed to ride up and down with level changes. This float, as shown in figure 3.5a, is connected by linkage to a secondary displacement measuring system such as potentiometric device or an LVDT core.

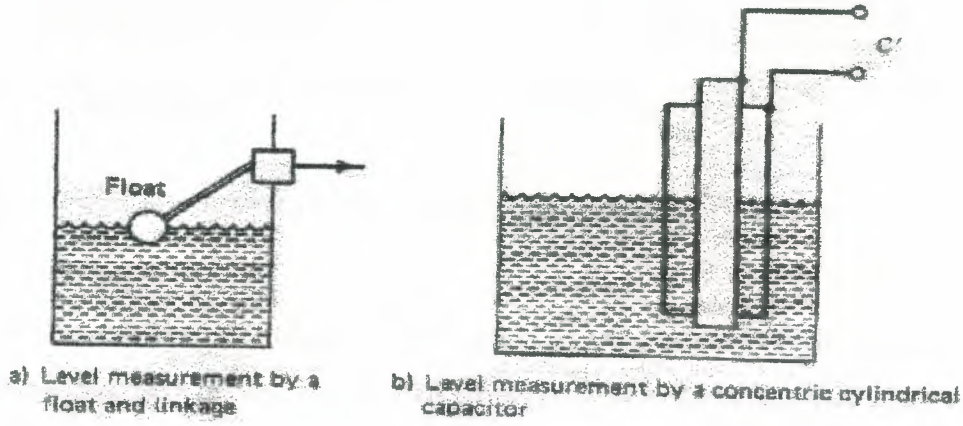

Figure 3.5: There are many level measurement techniques.

Electrical

They are several purely electrical methods of measuring level. For example, one may use the inherent conductivity of a liquid or solid to vary the resistance seen by the probes inserted into the material. Another common technique is illustrated in figure 3.5b. In this case, two concentric cylinders are contained in a liquid tank. The level of the liquid partially occupies the space between the parallel, one with the dielectric constant of air (≈ 1) and the other with that of the liquid. Thus, variation of liquid level causes variation of the electrical capacity measured between the cylinders.

Ultrasonic

The use of the ultrasonic reflection to measure level is favored because it is a non-sensitive technique; that is, it does not involve placing anything in the material. Figure 3.6 shows the external and internal techniques.

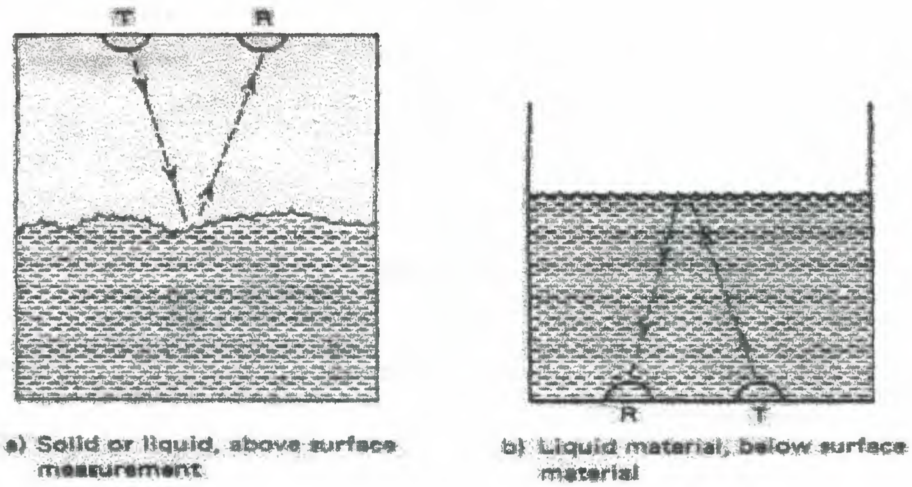

Figure 3.6: Ultrasonic measurement needs no physical contact with material, just a transmitter T and receiver R.

Obviously, the external technique is better suited to solid material level material. In both cases the measurement depends on the length of time taken for reflections of an ultrasonic pulse from the surface of the material. Ultrasonic techniques based on reflection time also have become popular for ranging measurements.

Pressure

For liquid measurement, it is also possible to make a no contact measurement of level if the density of the liquid is known. This method based on the well-known relationship between pressure at the bottom of a tank and the height and density of the liquid.

3.3 Strain Sensors

Although not obvious at first, the measurement of strain in solid objects is common in process control. The reason it is not obvious that strain sensors are used as a secondary step in sensors to measure many other process variables, including flow, pressure, weight and acceleration. Strain measurements have been used to measure pressures from over a million pounds per square inch to those within living biological systems. We shall first review the concept of strain and how it is related to the forces that produce it and then discuss the sensors used to measure strain.

3.3.1 Strain and Stress

Strain is the result of the application of force to solid objects. The forces are defined in a special way described by general term, stress.

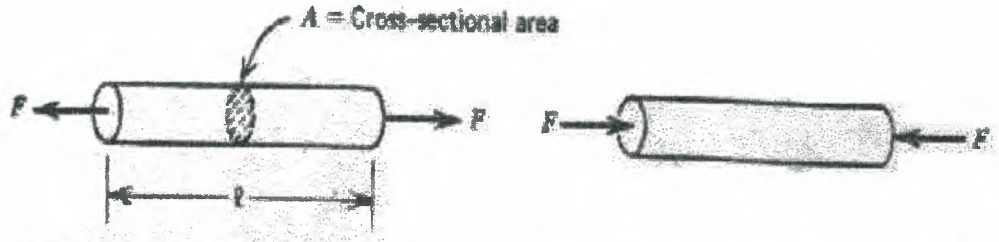

Figure 3.7: Tensile and Compressional stress can be defined in terms of forces applied to a uniform rod.

A special case exists for the relation between force applied to a solid object and the resulting deformation of that object is called strain. Solids are assemblages of atoms in which the atomic spacing has been adjusted to render the solid in equilibrium with all external forces acting on the solid. This spacing determines the physical dimensions of the solid. If the applied forces are changed, the object atoms rearrange themselves again to come into equilibrium with the mew set of forces. This rearrangement results in a change in physical dimensions that is referred to as a deformation of the solid.

The study of this phenomenon has evolved into an exact technology. The effect of applied force is referred to as a stress and the resulting deformation as a strain. To facilitate a proper analytical treatment of the object, stress and the resulting are carefully defined to emphasize the physical properties of the material being stressed and the specific type of stress applied. We delineate here the three most common types of stress-strain relationships.

Tensile stress Strain

In figure 3.7, the nature of a tensile force is shown as a force applied to a sample of material so as to elongate or pull apart sample. In this case, the stress is defined as:

$$Tensile\ \ stress = \frac{F}{A}$$

Where, F= Applied force in N

A= Cross-sectional area of the sample in m^2

We see that the units of stress are N/m^2 in SI units and they are like a pressure.

The strain in this case is defined as the fractional change in the length of the sample and Strain is unitless quantity.

$$Tensile\ \ stress = \frac{\Delta L}{L}$$

Compressional stress Strain

The only differences between Compressional and tensile stress are the direction of applied force and the polarity of the change in length. Thus, in a Compressional stress, the force pressed in on a sample, as shown in figure 3.7b.

Shear stress Strain

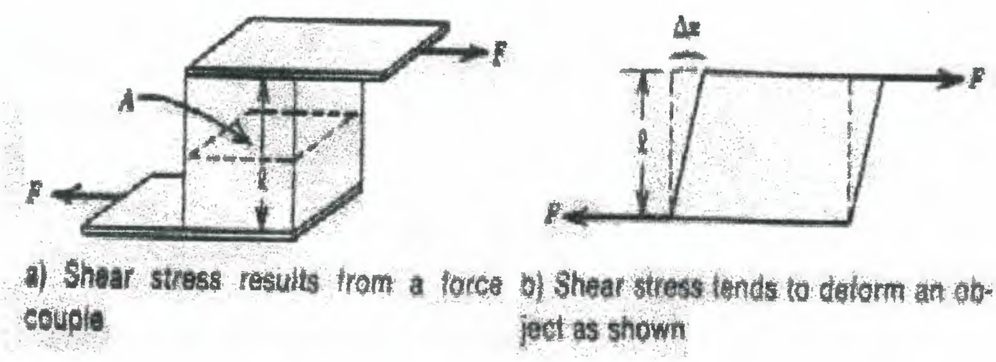

Figure 3.8: Shear stress is defined in terms of a couple that tends to deform a joining member.

Figure 3.8, shows the nature of shear stress. In this case, the force is applied as a couple (that is, not along the same line), tending to shear off the solid object that separates the force arms. In this case the stress is again the same as that of previous sections.

3.3.2 Strain gauge Principle

Metal resistance of a sample is given as:

$$R_o = \rho \frac{L_o}{A_o}$$

Where, R_o= Sample resistance in Ω

ρ = Sample resistivity in Ω-m

L_o= Length in m

A_o= Cross sectional area in m^2

Suppose the sample is now stressed by the application of a force F as shown in figure 3.7a. Then we know that the material elongates by some amount ΔL so that the new length is L= L+ ΔL. It is also true that in such a stress-strain condition, although the sample lengths, its volume will remain nearly constant. Because the volume unstressed V= L_o A_o, it follows that if the volume remains constant and the length increases, then the area must decrease by some amount ΔA:

$$V = L_o A_o = (L_o + \Delta L)(Ao - \Delta A)$$

Because both length and area have changed, we find that the resistance of the sample will have also changed:

$$R = \rho \frac{L_o + \Delta L}{A_o - \Delta A}$$

By combining these two equations, we shall find:

$$R \cong \rho \frac{L_o}{A_o}\left(1 + 2\frac{\Delta L}{L_o}\right)$$

For which we conclude that the change in resistance is:

$$R \cong 2R_o \frac{\Delta L}{L_o}$$

This is the final equation that underlies the use of metal strain gauges because it shows that the strain $\Delta L/L$ converts directly into a resistance change.

Measurement Principle

The basic technique of strain gauge (SG) measurement involves attaching (gluing) a metal wire or foil to the element whose strain is to be measured. As stress is applied and the element deforms, the SG material experiences the same deformation, if it is securely attached. Because the strain is a fractional change in length, the change in SG resistance reflects the strain of both the gauge and the element to which it is secured.

Temperature Effects

If not for temperature compensation effects, the aforementioned method of SG measurement would be useless. To see this, we need only note that the metals used in SG construction have linear temperature coefficients of $\alpha \cong 0.004/^{o}C$, typically for most metals. Temperature changes of $1^{o}C$ are not uncommon in measurement conditions in the industrial environment.

3.3.3 Metal Strain Gauges (SGs)

Metal SGs are devices that operate on the principles discussed earlier. The following items are important to understanding SG applications.

Gauge Factor

Relation between strain and resistance change is approximately true. Impurities in the metal, the type of metal, and other factors lead to slight corrections. An SG specifications always indicates the correct relation through statement of a gauge factor (GF), which is defined as:

$$\text{GF}=\frac{\Delta R/R}{Strain}$$

Where, $\Delta R/R$ = Fractional change in gauge resistance because of strain

Strain= $\Delta L/L$ = Fractional change in Length

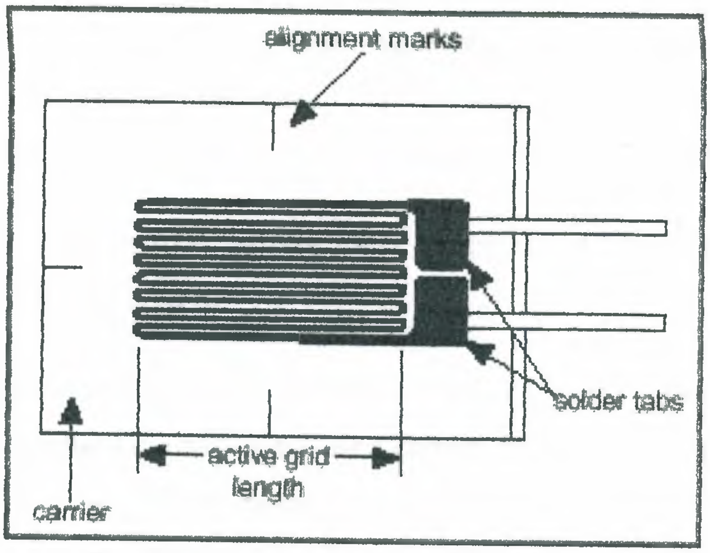

Figure 3.9: A metal strain gauge is resistance for a given strain and is easier to measure.

For metal gauges, this number is always close to 2. For some special alloys and carbon gauges, the GF may be as large as 10. A high gauge factor is desirable because it indicates a larger change in resistance for a given strain and is easier to measure.

Construction

Strain gauges are used in two forms, wire and foil. The basic characteristics of each type are the same in terms of resistance change for a given strain. The design of SG itself is such as to make it very long in order to give a large enough nominal resistance (to be practical) and to make the gauge of sufficiently fine wire or foil so as not to resist strain effects. Finally, often the gauge sensitivity is made unidirectional; that is, it responds to strain in only one direction. In figure 3.9, we see the common pattern of SGs that provides these characteristics. By folding the material back and forth as shown, we achieve a long length to provide high resistance. Further, if a strain is applied transversely to the SG length, the pattern will tend to unfold rather than stretch, with no change in resistance. These gauges are usually mounted on a paper backing that is bonded (using epoxy) to the elements whose strain is to be measured. The nominal SG resistances (no strain) available are typically 60, 120, 240, 350, 500 and 1000 Ω.

Signal Conditioning

The effects are critical in the signal conditioning techniques used for SGs. The first is the small, fractional changes in resistance that require carefully designed resistance measurement circuits. A good SG system might require a resolution of 2µm/m strain.

The second effect is the need to provide some compensation for temperature effects to eliminate masking changes in strain.

The bridge circuit provides the answer to both effects. The sensitivity of the bridge circuit for detecting small changes in resistance is well known. Further more, by using the dummy gauge, we can provide the required temperature compensation. In particular, the dummy is mounted in an intensive orientation but in the same proximity so the active SG. Then, both gauges change in resistance from temperature effects, but the detector does mot respond to a change in both strain gauges. Only the active SG responds to strain effects. This is called one arm bridge. The sensitivity of this bridge to strain can be found by consideration of the equation for bridge offset voltage also shown in terms of strain.

$$\Delta V \approx -\frac{V_S}{4}\frac{\Delta R}{R} = -\frac{V_S}{4}GF\frac{\Delta L}{L}$$

Another configuration that is often employed uses active strain gauges in two arms of the bridge and is thus called a two armed bridge. All four arms are strain gauges, but two are for temperature compensation only. This has the added advantage of doubling the sensitivity. The bridge off-null voltage in terms of strain is given by:

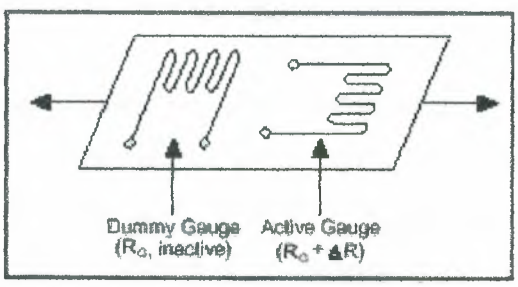

Figure 3.10: The structure shows how four gauges can be used to measure beam bending. Two respond to bending and two are for temperature compensation.

$$\Delta V = -\frac{V_S}{2} GF \frac{\Delta L}{L}$$

Obviously, the placement of the active and dummy gauges in the environment and in the bridge circuit is important. Figure 3.10shows a common application of the strain gauges to measure deflection of a cantilever beam. This is a beam that is supported at only one end, and deflects as shown when the load is applied.

3.3.4 Semiconductor Strain Gauges (SGs)

The use of semiconductor material, notably silicon, for SG application has increased over the past few years. There are presently several disadvantages to these devices compared to the metal variety, but numerous advantages for their use.

Principles

As in the case of metal SGs, the basic effect is change of resistance with strain. In this case of a semiconductor the resistivity also changes with strain along with the physical dimensions. This is due to changes in electron and hole mobility with changes in crystal structure as strain is applied. The net result is a much larger gauge factor than is possible with metal gauges.

Gauge Factor

The semiconductor device gauge factor (SG) is still given by equation:

$$\mathrm{GF} = \frac{\Delta R/R}{Strain}$$

However the value of the semiconductor gauge factor varies between -50 and -200. Thus, resistance changes will be factors from 25 to 100 times those available with metal SGs. It must also be noted, however, that these devices are highly nonlinear in resistance versus strain. In other worlds, the gauge factor is not a constant as the strain takes place. Thus, the gauge factor may be -150 with no strain, but drop (non-linearity) to -50 at 5000µm/m.

Construction

The semiconductor strain gauge physically appears as a band or strips of material with electrical connection, as shown in figure 3.11. The gauge is either bonded directly into the test element or, if encapsulated, is attached by the encapsulation material. These SGs also appear as IC assemblies in configurations used for other measurements.

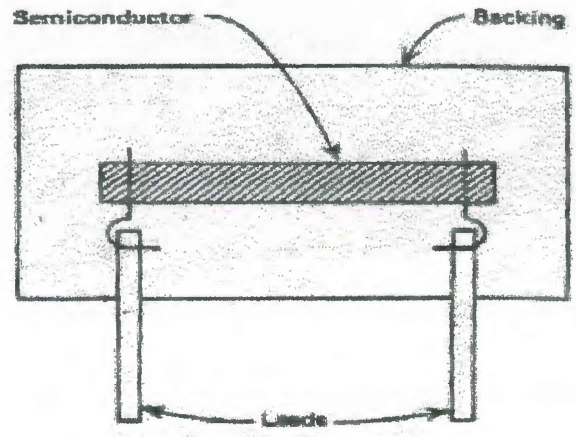

Figure 3.11: Typical semiconductor strain gauge structure.

Signal Conditioning

The signal conditioning is still physically a bridge circuit with temperature compensation. An added problem is the need for linearization of the output because the basic resistance versus strain characteristics is nonlinear.

3.3.5 Load Cell

One important direct application of SGs is for the measurement of force or weight. These transducer devices, called load cell, measure deformations produced by the force or weight. In general, a beam or yoke assembly is used that has several strain gauges mounted so that the application of a force causes a strain in the assembly that is measured by the gauges. A common application uses one of these devices in support of a hopper or feed of dry or liquid materials. A measure of the weight through a load cell yields a measure of the quantity of material in the hopper. Generally, these devices are calibrated so that the force (weight) is directly related to the resistance change. Forces as high as 5MN (approximately10^6 Lb) can be measured with an appropriate load cell.

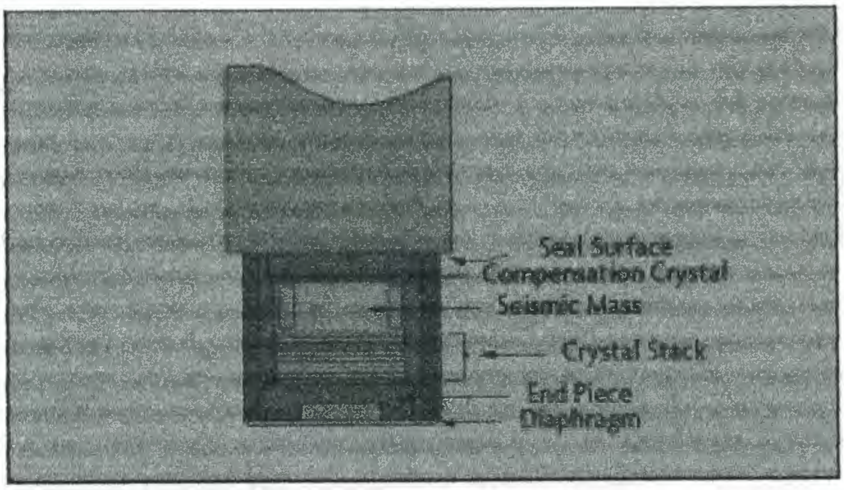

Figure 3.12: figure shows how load cell works in order to change in length or deformation.

The form of load cell considered in figure 3.12 is fine and illustrating principles, but real load cells cannot be made in this simple way. The problem is that forces applied to the top of the load cell may cause it to lean or bent, instead of simply compressing. In such a case, one side surface of the beam may experience compression while the other side undergoes tension. Obviously, this will alter the correct interpretation of the result.

Practical load cells are made with yoke assemblies designed so that mounted strain gauges cannot be exposed to stresses other than those caused by the Compressional force applied to that cell.

3.4 Motion sensors

Motion sensors are designed to measure the rate of change of position, location or displacement of an object that is occurring. If the position of an object as a function of time is x(t), then the first derivative gives the speed of the object, v(t), which is called the velocity if a direction is also specified. If the speed of the object is also changing, then the first derivative of the speed gives the acceleration. This is also the second derivative of the position.

The primary form of the sensor is the accelerometer. This device measures the acceleration a(t) of an object. Thus in accelerometer we have a sensor that can provide the acceleration, speed or position information.

3.4.1 Types of motion

The design of a sensor to measure the motion is often tailored to the type of motion that is to be measured. It will help us to understand these sensors if we have a clear understanding of these type of motions.

The proper unit of acceleration is meter per second squared (m/s^2). Then speed will be in meter per second (m/s) and position of course in meters (m). Often, acceleration is expressed by comparison with the acceleration due to gravity at the earth's surface. This amount of acceleration, which is approximately 9.8 m/s^2, is called a "gee", which is given as a bold **g** in the text.

Rectilinear

This type of motion is characterized by velocity and acceleration which is composed of straight-line segments. Thus, objects may accelerate forward to a certain velocity, decelerator to a stop, reverse, and so on. There are many types of sensors designed to handle this type of motion. Typically, maximum acceleration is less than few **g**s, and a little angular motion is allowed. If there is angular motion, then several rectilinear sensors must be used, each sensitive to one line of motion.

Thus, if vehicle is to be measured, two transducers may be used, one to measure motion in forward direction of vehicle motion and the other perpendicular to the forward axis of the vehicle.

Angular

Some sensors are designed to measure only relations about some axis, such as the angular motion of the shaft of a motor. Such devices can not be used to measure the physical displacement of the whole shaft, but only its rotation.

Vibration

In normal experiences of daily living, a person rarely experiences accelerations that vary from I **g** by more than a few percent. Even the severe environments of a rocket launching involve accelerations of only 1**g** to 10**g**. On the other hand, if an object is placed in periodic motion about some equilibrium position, very large peak accelerations may result that reach to 100**g** or more. This motion is called vibration. Clearly, the measurement of acceleration of this magnitude is very important to industrial environments, where vibrations are often encountered from machinery operations. Often, vibrations are somewhat random in both the frequency of periodic motion and the magnitude of displacements from equilibrium. For analytical treatments, vibration is defined in terms of a regular periodic motion.

Shock

A special type of acceleration occurs when an object that may be in uniform motion or modestly accelerating is suddenly brought to rest, as in a collision. Such phenomena are the result of very large accelerations, or actually decelerations, as when an object is dropped from some height onto a hard surface. The name shock is given to decelerations that are characterized by very short times, typically in the order of milliseconds, with peak accelerations over 500**g**.

3.4.2 Accelerometer

These are several physical processes that can be used to develop a sensor to measure acceleration. In applications that involve flight, such as aircraft and satellite, accelerometers are based on properties of rotating masses. In industrial world, however, the most common design is based on combination of Newton's law of mass acceleration and Hook's law of spring action.

Spring mass System

Newton's law simply states that if a mass (m) is undergoing an acceleration (a) then there must be a force (F) acting on the mass and given by F=ma. Hook's law states that if a spring constant (k) is stretched (extended) from its equilibrium position for a distance Δx, then there must be a force acting on the spring given by F=k Δx.

In figure 3.13a, we have a mass that is free to slide on a base. The mass is connected to the base by a spring that is in its un-extended state and exerts no force on the mass. In figure 3.13 b, the whole assembly is accelerated to the left, as shown. Now the spring extends in order to provide the force necessary to accelerate the mass. This condition is described by equation Newton's and Hook's law:

$$ma = k\,\Delta x$$

Where,

k= Spring constant in N/m

Δx= Spring extension in m

m= mass in Kg

a= acceleration in m/s^2

This equation allows the measurement to be reduced to a measurement of spring extension (linear displacement) because

$$a = \frac{k}{m}\,\Delta x$$

If the acceleration is reversed, the same physical argument would apply, except that the spring is compressed instead of extended. Above equation still describes the relationship between spring displacement and acceleration.

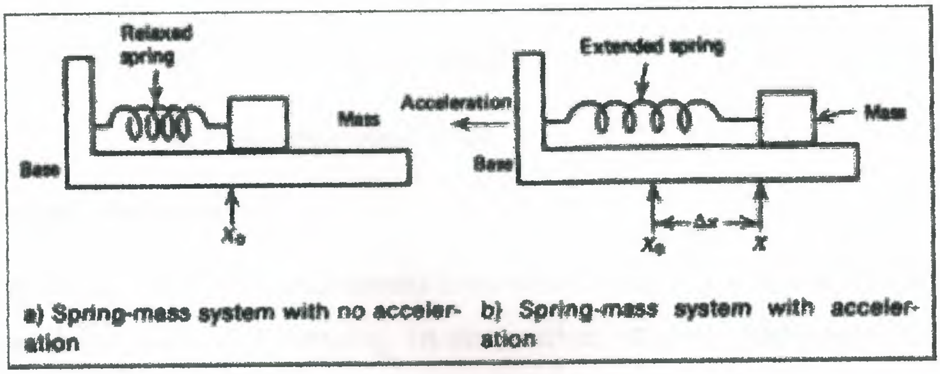

Figure 3.13: The basic spring mass accelerometer.

The spring-mass principle applies to many common accelerometer designs. The mass that converts the acceleration to spring displacement is referred to as the test mass or seismic mass. We see then that acceleration measurement reduces to linear displacement measurement; most designs differ in how this displacement measurement is made.

Natural frequency and Damping

On close examination of the simple principle just described, we find another characteristic of spring-mass system that complicates the analysis. In particular, a system consisting of a spring and attached mass always exhibits oscillations at some characteristic natural frequency. Experiments tell us that if we pull a mass back and then release it (in the absence of acceleration), it will be pulled back by the spring, overshoot the equilibrium and oscillate back and forth. Only friction associated with the mass and base eventually brings the mass to rest. Any displacement measuring system will respond to this oscillation as if an actual acceleration occurs. This natural frequency is given by:

$$f_N = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

The friction that eventually brings the mass to the rest is defined by a damping coefficient (α), which has the units of S^{-1}. In general, the effect of the oscillation is called transient response, described by a periodic damped signal whose equation is

$$X_T(t) = X_o e^{-\alpha t}\sin(2\pi\, f_N t)$$

Where, $X_T(t)$ = Transient mass position

X_o = peak position, initially

α = damping coefficient

3.4.3 Types of Accelerometer

The variety of accelerometers used results from different applications with requirements of range, natural frequency and damping. In this section, various accelerometers with their special characteristics are reviewed. The basic difference is in the method of mass displacement measurement. In general, the specification sheets for an accelerometer will give the natural frequency, damping coefficient and a scale factor that relates the output to an acceleration input. The values of test mass and spring constant are seldom known or required.

Potentiometric

This simplest accelerometer type measures mass motion by attaching the spring mass to the wiper arm of the potentiometer. In this manner, the mass position is conveyed as a changing resistance. The natural frequency of these devices is generally less than 30Hz, limiting their application to steady state acceleration or low frequency vibration measurement. Numerous signal conditioning schemes are employed to convert the resistance variation into a voltage change or current signal.

LVDT

A second type of accelerometer takes advantage of the natural linear displacement measurement of the LVDT to measure mass displacement. In these instruments, the LVDT core itself is the seismic mass. Displacements of the core are converted directly into a linearly proportional AC voltage. These accelerometers generally have a natural frequency less than 80Hz and are commonly used for steady state and low frequency vibrations. Figure 3.14 shows the basic structure of such an accelerometer.

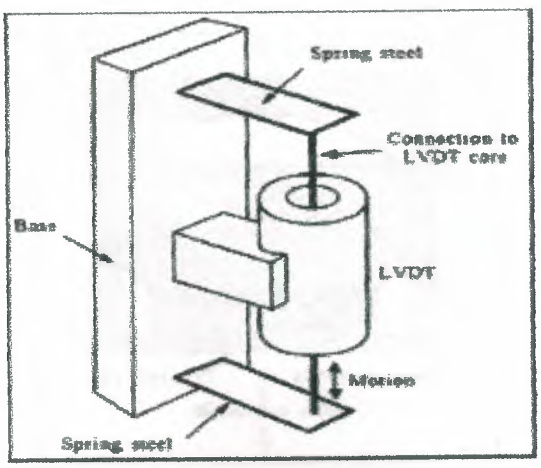

Figure 3.14: An LVDT is often used as an accelerometer with core serving as mass.

Variable Reluctance

This accelerometer type falls in the same general category as the LVDT in that an inductive principle is employed. Here, the test mass is usually a permanent magnet. The measurement is made from the voltage induced in a surrounding coil as the magnetic mass moves under the influence of acceleration. This accelerometer is used in vibrations and shock studies only, because it has an output only when the mass is in motion. Its natural frequency is typically less than 100Hz. This type of accelerometer often is used in oil exploration to pick up vibration reflected from underground rock strata. In this form, it is commonly referred to as geophone.

Piezoelectric

The piezoelectric accelerometer is based on a property exhibited by certain crystals where a voltage is generated across the crystal when stressed. This property is also the basis for such familiar sensors as crystal phonograph cartridges and crystal microphones. For accelerometers, the principle is shown in figure 3.15. Here, a piezoelectric crystal is spring loaded with a test mass in contact with the crystal. When exposed to acceleration, the test mass stresses the crystal by the force, resulting in a voltage generated across the crystal. A measure of this voltage is then a measure of acceleration. Output levels are typically in the mill volt ranges. The natural frequency in these devices may exceed 5 KHz, so that they can be used for vibration and shock measurements.

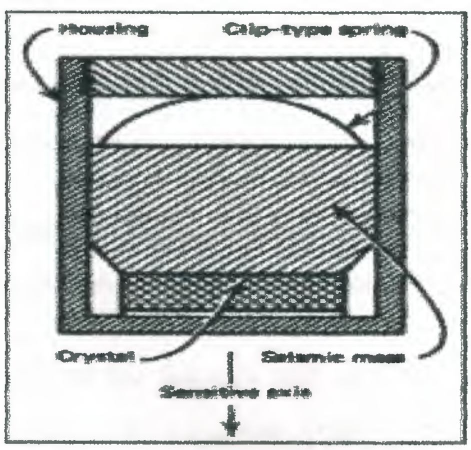

Figure 3.15: A piezoelectric accelerometer has a very high natural frequency.

3.4.4 Application

A few notes about the application of accelerometers will help in understanding how the selection of a sensor is made in a particular case.

3.4.4.1 Steady state Acceleration

In steady state acceleration, we are interested in a measure of acceleration what may vary in time but that is non-periodic. Thus, the stop-go motion of an automobile is an example of steady state acceleration. For these steady state accelerations, select a sensor having:

- Adequate range to cover expected acceleration magnitudes
- Natural frequency sufficiently high that its period is shorter than the characteristic time span over which the measured acceleration changes

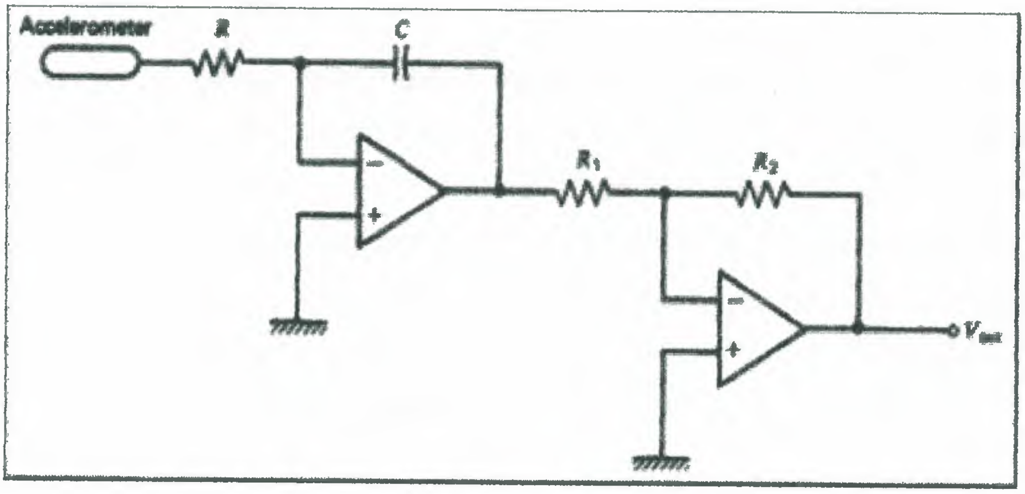

Figure 3.16: An integrator can be used to obtain velocity information from an accelerometer.

By using electronic integrators, the basic accelerometer can provide both velocity (first integration) and position (second integration) information.

Now we need an integrator to get the velocity and amplifier to provide the proper scale. Such a circuit is shown in figure 3.16. We chose T=RC=1 so that the integrator output is scaled at:

$$\left(1.43\frac{mV}{m/s^2}\right)\left(\frac{-1}{1s}\right) = -1.43\frac{mV}{m/s}$$

3.4.4.2 Vibration

The application of accelerometers for vibration first requires that the applied frequency is less than the natural frequency of the accelerometer. Second, one must be sure the stated range of acceleration measured will never exceed that of the specification for the device.

3.4.4.3 Shock

The primary elements of importance in shock measurements are that the device has a natural frequency that is greater than 1 KHz and a range typically greater than 500g. The primary accelerometer that can satisfy these requirements is piezoelectric type.

3.5 Pressure Sensors

The measurement and control of fluid (liquid and gas) pressure has to be one of the most common in all the process industries. Because of the great variety of conditions, ranges and materials for which pressure must be measured. There are many different types of pressure sensors designs. In the following paragraphs, the basic concepts of pressure are presented, and a brief description is given of the most common types of pressure sensors. We shall see that pressure measurement is often accomplished by conversion of the pressure information to some intermediate form, such as displacement, which is then measured by a sensor to determine the pressure.

3.5.1 Pressure Principles

Pressure is simply the force per unit area that a fluid exerts on its surroundings. If it is a gas, then the pressure of the gas is the force pre unit area that the gas exerts on the walls of the container that holds it. If the fluid is a liquid, then the pressure is the force per unit area that the liquid exerts on the container in which it is contained. Obviously, the pressure of the gas will be uniform on the walls that must enclose the gas completely. In a liquid, the pressure will vary, being greatest on the bottom of the vessel and zero on the top surface, which not be enclosed.

3.5.1.1 Static Pressure

The statements made in the previous paragraph are explicitly true for a liquid that is not moving in space, that is not being pumped through pipes or flowing through the channel. The pressure in cases where no motion is occurring is referred to as static pressure.

3.5.1.2 Dynamic Pressure

It is a fluid in motion; the pressure that it exerts on its surroundings depends on the motion. Thus, if we measure the pressure of the water in a hose with the nozzle closed, we find a pressure of, say, 40 pounds per square inch (note: force per unit area). If the nozzle is opened, the pressure is the hose will drop to a different value, say, 30 pounds per square inch. For this reason, a through description of pressure must note the circumstances under which it is measured. Pressure can depend on flow, compressibility of the fluid, external forces and numerous other factors.

3.5.1.3 Gauge Pressure

In many cases, the absolute pressure is not the quantity of major interest in describing the pressure. The atmosphere of gas that surrounds in the earth exerts a pressure, because of its weight, at the surface of the earth of approximately 14.7 psi. If a closed vessel at the earth's surface contains a gas at an absolute pressure of 14.7 psi, then it would exert no effective pressure on the walls of the container because the atmospheric gas exerts the same pressure from the outside. This gauge pressure is given by:

$$P_g = p_{abs} - p_{at}$$

Where, P_g = Gauge pressure

p_{abs} = Absolute pressure

p_{at} = Atmospheric pressure

3.5.1.4 Head Pressure

For liquids, the expression head pressure or pressure head is often used to describe the pressure of the liquid in a tank or pipe. This refers to the static pressure produced by the weight of the liquid above the point at which the pressure is being described. This pressure depends only on the height of the liquid above that point and the liquid density (mass per unit volume). In terms of an equation, if a liquid is contained in a tank, then the pressure at the bottom of the tank is given by

$$p = \rho gh$$

Where, p= Pressure in Pa

ρ = Density in Kg/m^3

g= Acceleration due to gravity ($9.8 m/s^2$)

h= Depth of liquid in m

3.5.2 Pressure Sensors (p>1atm)

In general, the design of pressure sensors employ for measurement of pressure higher than one atmosphere differs from those employed for pressure less than one atmosphere. In this section the basic operating principles of many types of pressure sensors used for the higher pressures are considered. We should be aware of many types of pressure sensors used for the higher pressures are considered. We should be aware that this is not a rigid separation, because we shall find many of these same principles employed in the lower (vacuum) pressure measurement. Measurement of pressure requires techniques for producing the displacement and means for converting such displacement into a proportional electrical signal.

3.5.2.1 Diaphragm

One common element used to convert pressure information into a physical displacement is the diaphragm shown in figure 3.17. If a pressure $p_1$exists of one side of the diaphragm and p_2 on the other, then a net force is exerted given by:

$$F = (p_2 - p\ )A$$

Where, A= Diaphragm area in m^2

p_1, p_2=pressure in N/ m^2

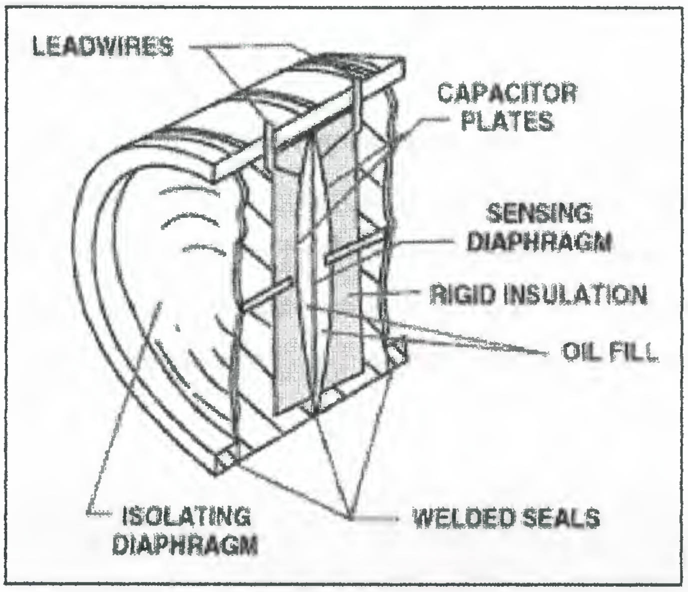

Figure 3.17: A diaphragm is used in many pressure sensors. Displacement varies with pressure difference.

A diaphragm is like a spring, and therefore extends or contracts until a Hook's law force is developed that balances the pressure difference force.

3.5.2.2 Bourdon tube

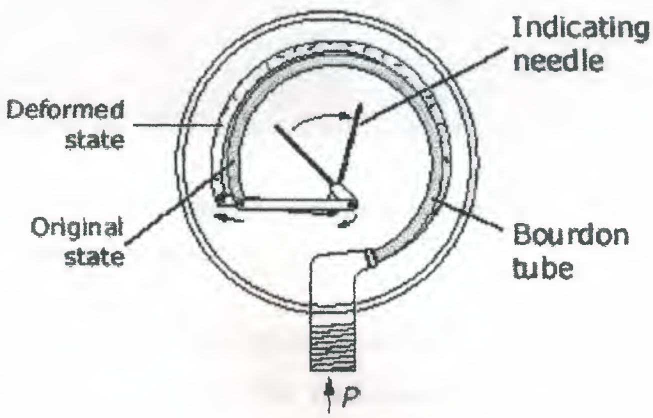

Figure 3.18: A bourdon tube is a common transducer for converting pressure of displacement.

A common pressure-to-displacement conversion is accomplished by a specially constructed tube, shown in figure 3.18. If a section of tubing is partially flatted and coiled as shown, then the application of pressure inside the tube causes the tube to uncoil. This then provides a displacement that is proportional to pressure.

3.5.2.3 Electronic Conversions

Many techniques are used to convert the displacements generated in the previous example into electronic signals. The simplest technique is to use mechanical linkage connected to a potentiometer. In this fashion, pressure is related to a resistance change. Other methods of conversion employ strain gauges directly on a diaphragm. LVDTs and other inductive devices are used to convert bellows or bourdons tube motions into proportional electrical signals.

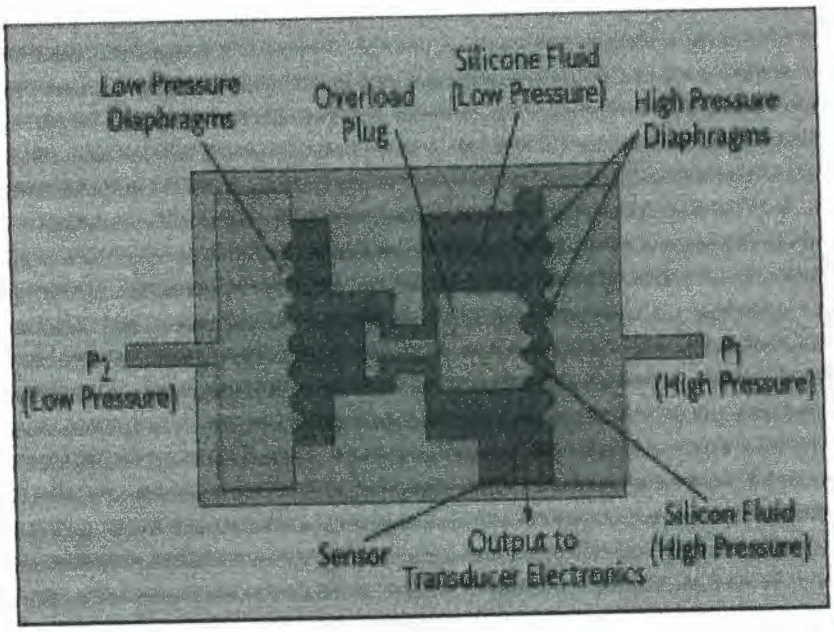

Figure 3.19: A differential pressure (DP) cell measures pressure difference with a diaphragm. A feedback system minimizes actual diaphragm motion.

Often, pressure measurement is accomplished using a diaphragm in a special feedback configuration, shown in figure 3.19. The feed back system keeps the diaphragm from moving, using an induction motor. The error in the feedback system provides an electrical measurement of the pressure.

3.5.3 Pressure sensors ($p < 1$ atm)

Measurements of pressure less than 1 atm are most conveniently made using purely electronic methods. There are three common methods of electronic pressure measurements. The first two devices are useful for pressure less than1 atm, down to about 10^{-3}atm. They are both based on the rate at which heat is conducted and radiated away from a heated filament placed in the low pressure environment. The heat loss is proportional to the number of gas molecules per unit volume, and thus, under constant filament current, the filament temperature is proportional to gas pressure. We have thus transduced a pressure measurement to a temperature measurement.

3.5.3.1 Pirani gauge

This gauge determines filament temperature through a measure of filament resistance. Filament excitation and resistance measurement are both performed with a bridge circuit. The response of resistance versus pressure is highly nonlinear.

3.5.3.2 Thermocouples

A second pressure transducer or gauge measures filament temperature using a thermocouple directly attached to the heated filament. In this case, ambient room temperature serves as a reference for the thermocouple, and the voltage output, which is proportional to pressure, is highly nonlinear. Calibration of both Pirani and thermocouple gauges depends on the type of the gas for which the pressure is being measured.

3.6 Flow Sensors

The measurement and control of flow can be said to be very heart of process industries. Continuously operating manufacturing processes involve the movement of raw materials, products and waste throughout the process. All such functions can be considered as flow, whether automobiles through an assembly line or methyl chloride through a pipe. It would be unreasonable to try to present every type of flow sensor, and in this case we shall consider flow on three broad fronts—solid, liquid and gas.

3.6.1 Solid Flow Meters

The most common solid flow measurement occurs when material in the form of small particles, such as crushed material or powder, is carried by the conveyer belt system or by some other host material. For example, if the solid is suspended in a liquid host, the combination is called slurry, which is then pumped through pipes like a liquid. We shall consider the conveyor system and leave slurry to be treated as liquid flow.

Conveyer Flow Concept

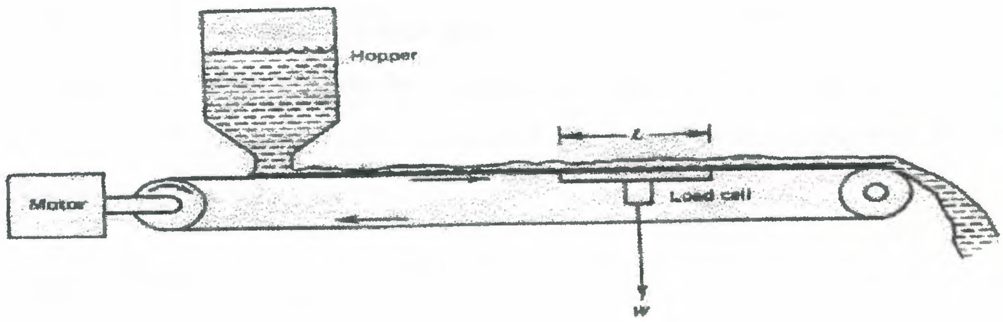

Figure 3.20: Conveyor system for illustrating solid flow measurement.

For solid objects, the flow is usually described by a specification of the mass or weight per unit time that is being transported by the conveyor system. The units will be in many forms, for example, Kg/min or lb/min. To make a measurement of flow, it is only necessary to weight the quantity of material on the some fixed length of the conveyor system. Knowing the speed of the conveyer allows calculation of the material flow rate.

In figure 3.20, a typical conveyor system is shown where material is drawn from the hopper and transported by the conveyor system. Assuming that the material can flow freely from the hopper, the faster the conveyor is moved, the faster material will flow from the hopper, and the greater the material flow rate on the conveyor. In this case, flow rate can be calculated from:

$$Q = \frac{WR}{L}$$

Where, Q= flow in Kg/min

W= weight of material on section of length L

R= conveyor speed in m/min

L= length of weighing plate-form in m

In this example with which we are working in figure 3.20, it is evident that the flow sensor is actually the assembly of conveyor, hopper opening and weighing plate-form. It is the actual weighing plate-form that performs the measurement from which flow rate is determined. We see that flow measurement becomes weight measurement. In this case, we have suggested that this weight is measured by means of a load cell, which is then a strain gauge measurement. Another popular device for weight measurement of moving systems like this is a LVDT that measures the droop of the conveyor at the point of measurement because of the material that it carries.

3.6.2 Liquid flow Meters

The measurement of liquid flow is involved in nearly every facet of the process industry. The conditions under which the flow occurs and the vastly different types of the material that flow result in a great many types of flow measurement methods.

Flow Units

1. Volume flow rate: Expressed as a volume delivered per unit time. Typical units are Gallons/min, m^3/hr, ft^3/hr.
2. Flow velocity: Expressed as the distance, the liquid travels in the carrier per unit time. Typical units are m/min. This is related to the volume flow rate by:

$$V = \frac{Q}{A}$$

Where, V= Flow velocity

Q= Volume flow rate

A= Cross-sectional area of flow carrier (pipe and so on)

3. Mass or weight flow rate: Expressed as mass or weight flowing per unit time. Typical units are Kg/hr, lb/hr. This is related to the volume flow rate by:

$$F=\rho Q$$

Where, F= Mass or weight flow rate

ρ= Mass density or weight density

Q= Volume flow rate

Pipe Flow Principle

The flow rate of liquids in pipes is determined primarily by the pressure that is forcing the liquid through the pipe. The concept of pressure head or simply head is often used to describe this pressure, because it is easy to relate the forcing pressure to that produced by a depth of liquid in a tank from which the pipe exit. In figure 3.21, flow through pipe p is driven by the pressure in the pipe, but this pressure is caused by the weight of liquid in the tank of height h (head). Many other factors affect the actual flow rate produced by this pressure, including liquid velocity, pipe size, pipe roughness (friction), turbulence of flowing liquid and others.

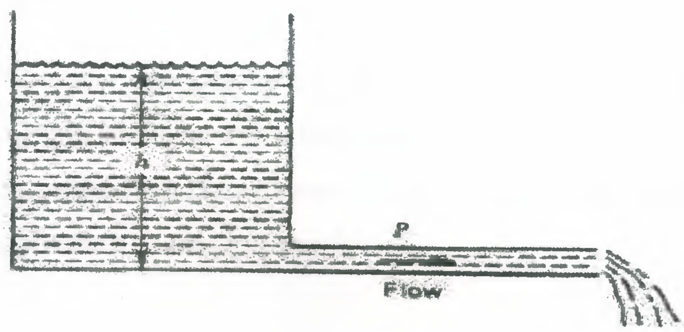

Figure 3.21: Flow through pipe P is determined in part by the pressure due to head h.

Restriction Flow Sensors

One of the most common methods of measuring the flow of liquids in pipes is given by introducing a restriction in the pipe and measuring the pressure drop that results across the restriction. When such a restriction increases, the pressure in the restriction is decreases. We find that there is relationship between the pressure drop and the rate of flow such that as the flow increases, the pressure drops. In particular, one can find an equation of the form:

$$Q = K\sqrt{\Delta p}$$

Where, Q= Volume flow rate

K= A constant for the pipe and liquid type

Δp = Drop in pressure across the restriction

The constant K depends on many factors, including the type of liquid, size of pipe, velocity of flow, temperature and so on. The type of restriction employed also will change the value of the constant used in this equation. The flow rate is linearly dependent not on the pressure drop but on the square root. Thus, if the pressure drop in a pipe is increased by a factor of 2 when the flow rate was increased, the flow rate will have increased only by a favor of 1.4 (the square root of 2). Certain standard types of restriction are employed in exploiting the pressure-drop method of measuring flow.

Obstruction Flow Sensor

Another type of flow sensor operates by the effect of flow in an obstruction placed in the flow stream. If the turbine is attached to a tachometer, a convenient electrical signal can be produced. In all these methods of flow measurement, it is necessary to present a substantial obstruction into the flow path to measure the flow.

Magnetic Flow Meter

if can be shown that if charged particles move across a magnetic field, a potential is established across the flow, perpendicular to the magnetic field. Thus, if the flowing liquid is also a conductor (even if not necessarily a good conductor) of electricity, the flow can be measured by allowing the liquid to flow through a magnetic field and measure the transverse potential produced. The pipe section in which this measurement is made must be insulated and a conductor itself, or the potential produced will be cancelled by currents in the pipe. A diagram of this type of flow meter is presented in figure 3.22. This type of sensor produces an electrical signal directly and is convenient for process control applications involving conducting fluid flow.

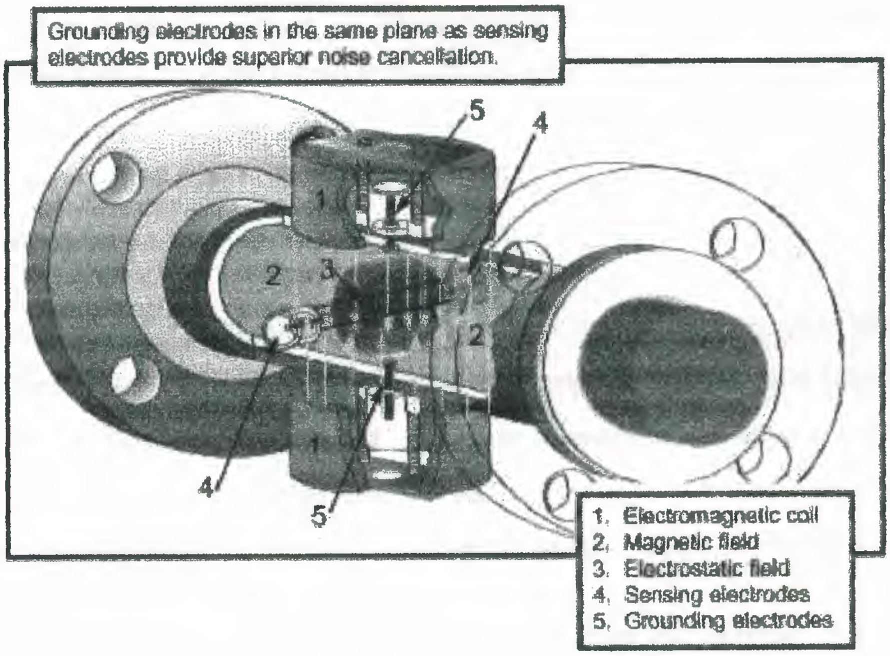

Figure 3.22: A magnetic flow meter will work only with conducting fluid.

4. OPTICAL SENSORS

4.1 Introduction

A desirable characteristic of sensors is that they have negligible effect on the measured environment, that is, the process. When electromagnetic (EM) radiation is used to perform process variable measurements, transducers that do not affect the system measured emerge. Such systems of measurements are called nonlinear or non-contact because no physical contact is made with the environment of the variable. Non-contact characteristic measurements often can be made from a distance.

In process control, EM radiation is either the visible or infrared light band is frequently use in measurement applications. The techniques of such applications are called optical because such radiation is close to visible light. A common example of optical transduction is measurement of an object's temperature by its emitted EM radiation. Another example involves radiation reflected off the surface to yield a level or displacement measurement.

Optical technology is a vast subject covering a span from geometrical optics, including lenses, prisms, gratings and the like to physical optics with lasers, parametric frequency conversion and nonlinear phenomena. These subjects are all interesting but all that is required for our purposes is a familiar with optical principles and knowledge of specific transduction and measurement methods.

4.2 Fundamentals of EM radiation

We are familiar with EM radiation as visible light. Visible light is all around us. EM radiation is also familiar in other forms, such as radio or TV signals and ultraviolet or infrared light.

This section covers a general method of characterizing EM radiation. Although much of what follows is valid for the complete range of radiation, particular attention is given to the infrared, visible and ultraviolet, because most sensor applications are concerned with these ranges.

4.2.1 Nature of EM Radiation

EM radiation is a form of energy that is always in motion, that is, it propagates through space. An object that releases or emits such radiation loses energy. One that absorbs radiation gains energy.

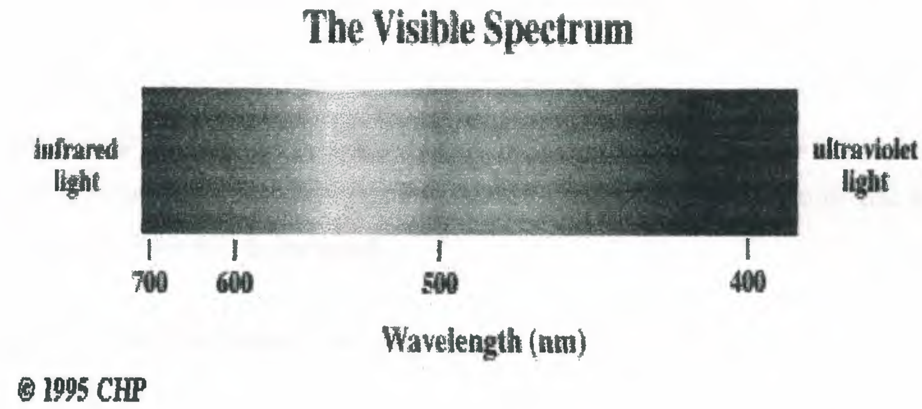

Figure 4.1: It covers everything of the electromagnetic radiation spectrum from very low frequency (VLF) radio to X-rays and beyond.

Figure 4.1 sows the range of EM radiation from very low frequency to very high frequency, together with the associated wavelength in meters and how the bands of frequency relate to our world.

Visible Light

The small band of radiation between approximately 400nm and 760nm represents visible light. This radiation band covers those wavelengths to which our eyes (or radiation detectors in our heads) are sensitive.

Infrared light

The longer wave radiation band that extends from the limit of eye sensitivity at 0.7μm to approximately 100μm is called infrared (IR) radiation. In some cases, the band is further subdivided so that radiation of wavelength 3 to 100μm is called far infrared.

4.3 Photo-detectors

An important part of any application of light to an instrumentation problem is how to measure or detect radiation. In most process control related applications, the radiation lies in the range from IR through visible and sometimes UV bands. The measurement sensors generally used are called photo-detectors to distinguish them from other spectral ranges of radiation such as RF detectors in radio frequency (RF) applications.

The particular characteristic related to EM radiation detection is the spectral sensitivity. This is given as graph of sensor response relative to the maximum as a function of radiation wavelength. Obviously, it is important to match the spectral response of the sensor to the environment in which it is to be used.

4.3.1 Photo-conductive Detectors

One of the most common detectors is based on the change in conductivity of a semiconductor material with radiation intensity. The change in conductivity appears as a change in resistance, so that these devices also are called photo-resistive cells.

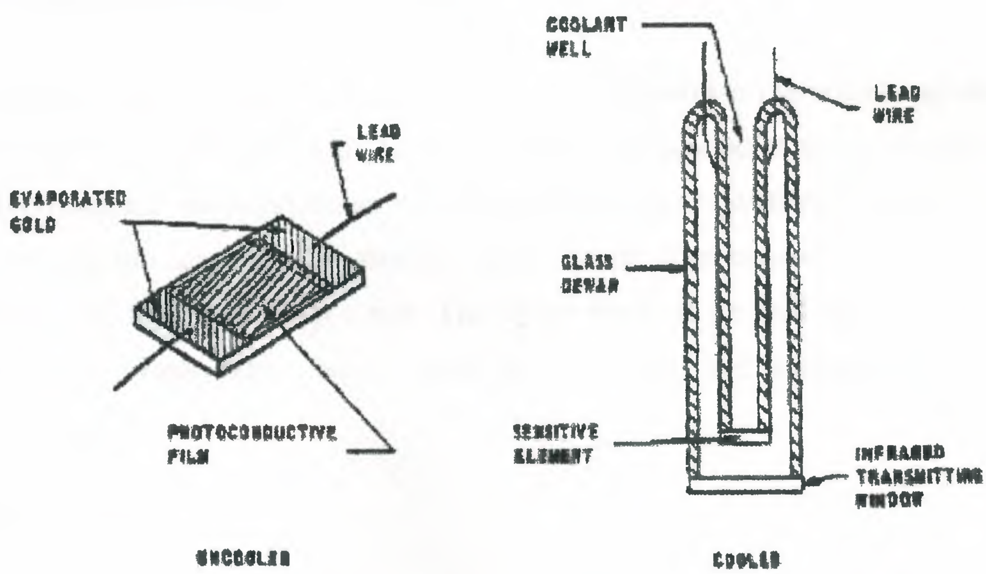

Figure 4.2: Photoconductive cell has a structure to maximize exposure and minimize resistance.

Principle

In a semiconductor photo-detector, a photon is absorbed and thereby excited into the conduction band, the semiconductor resistance decreases, making the resistance an inverse function of radiation intensity. For the photon to provide such an excitation it must carry at least as much energy as the gap.

Following equation shows the maximum wavelength as:

$$E_p = \frac{hc}{\lambda_{max}} = \Delta W_g$$

$$\lambda_{max} = \frac{hc}{\Delta W_g}$$

Where, h= Plank's constant

ΔW_g= Semiconductor energy gap (J)

λ_{max} = Maximum detectable radiation wavelength (m)

Any radiation with a wavelength greater than that predicted by the equation cannot cause any resistance change in the semiconductor.

It is important to note that the operation of a thermistor involves thermal energy excitation electrons in the conduction band. To prevent the photoconductor from showing similar thermal effects, it is necessary either to operate the devices at a controlled temperature or to make the gap too large for the thermal effects to produce conduction electrons. Both approaches are employed in practice. The upper limit of the cell spectral response is determined by many other factors, such as reflectivity and transparency to certain wavelengths.

Cell Characteristics

Two common photo-conductive semiconductor materials are cadmium sulfide (CdS) and cadmium selenide (SdSe). The characteristics of photo-conductive detectors vary considerably when different semiconductor materials are used as the active element.

Signal Conditioning

Various Op. Amp. Circuits using the photoconductor as a circuit element are used to convert the resistance change to a current or voltage change. It is important to note that the cell is a variable sensor, and therefore has some maximum power dissipation that cannot be exceeded. Most cells have dissipation from 50 to 500 mW, depending on size and construction.

4.3.2 Photovoltaic Detectors

Another important class of photo-detectors generates a voltage that is proportional to incident EM radiation intensity. These devices are called photovoltaic cells because of their voltage generating characteristics. They actually convert the EM energy into electrical energy. Applications are found as both EM radiation detectors and power sources converting solar radiation into electrical power. The emphasis of our consideration is on instrumentation type applications.

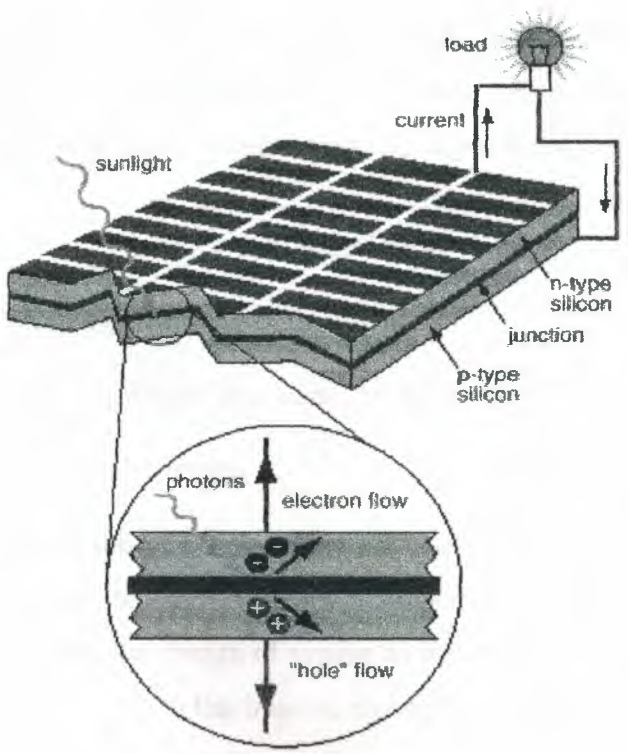

Figure 4.3: A photovoltaic solar cell is a giant pn junction diode.

Principle

Operating principles of the photovoltaic cell are best described by figure 4.3. We see that the cell is actually a giant diode that is constructed using a pn junction between appropriately doped semiconductors. Photons, striking the cell, pass through the thin p-diode upper layer and are absorbed by electrons in the n-layer, which cause formation of conduction electrons and holes. The depletion-zone potential of the pn junction then separates these conduction electrons and holes, which causes a difference of potential to develop across the junction. The upper terminal is positive and the lower negative. It is also possible to build a cell with a thin n-doped layer on top so that all polarities are opposite.

Photovoltaic cells also have a range of spectral response within which a voltage will be produced. Clearly, if the frequency is too small, the individual photons will have insufficient energy to create an electron-hole pair and no voltage will be produced. There is also upper limit to the frequency because of the optical effects such as radiation penetration through the cell.

Since the photovoltaic cell is a battery, it can be modeled as an ideal voltage source, Vc, in series with an internal resistance Rc as shown in figure 4.4. It turns out that the voltage source varies with light intensity in an approximately logarithmic fashion:

$$V_c = \mathrm{V_o} \log_e(1 + I_R)$$

Where, Vc= Open-circuit cell voltage

Vo= Constant, dependant on cell material

I_R= light intensity

The internal resistance of the cell also varies with light intensity. At low intensity the resistance may be thousands of ohms, whereas at higher intensities it may drop to less than fifty ohms. This complicates the design of system to derive maximum power from the cell, since the optimum load is equal to the internal resistance. Fortunately, at higher intensities the internal resistance is nearly constant.

Signal Conditioning

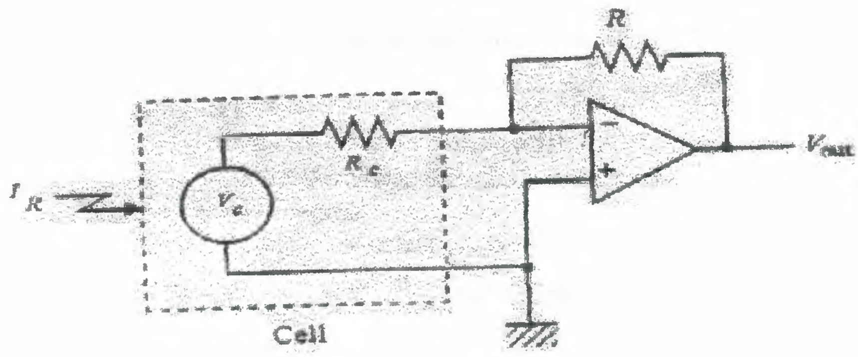

Figure 4.4: This circuit allows conversion of the cell short circuit current into a proportional voltage.

Since the short circuit current Isc is nearly related to radiation intensity, it is preferable to measure this current when using the cell in measurement and instrumentation.

Figure 4.4 shows how Isc can be obtained by connecting the cell directly to an Op Amp. Since the current to the Op Amp input must be zero, the feedback current through R must equal Isc. Therefore, the output voltage is given by:

$$V_{out} = RI_{SC}$$

Since the current is linearly proportional to light intensity, so it is the output voltage.

Cell Characteristics

The properties of photovoltaic cell depend on the material employed for the cell and the nature of the doping used to provide the n and p layer. Some cells are used only at low temperatures to prevent thermal effects from obscuring radiation detection. The silicon photovoltaic cell is probably the most common.

4.3.3 Photodiode Detectors

The previous section showed one way that the pn junction of a diode is sensitive to EM radiation, the photovoltaic effect. A pn diode is sensitive to EM radiation in another way as well, which gives rise to the fact that photodiodes as sensors.

NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical and Electronic Engineering

Sensors & Measurements

Graduation Project

EE- 400

Student: Muhammad Rizwan (991226)

Supervisor: Assist. Prof. Dr Kadri Bürüncük

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ABSTRACT

The classes of sensors that perform the control and measurement of temperature are known as thermal sensors. Resistance-temperature detectors, thermistors and Thermocouples are used to develop a voltage which is proportional to the change in temperature. Bimetallic strip converts temperature into a physical motion of metal elements. Gas and vapor-pressure temperature sensors convert temperature into gas pressure, which then is converted to an electrical signal or is used directly in pneumatic system.

Position, location, and displacement sensors include the Potentiometric, capacitive and LVDTs to convert the displacement linearly into voltage. Strain-gauges convert strain into a change of resistance. Accelerometers are used to measure the acceleration of objects because of rectilinear motion, vibration and shock. For gas pressure less than 1 atm, purely electrical techniques are used. Flow sensors are very important in the manufacturing world. Fluid flow through pipes or channels is typically measured by converting the flow information into pressure by restriction or obstruction in the flow system.

In the world of optical sensors there are four photo-detectors: photoconductive, photovoltaic, photo-emissive and photodiode. Each has its special characteristics relative to spectral sensitivity, detectable power and response time. Applications of optical techniques are particularly useful where contact measurement is difficult. Optical encoders play an important role in our industrial life to measure the motion of objects with Incremental encoders and exact position with Absolute encoders.

CONTENTS

1. INTRODUCTION

The component of an instrument that converts an input signal into a quantity that is measured by another part of the instrument and changed into a useful signal for an information-gathering system is called sensor.

There are multiple ways of sensing and estimating just about every physical attribute of the earth, atmosphere, and aircraft. Physical sensors that provide the raw data vary in quality, reliability, and the extent to which their values must be filtered and combined with others to obtain useful estimates.

The second chapter is about thermal sensors. The objective of this chapter stress the understanding required for application of measurement and instrumentation sensors. We shall be able to know about temperature and thermal energy, design the application of an RTD temperature sensor to specific problems in temperature measurements, design the application of thermistor to specific temperature measurement problems, design the application of thermocouples to specific temperature measurement problems, explanation of a bimetal strip for temperature measurement, operation of a gas thermometer and vapor pressure thermometer.

Third chapter is about mechanical sensors. This chapter describes the various types of mechanical sensors. We shall be able to know the definition of relationship among acceleration, velocity and position, design the application of an LVDT to a displacement measurement problem, types of accelerometer and the characteristics of each type, design of a system of strain measurements using metal foil strain gauges, definition of two types of pressure measurements with electrical signal output and system of flow measurements using differential pressure measurement.

The Fourth chapter is about optical sensors. This chapter describes the EM radiation in terms of frequency and spectrum, comparison of photoconductive, photovoltaic and photo-emissive type photo-detectors, incandescent and laser light sources by the characteristics of their light and design of the application of optical techniques to process-control measurement application.

2. THERMAL SENSORS

2.1 Definition

Process control is a term used to describe any condition, by which a physical quantity is regulated. There is no more widespread evidence of such control than that associated with temperature and other thermal phenomena. In our natural surrounding, some of the most remarkable techniques of temperature regulation are found in the bodily functions of living creatures. On the artificial side, humans have been vitally concerned with temperature control since the first fire waves struck for warmth. Industrial temperature regulation has always been of paramount important and becomes even more so the advance of technology. In this chapter we shall be concerned first with developing an understanding of the principles of the thermal energy and temperature and then with developing a working knowledge of the various thermal sensors employed for temperature measurements.

2.2 Temperature

If we are to measure the thermal energy, we must have some sort of units by which to classify the measurement. The original units used were "hot" and "cold". These were satisfactory for their time but are inadequate for modern use. The proper unit for energy measurement is the Joules of the sample in the SI system, but this would depend on the size of the material so it would indicate the total thermal energy.

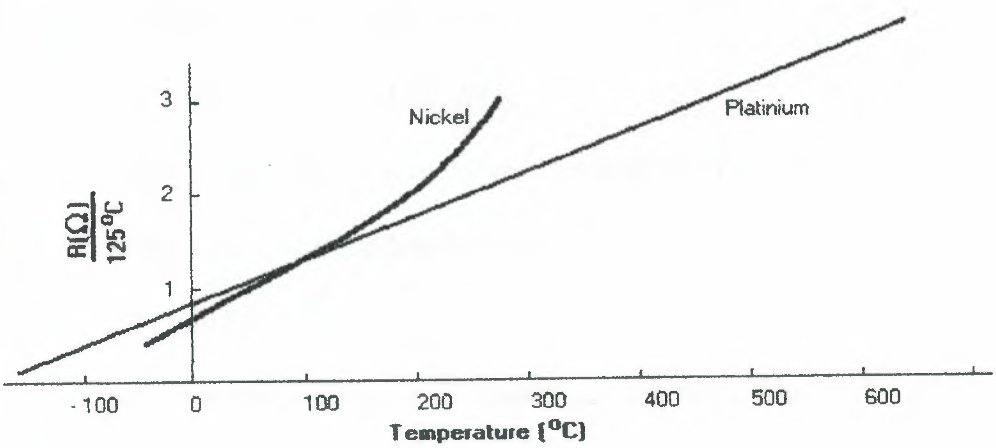

Figure 2.1: Metal resistance increases almost linearly with temperature but the slope is very small.

2.3 Resistance versus Temperature Approximation

An approximation of the resistance versus temperature curves of figure 2.1 shows that the curves are very nearly linear, that is, a straight line. In fact, when only short temperature spans are considered, the linearity is even evident. This fact is employed to develop approximate analytical equation for the resistance versus temperature of a particular metal.

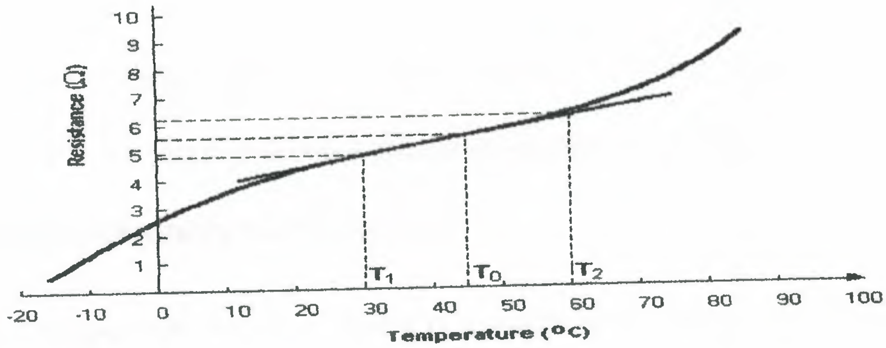

Figure 2.2: Line represents a linear approximation of resistance versus temperature between T_1 and T_2.

Linear Approximation

A linear approximation means that we may develop an equation for a straight line that approximates the resistance versus temperature (R-T) curve over some specified span. In the figure 2.2, we see a typical R-T curve of some material that represent temperature T_1 and T_2 as shown, and T_0 represents the midpoint temperature. The equation of this straight line is the linear approximation to the curve over a span T_1 to T_2 is written as:

$$R(T) = R(T_0)\,[1+\alpha_0\,\Delta T\,] \qquad T_1 < T < T_2$$

Where, $R(T)$ = Approximation of the resistance at temperature T

$R(T_0)$ = Resistance at temperature T_0

$\Delta T = T - T_0$

α_0 = Fractional change in resistance per degree of temperature at T_0

$$\alpha_0 = \frac{1}{R(T)}\,(\text{slope at } T_0)$$

Quadratic Approximation

A quadratic approximation to the R-T curve is more nearly accurate representation of R-T curve over some span of temperature. It includes both a linear term, as before, and a term that varies as the square of the temperature. Such an analytical approximation is usually written as:

$$R(T) = R(T_0)\,[1+\alpha_1\,\Delta T + \alpha_2\,(\Delta T)^2]$$

Where, α_1 = Linear fractional change in resistance with temperature

α_2 = Quadratic fractional change in resistance with temperature

2.4 Resistance-Temperature Detectors

A resistance temperature detector (RTD) is a temperature sensor that is based on the principle, that is, Metal resistance increases with temperature. Metals used in these devices vary from Platinum, which is very repeatable, quite sensitive and very expensive, to Nickel, which is not quite as repeatable, more sensitive and less expensive.

Sensitivity

An estimate of RTD sensitivity can be noted from typical values of α_0. For Platinum, this number is typically on the order of 0.004/ ^{0}C, and for Nickel a typical value is 0.005/ ^{0}C. Thus with platinum, for example, a change of 0.4Ω would be expressed for a 100Ω RTD if the temperature is changed by 1 ^{0}C. Usually a specification will provide the calibrated information either as a graph of resistance versus temperature or as a table of values from which the sensitivity can be determined.

Response Time

In general, RTD has a response time of 0.5 to 5 seconds or more. The slowness of response is due principally to the slowness of thermal conductivity in bringing the devices into thermal equilibrium with its environment. Generally, time constants are specified either for a "free air" condition (or its equivalent) or an "oil bath" condition (or its equivalent). In the

former case, there is poor thermal contact and hence slow response, and in the latter, good thermal contact and fast response. These numbers yield a range of response times depending on the application.

Construction

An RTD, of course, is simply a length of wire whose resistance is to be monitored as a function of temperature. The construction is typically such that the wire is wound on a form (in a coil) to achieve small size and improve thermal conductivity to decrease response time. In many cases, the coil is protected from the environment by the sheath or protective tube that inevitably increases response time but may be necessary in the hostile environments. A loosely applied standard sets the resistance at multiples of 100Ω for the temperature of 0 ^{0}C.

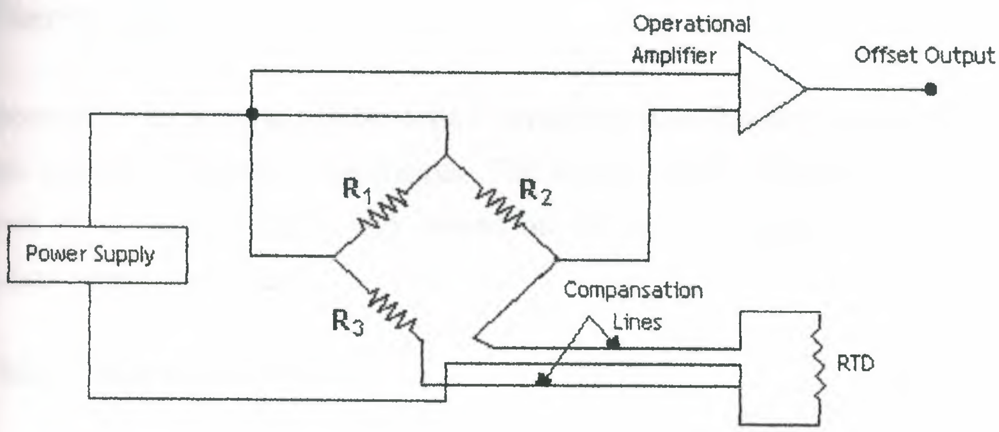

Figure 2.3: Note the compensation lines in this typical RTD signal conditioning circuit.

Signal Conditioning

In view of the very small fractional changes of resistance with temperature (0.4%), the RTD is generally used in a bridge circuit. Figure 2.3 illustrates the essential features of such a system. The compensation line in the R_3 leg of the bridge is required when lead lengths are so long that thermal gradients along the RTD leg may cause changes in line resistance. These changes show up as false information, suggesting changes in RTD resistance. By

using the compensation line, the same resistance changes also appear on the R_3 side of the bridge and cause no net shift in the bridge null.

Dissipation Constant

Because the RTD is a resistance, there is an I^2R power dissipated by the device itself that causes a slight heating effect, self-heating. This may also cause an erroneous reading or even upset the environment in delicate measurement conditions. Thus the current though the RTD must be kept sufficiently low and constant to avoid self-heating. Typically, dissipation constant is provided in RTD specifications. This number relates the power required to raise the RTD temperature by one degree of temperature. Thus, 25mW / ^{0}C dissipation constant shows that if I^2R power losses in the RTD equal to 25mW, then the RTD will be heated by 1^0C.

2.5 Thermistors

The thermistor represents to another class of temperature sensors that measures temperature through changes of material resistances. The characteristics of these devices are very different from those of RTDs and depend on the peculiar behavior of semiconductor resistances versus temperature.

2.5.1 Thermistor Characteristics

A thermistor is a temperature sensor that has been developed from the principles of semiconductor resistance change with temperature. The particular semiconductor material used varies widely to accommodate temperature ranges, sensitivity, resistance ranges and other factors. The devises are usually mass produced for a particular configuration and tables or graphs of resistance versus temperature are provided for calibration.

Sensitivity

The sensitivity of the thermistor is a significant factor in the application. Changes in resistance of 10% per ^{0}C are not uncommon. Thus, a thermistor with a nominal resistance of 10 KΩ at some temperature may change by 1 KΩ for a 1^0C change in temperature.

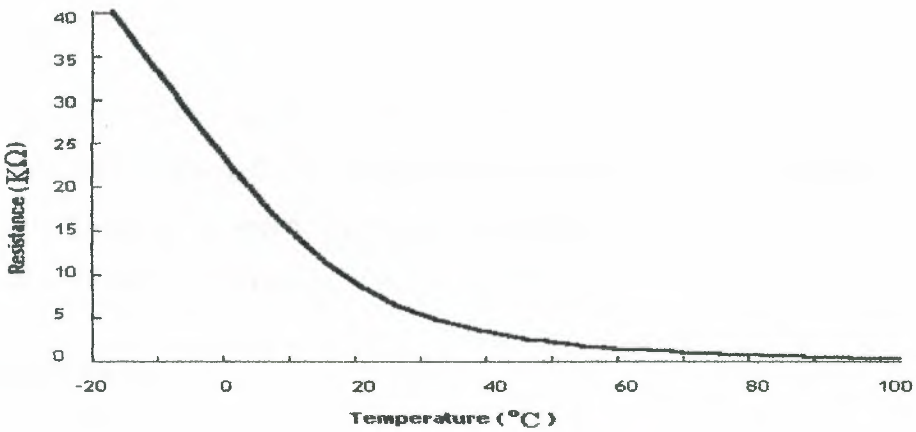

Figure 2.4: Thermistor resistance versus temperature is highly nonlinear and usually has a negative slope.

Construction

Because the thermistor is a bulk semiconductor, it can be fabricated in many forms. Thus, common forms include discs, beads and rods, varying in size from a bead of 1mm to a disc of several centimeters in diameter and several centimeters thick. By variation of doping and use of different semiconductor material, a manufacturer can provide a wide range of resistance values at any particular temperature.

Range

The temperature range of thermistor depends on the material used to construct the sensor. In general, there are three range limitation effects:

1. Melting or deterioration of the semiconductor
2. Deterioration of encapsulation material
3. Insensitivity at higher temperatures

The semiconductor material melts or deteriorates as the temperature is raised. This condition generally limits the upper temperature to less than 300 ^{0}C. At the low end, the principle limitation is that the thermistor resistance becomes very high, into the MΩ's, making practical applications difficult. For thermistor shown in figure 2.4, if extended, the lower limit is about -80^{0}C, where its resistance has risen to over 3MΩ! Generally the lower limit is -50^{0}C to -100^{0}C.

Response Time

The response time of the thermistor depends principally on the quantity of material present and the environment. Thus, for the smallest bead thermistor in an oil bath (good thermal contact), a response of ½ second is typical. The same thermistor in still air will respond with typical response of 10seconds.

Signal Conditioning

Because a thermistor exhibits such a large change in resistance with temperature, there are many circuit applications. In many cases, however, a bridge circuit is used because the nonlinear features of the thermistors make it difficult as an actual measurement device. Because these devices are resistances, care must be taken to ensure that power dissipation in the thermistor does not exceed limits specified or even interfere with the environment for which the temperature is being measured. Dissipation constants are quoted for thermistors as the power in milli-watts required to raise a thermistor's temperature 1^0C above its environment.

2.6 Thermocouples

In previous section we have considered the change in material resistance as a function of temperature. Such a resistance change is considered a variable parameter property in the sense that the measurement of resistance, and thereby temperature, requires external power resources. There exists another dependence of electrical behavior of materials on temperature that forms the basis of a large percentage of all temperature measurements. This effect is characterized by a voltage-generating sensor in which an electromotive force (emf) is produced that is proportional to temperature. Such an emf is found to be almost linear with temperature and very repeatable for constant materials. Devices that measure temperature on the basis of this thermoelectric principle are called thermocouples (TCs).

2.6.1 Thermoelectric Effect

The basic theory of the thermocouple effect is found from a consideration of the electrical

and thermal transport properties of different metals. In particular, when a temperature differential is maintained across a given metal, the vibration of atoms and motion of electrons is affected so that a difference in potential exists across the material. This potential difference is related to the fact that electrons in the hotter end of material have more thermal energy than those in the cooler end, and thus tend to drift toward the cooler end. This drift varies for different metals at the same temperature because of differences in their thermal conductivities. If a circuit is closed by connecting the ends through another conductor, a current is found to flow on the closed loop.

The proper description of such an effect is to say that an emf has been established in the circuit that is causing the current to flow. In figure 2.5a, we see a pictorial representation of this effect where two different metals A and B are used to close the loop with the connecting junctions at temperature T_1 and T_2.

We could not close the loop with the same metal because the potential differences across each leg would be the same, and thus no net emf would be present. The emf produced is proportional to the difference in temperature between the two junctions. Theoretical treatments of this problem involve the thermal activities of the two metals.

Seebeck Effect

Using solid state theory, the aforementioned situation may be analyzed to show that its emf can be given by integration over temperature

$$\varepsilon = \int_{T_2}^{T_1} (Q_A - Q_B)dt$$

Where, ε = emf produced in volts

T_1, T_2 = junction temperature in K

Q_A, Q_B = thermal transport constants of the two metals

This equation, which describes the Seebeck effect, shows that the emf produced is proportional to the difference in temperature and, further, to the difference in the metallic thermal transport constants.

Thus, if the metals are the same, the emf is zero, and if the temperature is also same, the emf is also zero. In practice it is found that the two constants Q_A *and* Q_B are nearly independent of temperature and that an approximate linear relationship exits as

$$\varepsilon = \alpha\,(T_2 - T_1)$$

Where α is a constant in volts/K

However, the small but finite temperature dependence of Q_A *and* Q_B is necessary for accurate consideration.

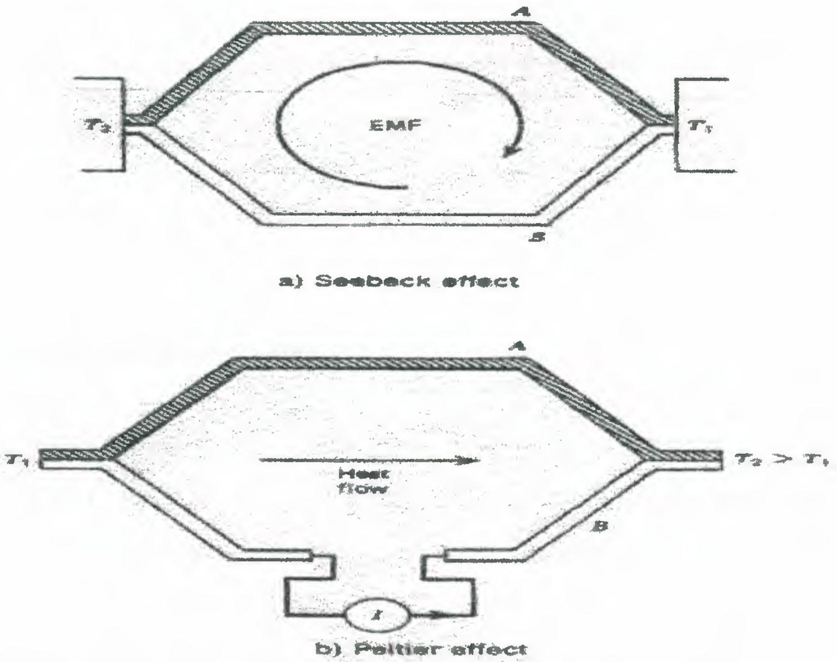

Figure 2. 5: The seebeck and peltier effects refer to the relation between emf and temperature in a two wire system.

Peltier Effect

An interesting and sometimes useful extension of the same thermoelectric properties occurs when the reverse of Seebeck effect is considered. In this case, we construct a closed loop of two different metals, A and B, as before. However, an external voltage is applied to the system to cause a current to flow in the circuit as shown in figure 2.5b. Because of the

different electro-thermal transport properties of the metals, it is found that one of the junctions will be heated and the other cooled; that is, the device is a refrigerator! This process is referred to as the Peltier effect. Some practical applications of such device, such as cooling small electronic parts, have been employed.

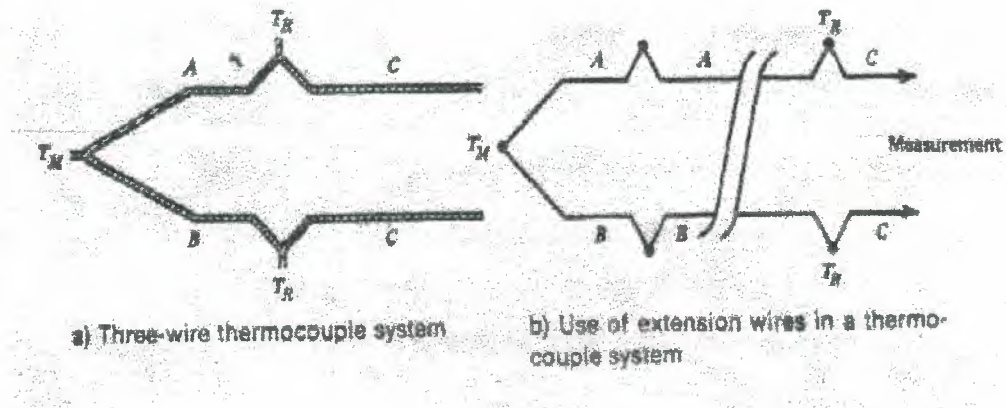

Figure 2.6: Practical measurements with a thermocouple system often employ extension wires to move the reference to a more secure location.

2.6.2 Thermocouple Characteristics

To use the Seebeck effect as the basis of a temperature sensor, we need to establish a definite relationship between the measured emf of the thermocouple and the unknown temperature. We see first that one temperature must already be known because the Seebeck voltage is proportional to the difference between the junction temperatures. Furthermore, every connection of different metals made in the thermocouple loop for measuring devices, extension leads, and so on will contribute an emf, depending on the difference in metals and various junction temperatures. To provide an output it is definite with respect to the temperature to be measured, an arrangement such as that shown in figure 2.6a is used. This shows that the measurement junction T_M is exposed to the environment whose temperature is to be measured. This junction is form of metals A and B as shown.

Two other junctions then are formed to a common metal C, which then connects to the measurement apparatus. The reference junctions are held at a common, known temperature T_R, the reference junction temperature. When an emf is measured, such problem as voltage

drops across resistive elements in the loop must be considered. In this arrangement, an open circuit voltage is measured (at high impedance) that is then a function of only the temperature difference ($T_M - T_R$) and the type of metal A and B. The voltage produced has a magnitude of the temperature difference and a polarity depend on the absolute magnitude of the temperature difference and a polarity dependant on which temperature is larger, reference or measurement junction. Thus, it is not necessary that the measurement junction have a higher temperature than the reference junctions, but both magnitude and sign of measured voltage must be noted.

To use the thermocouple to measure a temperature, the reference temperature must be known and the reference junctions must be held at the same temperature. The temperature must be constant, or at least not very much. In most industrial environments this would be difficult to achieve if the measurement junction and reference junction were close. It is possible to move the reference junction to a remote location without upsetting the measurement process by the use of extension wires, as shown in figure 2.6b. A junction is formed with the measurement system, but to wires of the same type as the thermocouple. These wires may be stranded and of different gauges, but they must be of the same type of metal as the thermocouple. The extension wires now can be run a significant distance to the actual reference junction.

2.6.3 Thermocouple Sensors

The use of a thermocouple for a temperature sensor has evolved from an elementary process with crudely prepared thermocouple constituents into a precise and exacting technique.

Sensitivity

Typically the range of the thermocouple voltages is less than 100mV. The actual sensitivity strongly depends on the type of the signal conditioning employed and on the TC itself.

Construction

A thermocouple by itself is, of course, simply a welded or even a twisted junction between

two metals, and in many cases that is the construction. There are cases, however, where the TC is sheathed in a protective covering or even sealed in the glass to protect the unit from a hostile environment. The size of the TC wire is determined by the application and can range from 0.02mm micro-wire in refined biological measurements of temperature.

Response

Thermocouple time response is simply related to the size of the wire and any protective material used with the sensor. The time response equates to how long it takes the TC system to reach thermal equilibrium with the environment.

Large industrial TCs using thick wire or encased in stainless steel sheathing may have time constants as high as 10to 20 seconds. On the other hand, a TC made from very small gauge wire can have a time constant as small as 10 to 20ms. Often the time constant is specified under conditions of good thermal contact and poor thermal contact as well, so that you can account for the environment.

Signal Conditioning

The key element in the use of thermocouples is that the output voltage is very small, typically less than 50mV. This means that considerable amplification will be necessary for practical application; in addition the small signal levels make the devices susceptible to electrical noise. In most cases the thermocouple is used with a high gain differential amplifier.

Noise

Perhaps the biggest obstacle to the use of the thermocouple for temperature measurement in Industry is their susceptibility to electrical noise. First, the voltages generated are less than 50mV, and often are 2 or 3mV, and in the industrial environment it is common to have hundreds of mill volts of electrical noise generated by large electrical machines in any electrical system. Second, a thermocouple constitutes an excellent antenna for pickup of noise from electromagnetic radiation in the radio, TV and microwave bands. In short, a

bare thermocouple may have many times more noise than temperature signal at a given time.

To use thermocouples effectively in industry, a number of noise reduction techniques are employed. The following three are the most popular:

The extension or lead wires from the thermocouple to the reference junction or measurement system are twisted ad them wrapped with a grounded foil sheath.

The measurement junction itself is grounded at the point of measurement. The grounding is typically to the inside of the stainless steel sheath that covers the actual thermocouple.

An instrumentation amplifier that has excellent common mode rejection is employed for measurement.

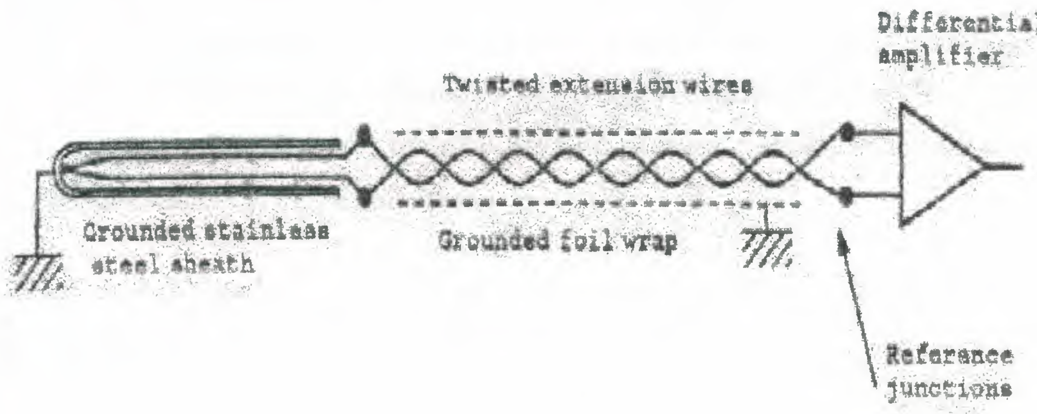

Figure 2.7: Since TC voltages are small, great care must be taken to protect against electrical noise such as by shielding, twisting, and differential amplification.

Figure 2.7 shows a typical arrangement for measurement with a thermocouple. Note that the junction itself is grounded through the stainless steel sheath. The differential amplifier must have very good common mode rejection to aid in the noise rejection process.

The advantages of grounding the measurement junction is that the noise voltage will be distributed equally on each wire of TC. Then the differential amplifier will, at least partially, cancel this noise because the voltage on these lines is subtracted.

Twisting is done to decouple the wires from induced voltages from varying electric and magnetic fields that permeate our environment. In principle, equal voltages are induced in each loop of the twisted wires but of opposite phase, so they cancel.

2.7 Bimetallic Strips

This type of the temperature sensor has the characteristics of being relatively inaccurate, having hysteresis, having relatively slow response time, and being low in cost. Such devices are use in numerous applications, particularly where an ON/OFF cycle rather than smooth or continuous control is described.

2.7.1 Thermal Expansion

We have seen that greater thermal energy causes the molecules of the solids to execute the greater amplitude and higher frequency vibrations about their average positions. It is natural to expect that an expansion of volume of a solid would accompany this effect, as the molecules tend to occupy more volume on the average with their vibrations. This effect varies in degree from material to material because of many factors, including molecular size and weight, lattice structure and others.

If we have a rod of length L_o at temperature T_o and the temperature is raised to a new value T, then the rod will be found to have new length L, given by:

$$L = L_0\left[1 + \gamma \Delta T\right]$$

Where, γ is the linear thermal expansion coefficient appropriate to the material of which the rod is made.

2.7.2 Bimetallic Sensor

The thermal sensor exploiting the effect discussed previously occurs when two materials with grossly different thermal expansion coefficients are bounded together. Thus, when heated, the different expansion rates cause the assembly curve shown in figure 2.8. This effect can be used to close the switch contact or to actuate an ON/OFF mechanism when

the temperature increases to some appropriate set point. This effect also is used for temperature indicators, by means of assemblages, to convert the curvature into dial rotation.

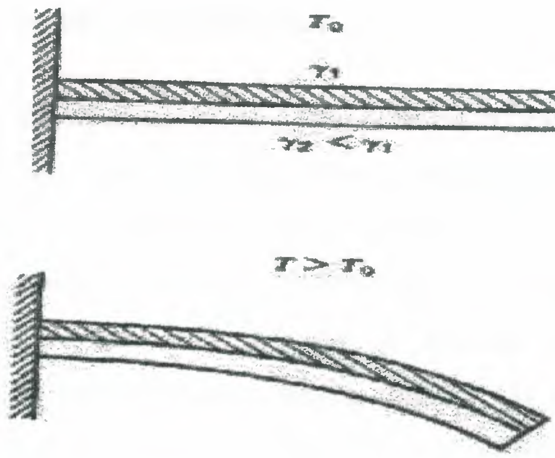

Figure 2.8: A bimetallic strip will curve when exposed to a temperature change because of differential thermal expansion coefficients. Metal thickness has been exaggerated in this figure.

2.8 Gas Thermometers

The operational principle of the gas thermometer is based on a basic law of gases. In particular, if a gas is kept in a container at constant volume and the pressure and temperature vary, then the ratio of gas pressure and temperature is a constant.

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Where, P_1, T_1 = Absolute pressure and temperature (in K) in state 1

P_2, T_2 = Absolute pressure and temperature (in K) in state 2

Because the gas thermometer converts temperature information directly into pressure signal, it is particularly useful in pneumatic systems. Such transducers are also advantageous because they are not moving parts and no electric stimulation is necessary. For electronic analog or digital process control applications, however, it is necessary system for converting the pressure to electrical signals. This type of sensor is often used with bourdon tubes to produce directly indicating temperature meter and recorders. The gas

most commonly employed is Nitrogen. Time response is slow in relation to the electrical devices because of the greater mass that must be heated.

2.9 Vapor-pressure Thermometers

A vapor pressure thermometer converts temperature information into pressure as does the gas thermometer, but it operates by the different process. If a closed vessel is partially filled with liquid, then the space above the liquid will consist of evaporated vapor of the liquid at a pressure that depends on the temperature. If the temperature is raised, more liquid will vaporize and the pressure will increase. A decrease in temperature will result in condensation of some of the vapor, and the pressure will decrease. Thus, vapor pressure depends on temperature. Different materials have different curves of pressure versus temperature, and there is no simple equation like that for a gas thermometer. Figure 2.9 shows a curve a curve of vapor pressure versus temperature for methyl chloride, which is often employed in these sensors. The pressure available is substantial as the temperature rises. As in case of gas thermometers, the range is not great and response time is slow (20 seconds or more) because the liquid and vessel must be heated.

2.10 Liquid expansion Thermometers

Just as solid experiences an expansion in dimension with temperature, a liquid also shows an expansion in volume with temperature. This effect forms the basis for the traditional liquid-in-glass thermometers that are so common in temperature measurement. The relationship that governs the operation of this device is:

$$V(T) = V(T_0)[1 + \beta \, \Delta T]$$

Where, V(T) = volume at temperature T

$V(T_0)$ = volume at temperature T_0

β = volume thermal expansion constant

In actual practice, the expansion effects of the glass container must be accounted for to obtain high accuracy in temperature indications. This type of temperature sensor is not

commonly used in process control work because further transduction is necessary to convert the indicated temperature into an electrical signal.

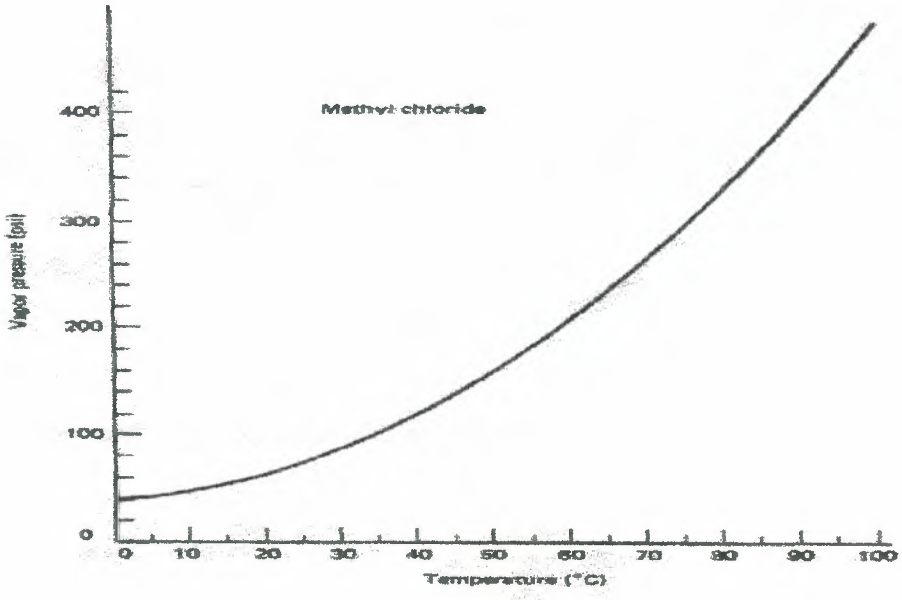

Figure 2.9: Vapor pressure curve for Methyl chloride.

2.11 Solid State Temperature Sensors

Many integrated manufacturers now market solid state temperature sensors for consumer and industrial applications. These devices offer voltages that vary linearly with temperature over a specified range. The operating temperature of these sensors is typically in the range of -50 °C to 150 °C. The time constant in good thermal contact varies in the range of 1 to 5 seconds, whereas in poor thermal contact it may increase to 60 seconds or more.

These sensors are easy to interface to control systems and computers, and are becoming popular for measurement within the somewhat limited range they offer. An important application is to provide automatic reference temperature compensation for thermocoupler. This is provided by connecting the sensors to the reference junction block of the TC and providing signal conditioning so that the reference corrections are automatically provided to the TC output, as shown in figure 2.10.

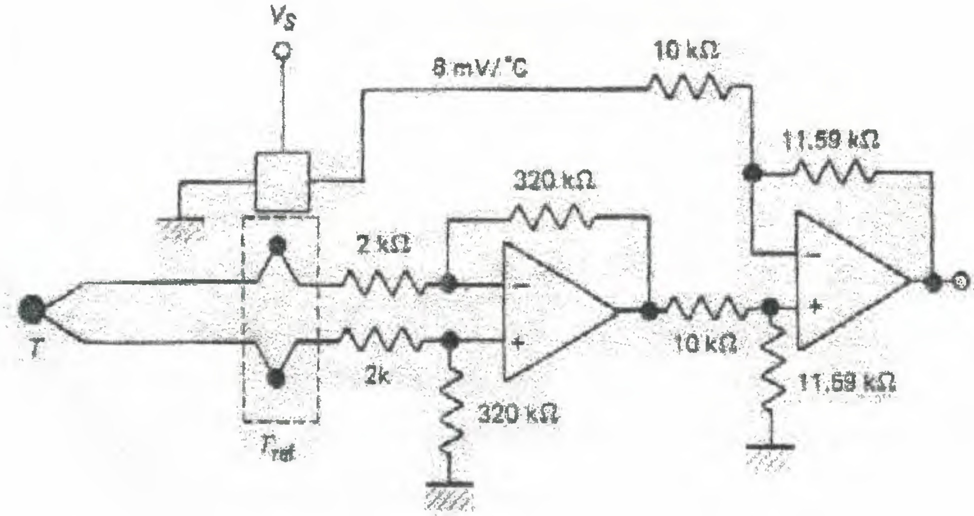

Figure 2.10: It shows the circuit diagram of solid state thermal sensor.

3. MECHANICAL SENSORS

3.1 Introduction

The class of sensors used for the measurement of mechanical phenomena is of special significance because of the extensive use of these devices through out the process control industry. In many instances, an interrelation exists by which a sensor designed to measure some mechanical variable is used to measure another variable. To learn to use the mechanical sensors, it is important to understand the mechanical phenomena themselves and the operating principles and application details of the sensors.

3.2 Displacement, Location or Position Sensors

The measurement of displacement, position or location is an important topic in the process industries. Examples of industrial requirements to measure these variables are many and varied and the required sensors are also of greatly varied designs. To give a few examples of measurement needs:

1. Location and position of objects on a conveyer system
2. Orientation of steel plates in a rolling mill
3. Liquid or solid level measurements
4. Location and position of work piece in automatic milling operation
5. Conversion of pressure to a physical displacement

3.2.1 Potentiometric

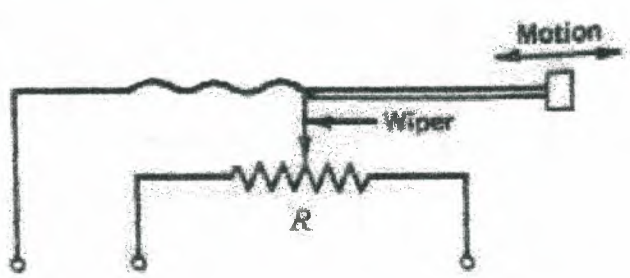

Figure 3.1: Potentiometric displacement sensor.

The simplest type of displacement sensor involves the action of displacement in moving the wiper of a potentiometer. This device then converts linear or angular motion into a changing resistance that may be converted directly to voltage and/or current signals. Such potentiometric device often suffer from the obvious problems of mechanical wear, friction in wiper action, limited resolution in wire-wound units and high electronic noise.

3.2.2 Capacitive and Inductive

The second class of sensors for displacement measurement involves changes in capacity and inductance.

Capacitive

The basic operation of a capacitive sensor can be seen from the familiar equation for a parallel-plate capacitor.

$$C = K\varepsilon_o \frac{A}{d}$$

Where, K= The dielectric constant

ε_o= Permittivity = 8.85 pF/m

A= Plate common area

d= Plate separation

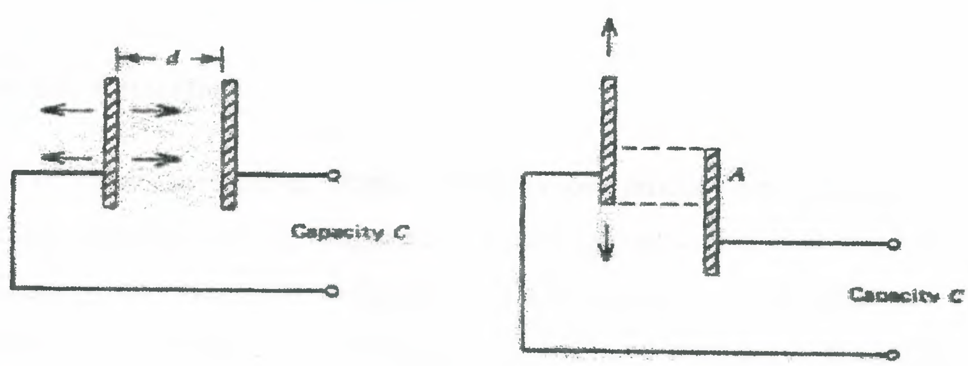

Figure 3.2: Capacity varies with distance between plates and common area. Both are used in sensors.

There are three ways to change the capacity:

- Variation of distance between the plates (d)
- Variation of shared area of the plates (A)
- Variation of the dielectric constant (K)

Inductive

If a permeable core is inserted into an inductor as shown in figure 3.3, the net inductance is increased. Every new position of the core produces a different inductance. In this fashion, the inductor and movable core assembly may be used as a displacement sensor. An AC bridge or other active electronic circuit sensitive to inductance then may be employed for signal conditioning.

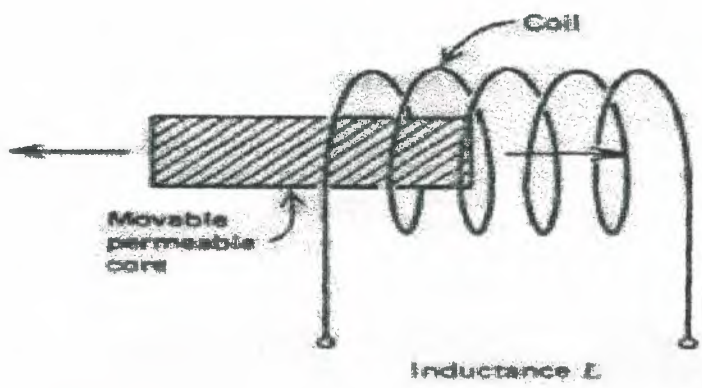

Figure 3.3: The variable reluctance displacement sensor changes the inductance in coil in response to core motion.

3.2.3 Variable Reluctance

The class of variable-reluctance displacement sensors differs from the inductive in that moving core is used to vary the magnetic flux coupling between two or more coils, rather than changing am individual inductance. Such devices find application in many circumstances for the measure of both translational and angular displacements. Many configurations of these devices exist, but the most common and extensively used is called a linear variable differential transformer (LVDT).

3.2.3.1 LVDT

The LVDT is an important and common sensor for displacement in the industrial environment. Figure 3.4 shows that an LVDT consists of three coils of wire wounded on a hollow form. A core of permeable material can slide freely through the centre of the form. Flux formed by the primary, which is excited by some AC source as shown. Flux formed by the primary is linked to the two secondary coils, inducing an AC voltage in each coil.

When the core is centrally located in assembly, the voltage induces in each primary is equal. If the core moves to one slide or the other, a larger AC voltage will be induced in one coil and a smaller AC voltage in the other because of changes in the flux linkage associated with the core as shown in figure 3.4.

When the core centrally located, the net voltage is zero. When the core is moved to one side, the net voltage amplitude will increase. In addition, there is a change in phase with respect to the source when the core is moved to one side or the other.

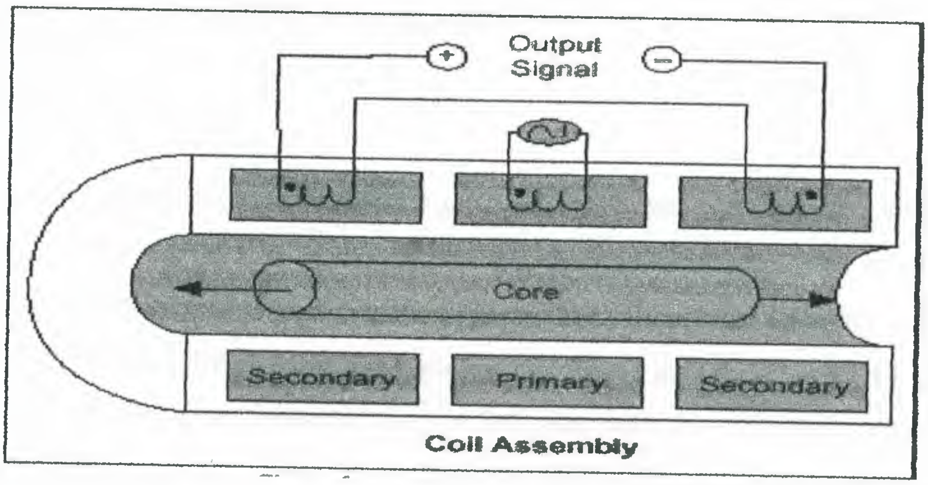

Figure 3.4: The LVDT has a movable core with three coils.

3.2.4 Level Sensors

The measurement of solid or liquid level calls for a special class of displacement sensor. The level measured is most commonly associated with material in a tank or hopper. A great variety of measurement techniques exists, as the following representative examples show.

Mechanical

One of the most common techniques for level measurement, particularly for liquids, is a float that is allowed to ride up and down with level changes. This float, as shown in figure 3.5a, is connected by linkage to a secondary displacement measuring system such as potentiometric device or an LVDT core.

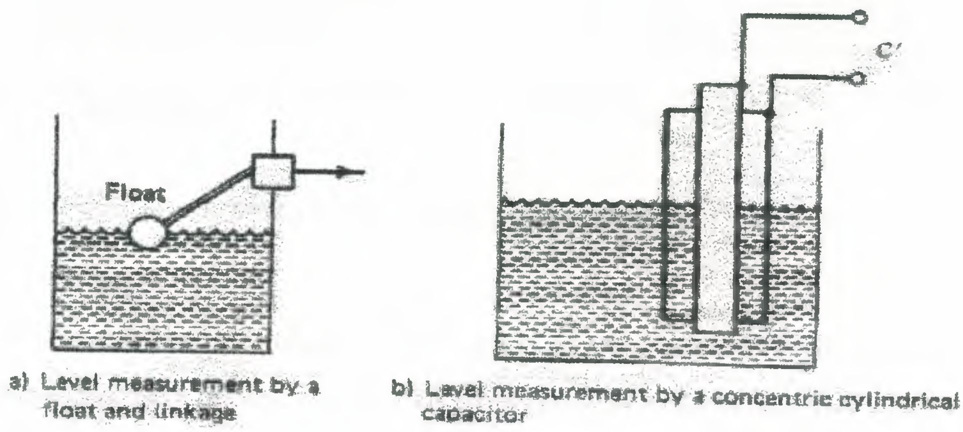

Figure 3.5: There are many level measurement techniques.

Electrical

They are several purely electrical methods of measuring level. For example, one may use the inherent conductivity of a liquid or solid to vary the resistance seen by the probes inserted into the material. Another common technique is illustrated in figure 3.5b. In this case, two concentric cylinders are contained in a liquid tank. The level of the liquid partially occupies the space between the parallel, one with the dielectric constant of air (≈ 1) and the other with that of the liquid. Thus, variation of liquid level causes variation of the electrical capacity measured between the cylinders.

Ultrasonic

The use of the ultrasonic reflection to measure level is favored because it is a non-sensitive technique; that is, it does not involve placing anything in the material. Figure 3.6 shows the external and internal techniques.

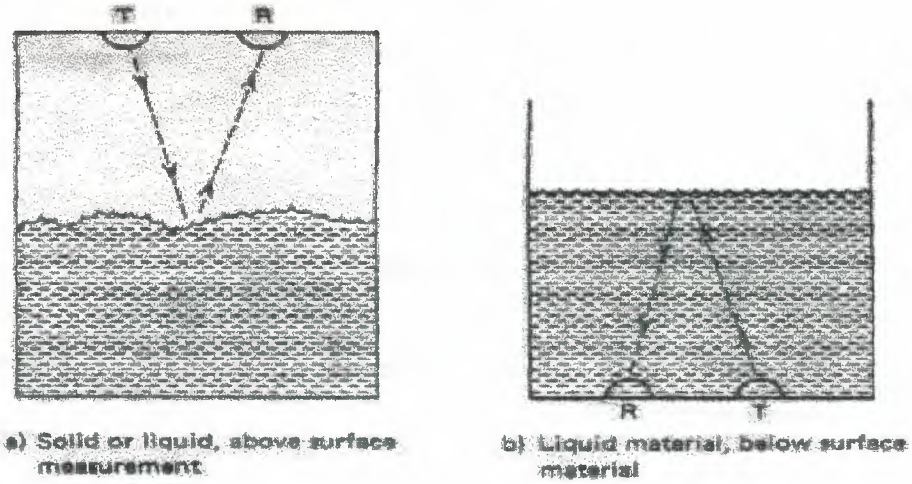

Figure 3.6: Ultrasonic measurement needs no physical contact with material, just a transmitter T and receiver R.

Obviously, the external technique is better suited to solid material level material. In both cases the measurement depends on the length of time taken for reflections of an ultrasonic pulse from the surface of the material. Ultrasonic techniques based on reflection time also have become popular for ranging measurements.

Pressure

For liquid measurement, it is also possible to make a no contact measurement of level if the density of the liquid is known. This method based on the well-known relationship between pressure at the bottom of a tank and the height and density of the liquid.

3.3 Strain Sensors

Although not obvious at first, the measurement of strain in solid objects is common in process control. The reason it is not obvious that strain sensors are used as a secondary step in sensors to measure many other process variables, including flow, pressure, weight and acceleration. Strain measurements have been used to measure pressures from over a million pounds per square inch to those within living biological systems. We shall first review the concept of strain and how it is related to the forces that produce it and then discuss the sensors used to measure strain.

3.3.1 Strain and Stress

Strain is the result of the application of force to solid objects. The forces are defined in a special way described by general term, stress.

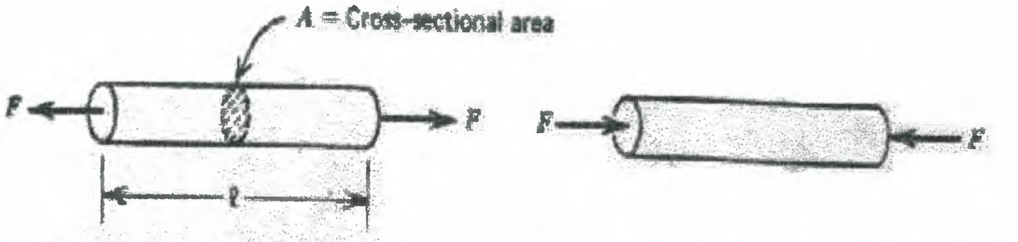

Figure 3.7: Tensile and Compressional stress can be defined in terms of forces applied to a uniform rod.

A special case exists for the relation between force applied to a solid object and the resulting deformation of that object is called strain. Solids are assemblages of atoms in which the atomic spacing has been adjusted to render the solid in equilibrium with all external forces acting on the solid. This spacing determines the physical dimensions of the solid. If the applied forces are changed, the object atoms rearrange themselves again to come into equilibrium with the mew set of forces. This rearrangement results in a change in physical dimensions that is referred to as a deformation of the solid.

The study of this phenomenon has evolved into an exact technology. The effect of applied force is referred to as a stress and the resulting deformation as a strain. To facilitate a proper analytical treatment of the object, stress and the resulting are carefully defined to emphasize the physical properties of the material being stressed and the specific type of stress applied. We delineate here the three most common types of stress-strain relationships.

Tensile stress Strain

In figure 3.7, the nature of a tensile force is shown as a force applied to a sample of material so as to elongate or pull apart sample. In this case, the stress is defined as:

$$Tensile\ stress = \frac{F}{A}$$

Where, F= Applied force in N

A= Cross-sectional area of the sample in m^2

We see that the units of stress are N/m^2 in SI units and they are like a pressure.

The strain in this case is defined as the fractional change in the length of the sample and Strain is unitless quantity.

$$Tensile\ stress = \frac{\Delta L}{L}$$

Compressional stress Strain

The only differences between Compressional and tensile stress are the direction of applied force and the polarity of the change in length. Thus, in a Compressional stress, the force pressed in on a sample, as shown in figure 3.7b.

Shear stress Strain

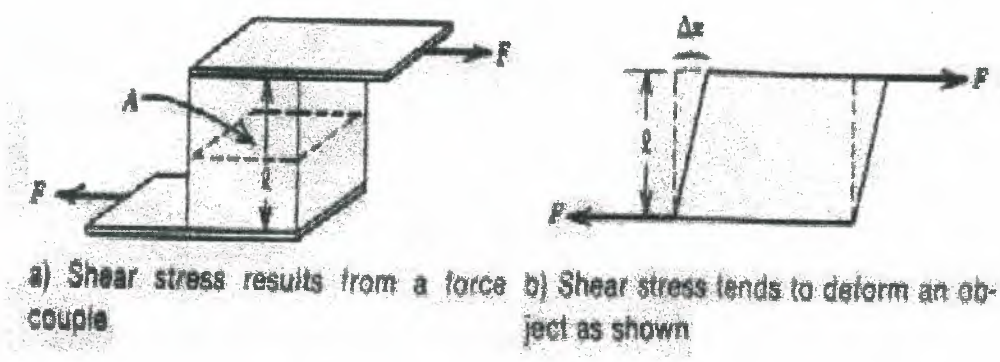

Figure 3.8: Shear stress is defined in terms of a couple that tends to deform a joining member.

Figure 3.8, shows the nature of shear stress. In this case, the force is applied as a couple (that is, not along the same line), tending to shear off the solid object that separates the force arms. In this case the stress is again the same as that of previous sections.

3.3.2 Strain gauge Principle

Metal resistance of a sample is given as:

$$R_o = \rho \frac{L_o}{A_o}$$

Where, R_o= Sample resistance in Ω

ρ = Sample resistivity in Ω-m

L_o= Length in m

A_o= Cross sectional area in m^2

Suppose the sample is now stressed by the application of a force F as shown in figure 3.7a. Then we know that the material elongates by some amount ΔL so that the new length is L= L+ ΔL. It is also true that in such a stress-strain condition, although the sample lengths, its volume will remain nearly constant. Because the volume unstressed V= L_o A_o, it follows that if the volume remains constant and the length increases, then the area must decrease by some amount ΔA:

$$V = L_o A_o = (L_o + \Delta L)(Ao - \Delta A)$$

Because both length and area have changed, we find that the resistance of the sample will have also changed:

$$R = \rho \frac{L_o + \Delta L}{A_o - \Delta A}$$

By combining these two equations, we shall find:

$$R \cong \rho \frac{L_o}{A_o}\left(1 + 2\frac{\Delta L}{L_o}\right)$$

For which we conclude that the change in resistance is:

$$R \cong 2R_o \frac{\Delta L}{L_o}$$

This is the final equation that underlies the use of metal strain gauges because it shows that the strain ΔL/L converts directly into a resistance change.

Measurement Principle

The basic technique of strain gauge (SG) measurement involves attaching (gluing) a metal wire or foil to the element whose strain is to be measured. As stress is applied and the element deforms, the SG material experiences the same deformation, if it is securely attached. Because the strain is a fractional change in length, the change in SG resistance reflects the strain of both the gauge and the element to which it is secured.

Temperature Effects

If not for temperature compensation effects, the aforementioned method of SG measurement would be useless. To see this, we need only note that the metals used in SG construction have linear temperature coefficients of $\alpha \cong 0.004/^{o}C$, typically for most metals. Temperature changes of 1°C are not uncommon in measurement conditions in the industrial environment.

3.3.3 Metal Strain Gauges (SGs)

Metal SGs are devices that operate on the principles discussed earlier. The following items are important to understanding SG applications.

Gauge Factor

Relation between strain and resistance change is approximately true. Impurities in the metal, the type of metal, and other factors lead to slight corrections. An SG specifications always indicates the correct relation through statement of a gauge factor (GF), which is defined as:

$$\text{GF}=\frac{\Delta R/R}{Strain}$$

Where, $\Delta R/R$ = Fractional change in gauge resistance because of strain

Strain= $\Delta L/L$ = Fractional change in Length

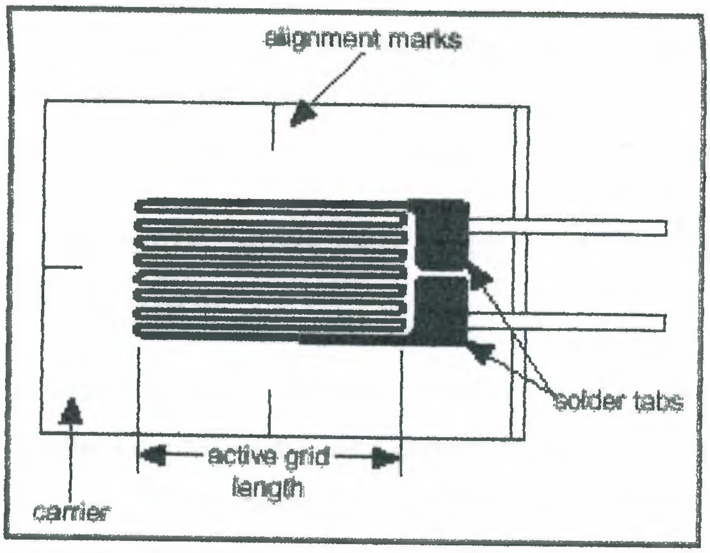

Figure 3.9: A metal strain gauge is resistance for a given strain and is easier to measure.

For metal gauges, this number is always close to 2. For some special alloys and carbon gauges, the GF may be as large as 10. A high gauge factor is desirable because it indicates a larger change in resistance for a given strain and is easier to measure.

Construction

Strain gauges are used in two forms, wire and foil. The basic characteristics of each type are the same in terms of resistance change for a given strain. The design of SG itself is such as to make it very long in order to give a large enough nominal resistance (to be practical) and to make the gauge of sufficiently fine wire or foil so as not to resist strain effects. Finally, often the gauge sensitivity is made unidirectional; that is, it responds to strain in only one direction. In figure 3.9, we see the common pattern of SGs that provides these characteristics. By folding the material back and forth as shown, we achieve a long length to provide high resistance. Further, if a strain is applied transversely to the SG length, the pattern will tend to unfold rather than stretch, with no change in resistance. These gauges are usually mounted on a paper backing that is bonded (using epoxy) to the elements whose strain is to be measured. The nominal SG resistances (no strain) available are typically 60, 120, 240, 350, 500 and 1000 Ω.

Signal Conditioning

The effects are critical in the signal conditioning techniques used for SGs. The first is the small, fractional changes in resistance that require carefully designed resistance measurement circuits. A good SG system might require a resolution of 2μm/m strain.

The second effect is the need to provide some compensation for temperature effects to eliminate masking changes in strain.

The bridge circuit provides the answer to both effects. The sensitivity of the bridge circuit for detecting small changes in resistance is well known. Further more, by using the dummy gauge, we can provide the required temperature compensation. In particular, the dummy is mounted in an intensive orientation but in the same proximity so the active SG. Then, both gauges change in resistance from temperature effects, but the detector does mot respond to a change in both strain gauges. Only the active SG responds to strain effects. This is called one arm bridge. The sensitivity of this bridge to strain can be found by consideration of the equation for bridge offset voltage also shown in terms of strain.

$$\Delta V \approx -\frac{V_S}{4}\frac{\Delta R}{R} = -\frac{V_S}{4}GF\frac{\Delta L}{L}$$

Another configuration that is often employed uses active strain gauges in two arms of the bridge and is thus called a two armed bridge. All four arms are strain gauges, but two are for temperature compensation only. This has the added advantage of doubling the sensitivity. The bridge off-null voltage in terms of strain is given by:

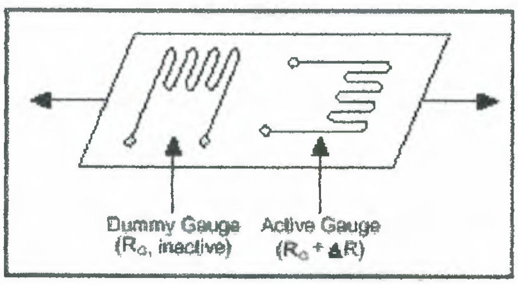

Figure 3.10: The structure shows how four gauges can be used to measure beam bending. Two respond to bending and two are for temperature compensation.

$$\Delta V = -\frac{V_S}{2} GF \frac{\Delta L}{L}$$

Obviously, the placement of the active and dummy gauges in the environment and in the bridge circuit is important. Figure 3.10shows a common application of the strain gauges to measure deflection of a cantilever beam. This is a beam that is supported at only one end, and deflects as shown when the load is applied.

3.3.4 Semiconductor Strain Gauges (SGs)

The use of semiconductor material, notably silicon, for SG application has increased over the past few years. There are presently several disadvantages to these devices compared to the metal variety, but numerous advantages for their use.

Principles

As in the case of metal SGs, the basic effect is change of resistance with strain. In this case of a semiconductor the resistivity also changes with strain along with the physical dimensions. This is due to changes in electron and hole mobility with changes in crystal structure as strain is applied. The net result is a much larger gauge factor than is possible with metal gauges.

Gauge Factor

The semiconductor device gauge factor (SG) is still given by equation:

$$\text{GF} = \frac{\Delta R/R}{Strain}$$

However the value of the semiconductor gauge factor varies between -50 and -200. Thus, resistance changes will be factors from 25 to 100 times those available with metal SGs. It must also be noted, however, that these devices are highly nonlinear in resistance versus strain. In other worlds, the gauge factor is not a constant as the strain takes place. Thus, the gauge factor may be -150 with no strain, but drop (non-linearity) to -50 at 5000µm/m.

Construction

The semiconductor strain gauge physically appears as a band or strips of material with electrical connection, as shown in figure 3.11. The gauge is either bonded directly into the test element or, if encapsulated, is attached by the encapsulation material. These SGs also appear as IC assemblies in configurations used for other measurements.

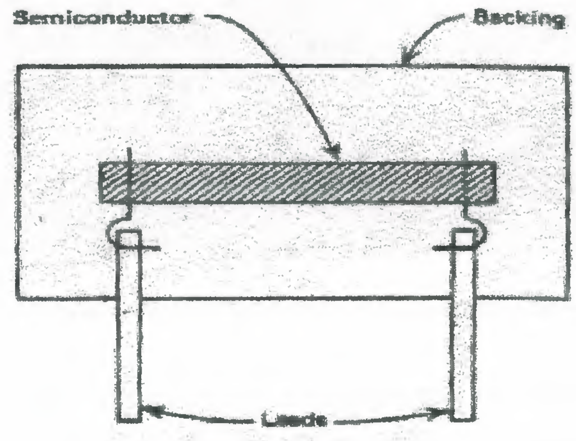

Figure 3.11: Typical semiconductor strain gauge structure.

Signal Conditioning

The signal conditioning is still physically a bridge circuit with temperature compensation. An added problem is the need for linearization of the output because the basic resistance versus strain characteristics is nonlinear.

3.3.5 Load Cell

One important direct application of SGs is for the measurement of force or weight. These transducer devices, called load cell, measure deformations produced by the force or weight. In general, a beam or yoke assembly is used that has several strain gauges mounted so that the application of a force causes a strain in the assembly that is measured by the gauges. A common application uses one of these devices in support of a hopper or feed of dry or liquid materials. A measure of the weight through a load cell yields a measure of the quantity of material in the hopper. Generally, these devices are calibrated so that the force (weight) is directly related to the resistance change. Forces as high as 5MN (approximately10^6 Lb) can be measured with an appropriate load cell.

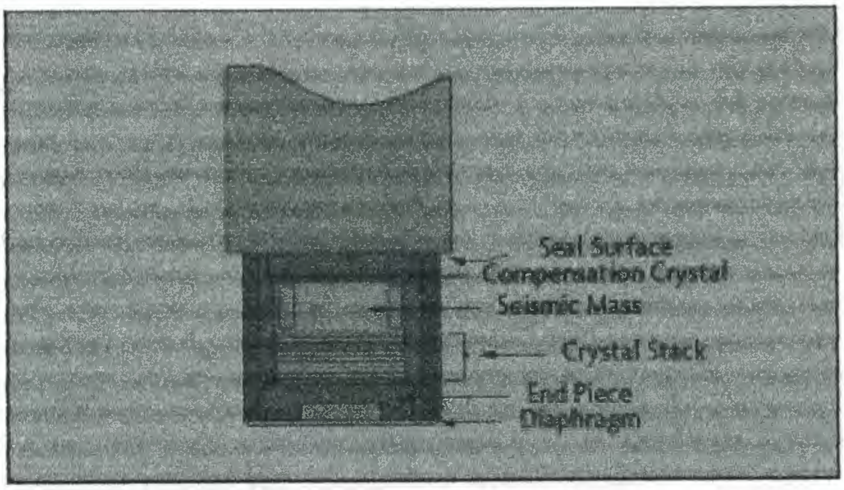

Figure 3.12: figure shows how load cell works in order to change in length or deformation.

The form of load cell considered in figure 3.12 is fine and illustrating principles, but real load cells cannot be made in this simple way. The problem is that forces applied to the top of the load cell may cause it to lean or bent, instead of simply compressing. In such a case, one side surface of the beam may experience compression while the other side undergoes tension. Obviously, this will alter the correct interpretation of the result.

Practical load cells are made with yoke assemblies designed so that mounted strain gauges cannot be exposed to stresses other than those caused by the Compressional force applied to that cell.

3.4 Motion sensors

Motion sensors are designed to measure the rate of change of position, location or displacement of an object that is occurring. If the position of an object as a function of time is x(t), then the first derivative gives the speed of the object, v(t), which is called the velocity if a direction is also specified. If the speed of the object is also changing, then the first derivative of the speed gives the acceleration. This is also the second derivative of the position.

The primary form of the sensor is the accelerometer. This device measures the acceleration a(t) of an object. Thus in accelerometer we have a sensor that can provide the acceleration, speed or position information.

3.4.1 Types of motion

The design of a sensor to measure the motion is often tailored to the type of motion that is to be measured. It will help us to understand these sensors if we have a clear understanding of these type of motions.

The proper unit of acceleration is meter per second squared (m/s^2). Then speed will be in meter per second (m/s) and position of course in meters (m). Often, acceleration is expressed by comparison with the acceleration due to gravity at the earth's surface. This amount of acceleration, which is approximately 9.8 m/s^2, is called a "gee", which is given as a bold **g** in the text.

Rectilinear

This type of motion is characterized by velocity and acceleration which is composed of straight-line segments. Thus, objects may accelerate forward to a certain velocity, decelerator to a stop, reverse, and so on. There are many types of sensors designed to handle this type of motion. Typically, maximum acceleration is less than few **g**s, and a little angular motion is allowed. If there is angular motion, then several rectilinear sensors must be used, each sensitive to one line of motion.

Thus, if vehicle is to be measured, two transducers may be used, one to measure motion in forward direction of vehicle motion and the other perpendicular to the forward axis of the vehicle.

Angular

Some sensors are designed to measure only relations about some axis, such as the angular motion of the shaft of a motor. Such devices can not be used to measure the physical displacement of the whole shaft, but only its rotation.

Vibration

In normal experiences of daily living, a person rarely experiences accelerations that vary from I g by more than a few percent. Even the severe environments of a rocket launching involve accelerations of only 1g to 10g. On the other hand, if an object is placed in periodic motion about some equilibrium position, very large peak accelerations may result that reach to 100g or more. This motion is called vibration. Clearly, the measurement of acceleration of this magnitude is very important to industrial environments, where vibrations are often encountered from machinery operations. Often, vibrations are somewhat random in both the frequency of periodic motion and the magnitude of displacements from equilibrium. For analytical treatments, vibration is defined in terms of a regular periodic motion.

Shock

A special type of acceleration occurs when an object that may be in uniform motion or modestly accelerating is suddenly brought to rest, as in a collision. Such phenomena are the result of very large accelerations, or actually decelerations, as when an object is dropped from some height onto a hard surface. The name shock is given to decelerations that are characterized by very short times, typically in the order of milliseconds, with peak accelerations over 500g.

3.4.2 Accelerometer

These are several physical processes that can be used to develop a sensor to measure acceleration. In applications that involve flight, such as aircraft and satellite, accelerometers are based on properties of rotating masses. In industrial world, however, the most common design is based on combination of Newton's law of mass acceleration and Hook's law of spring action.

Spring mass System

Newton's law simply states that if a mass (m) is undergoing an acceleration (a) then there must be a force (F) acting on the mass and given by F=ma. Hook's law states that if a spring constant (k) is stretched (extended) from its equilibrium position for a distance Δx, then there must be a force acting on the spring given by F=k Δx.

In figure 3.13a, we have a mass that is free to slide on a base. The mass is connected to the base by a spring that is in its un-extended state and exerts no force on the mass. In figure 3.13 b, the whole assembly is accelerated to the left, as shown. Now the spring extends in order to provide the force necessary to accelerate the mass. This condition is described by equation Newton's and Hook's law:

$$ma = k\,\Delta x$$

Where, k= Spring constant in N/m

Δx= Spring extension in m

m= mass in Kg

a= acceleration in m/s^2

This equation allows the measurement to be reduced to a measurement of spring extension (linear displacement) because

$$a = \frac{k}{m}\,\Delta x$$

If the acceleration is reversed, the same physical argument would apply, except that the spring is compressed instead of extended. Above equation still describes the relationship between spring displacement and acceleration.

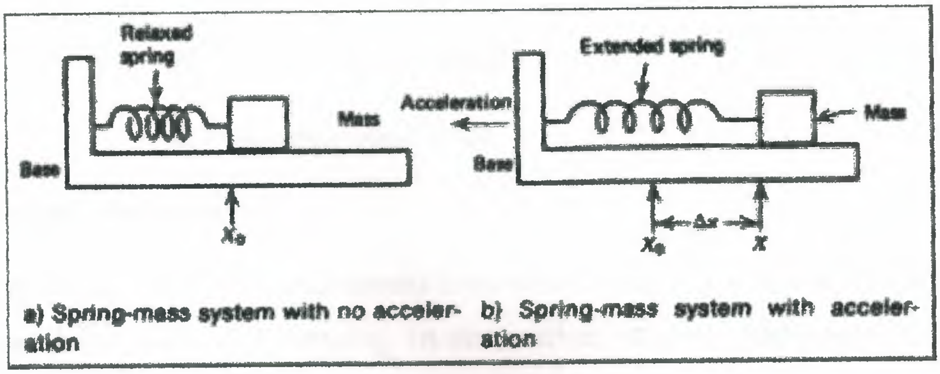

Figure 3.13: The basic spring mass accelerometer.

The spring-mass principle applies to many common accelerometer designs. The mass that converts the acceleration to spring displacement is referred to as the test mass or seismic mass. We see then that acceleration measurement reduces to linear displacement measurement; most designs differ in how this displacement measurement is made.

Natural frequency and Damping

On close examination of the simple principle just described, we find another characteristic of spring-mass system that complicates the analysis. In particular, a system consisting of a spring and attached mass always exhibits oscillations at some characteristic natural frequency. Experiments tell us that if we pull a mass back and then release it (in the absence of acceleration), it will be pulled back by the spring, overshoot the equilibrium and oscillate back and forth. Only friction associated with the mass and base eventually brings the mass to rest. Any displacement measuring system will respond to this oscillation as if an actual acceleration occurs. This natural frequency is given by:

$$f_N = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

The friction that eventually brings the mass to the rest is defined by a damping coefficient (α), which has the units of S^{-1}. In general, the effect of the oscillation is called transient response, described by a periodic damped signal whose equation is

$$X_T(t) = X_o e^{-\alpha t} \sin(2\pi\ f_N t)$$

Where, $X_T(t)$ = Transient mass position

X_o = peak position, initially

α = damping coefficient

3.4.3 Types of Accelerometer

The variety of accelerometers used results from different applications with requirements of range, natural frequency and damping. In this section, various accelerometers with their special characteristics are reviewed. The basic difference is in the method of mass displacement measurement. In general, the specification sheets for an accelerometer will give the natural frequency, damping coefficient and a scale factor that relates the output to an acceleration input. The values of test mass and spring constant are seldom known or required.

Potentiometric

This simplest accelerometer type measures mass motion by attaching the spring mass to the wiper arm of the potentiometer. In this manner, the mass position is conveyed as a changing resistance. The natural frequency of these devices is generally less than 30Hz, limiting their application to steady state acceleration or low frequency vibration measurement. Numerous signal conditioning schemes are employed to convert the resistance variation into a voltage change or current signal.

LVDT

A second type of accelerometer takes advantage of the natural linear displacement measurement of the LVDT to measure mass displacement. In these instruments, the LVDT core itself is the seismic mass. Displacements of the core are converted directly into a linearly proportional AC voltage. These accelerometers generally have a natural frequency less than 80Hz and are commonly used for steady state and low frequency vibrations. Figure 3.14 shows the basic structure of such an accelerometer.

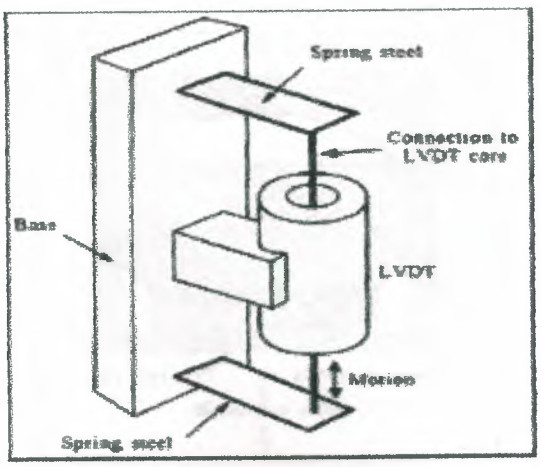

Figure 3.14: An LVDT is often used as an accelerometer with core serving as mass.

Variable Reluctance

This accelerometer type falls in the same general category as the LVDT in that an inductive principle is employed. Here, the test mass is usually a permanent magnet. The measurement is made from the voltage induced in a surrounding coil as the magnetic mass moves under the influence of acceleration. This accelerometer is used in vibrations and shock studies only, because it has an output only when the mass is in motion. Its natural frequency is typically less than 100Hz. This type of accelerometer often is used in oil exploration to pick up vibration reflected from underground rock strata. In this form, it is commonly referred to as geophone.

Piezoelectric

The piezoelectric accelerometer is based on a property exhibited by certain crystals where a voltage is generated across the crystal when stressed. This property is also the basis for such familiar sensors as crystal phonograph cartridges and crystal microphones. For accelerometers, the principle is shown in figure 3.15. Here, a piezoelectric crystal is spring loaded with a test mass in contact with the crystal. When exposed to acceleration, the test mass stresses the crystal by the force, resulting in a voltage generated across the crystal. A measure of this voltage is then a measure of acceleration. Output levels are typically in the mill volt ranges. The natural frequency in these devices may exceed 5 KHz, so that they can be used for vibration and shock measurements.

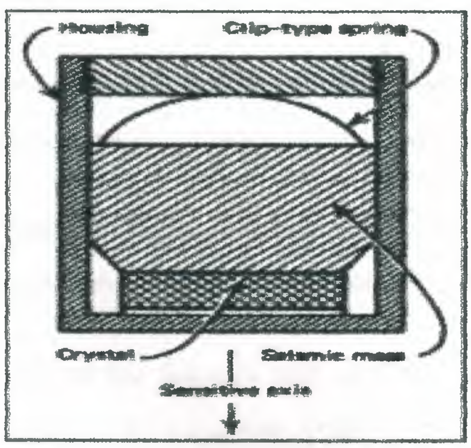

Figure 3.15: A piezoelectric accelerometer has a very high natural frequency.

3.4.4 Application

A few notes about the application of accelerometers will help in understanding how the selection of a sensor is made in a particular case.

3.4.4.1 Steady state Acceleration

In steady state acceleration, we are interested in a measure of acceleration what may vary in time but that is non-periodic. Thus, the stop-go motion of an automobile is an example of steady state acceleration. For these steady state accelerations, select a sensor having:

- Adequate range to cover expected acceleration magnitudes
- Natural frequency sufficiently high that its period is shorter than the characteristic time span over which the measured acceleration changes

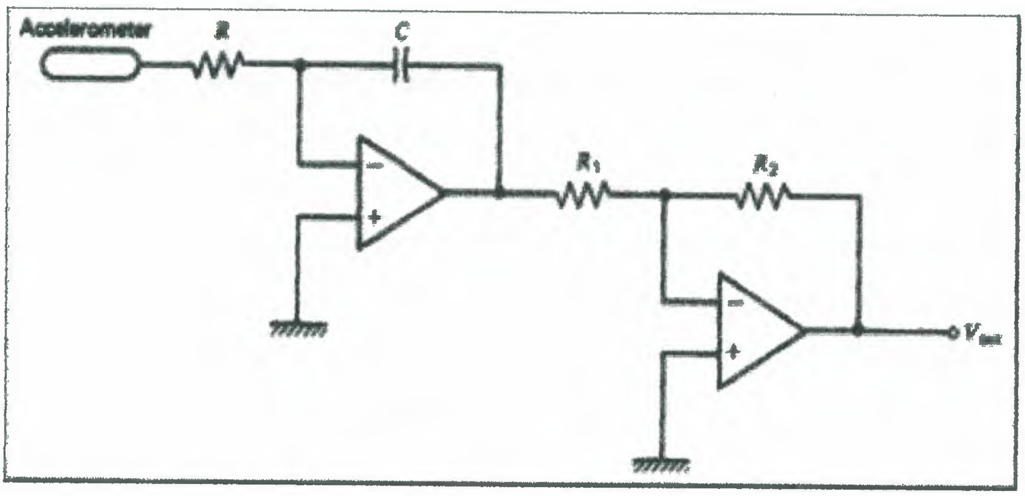

Figure 3.16: An integrator can be used to obtain velocity information from an accelerometer.

By using electronic integrators, the basic accelerometer can provide both velocity (first integration) and position (second integration) information.

Now we need an integrator to get the velocity and amplifier to provide the proper scale. Such a circuit is shown in figure 3.16. We chose T=RC=1 so that the integrator output is scaled at:

$$\left(1.43\frac{mV}{m/s^2}\right)\left(\frac{-1}{1s}\right) = -1.43\frac{mV}{m/s}$$

3.4.4.2 Vibration

The application of accelerometers for vibration first requires that the applied frequency is less than the natural frequency of the accelerometer. Second, one must be sure the stated range of acceleration measured will never exceed that of the specification for the device.

3.4.4.3 Shock

The primary elements of importance in shock measurements are that the device has a natural frequency that is greater than 1 KHz and a range typically greater than 500g. The primary accelerometer that can satisfy these requirements is piezoelectric type.

3.5 Pressure Sensors

The measurement and control of fluid (liquid and gas) pressure has to be one of the most common in all the process industries. Because of the great variety of conditions, ranges and materials for which pressure must be measured. There are many different types of pressure sensors designs. In the following paragraphs, the basic concepts of pressure are presented, and a brief description is given of the most common types of pressure sensors. We shall see that pressure measurement is often accomplished by conversion of the pressure information to some intermediate form, such as displacement, which is then measured by a sensor to determine the pressure.

3.5.1 Pressure Principles

Pressure is simply the force per unit area that a fluid exerts on its surroundings. If it is a gas, then the pressure of the gas is the force pre unit area that the gas exerts on the walls of the container that holds it. If the fluid is a liquid, then the pressure is the force per unit area that the liquid exerts on the container in which it is contained. Obviously, the pressure of the gas will be uniform on the walls that must enclose the gas completely. In a liquid, the pressure will vary, being greatest on the bottom of the vessel and zero on the top surface, which not be enclosed.

3.5.1.1 Static Pressure

The statements made in the previous paragraph are explicitly true for a liquid that is not moving in space, that is not being pumped through pipes or flowing through the channel. The pressure in cases where no motion is occurring is referred to as static pressure.

3.5.1.2 Dynamic Pressure

It is a fluid in motion; the pressure that it exerts on its surroundings depends on the motion. Thus, if we measure the pressure of the water in a hose with the nozzle closed, we find a pressure of, say, 40 pounds per square inch (note: force per unit area). If the nozzle is opened, the pressure is the hose will drop to a different value, say, 30 pounds per square inch. For this reason, a through description of pressure must note the circumstances under which it is measured. Pressure can depend on flow, compressibility of the fluid, external forces and numerous other factors.

3.5.1.3 Gauge Pressure

In many cases, the absolute pressure is not the quantity of major interest in describing the pressure. The atmosphere of gas that surrounds in the earth exerts a pressure, because of its weight, at the surface of the earth of approximately 14.7 psi. If a closed vessel at the earth's surface contains a gas at an absolute pressure of 14.7 psi, then it would exert no effective pressure on the walls of the container because the atmospheric gas exerts the same pressure from the outside. This gauge pressure is given by:

$$P_g = p_{abs} - p_{at}$$

Where, P_g = Gauge pressure

p_{abs} = Absolute pressure

p_{at} = Atmospheric pressure

3.5.1.4 Head Pressure

For liquids, the expression head pressure or pressure head is often used to describe the pressure of the liquid in a tank or pipe. This refers to the static pressure produced by the weight of the liquid above the point at which the pressure is being described. This pressure depends only on the height of the liquid above that point and the liquid density (mass per unit volume). In terms of an equation, if a liquid is contained in a tank, then the pressure at the bottom of the tank is given by

$$p = \rho gh$$

Where, p= Pressure in Pa

ρ = Density in Kg/m^3

g= Acceleration due to gravity (9.8m/s^2)

h= Depth of liquid in m

3.5.2 Pressure Sensors (p>1atm)

In general, the design of pressure sensors employ for measurement of pressure higher than one atmosphere differs from those employed for pressure less than one atmosphere. In this section the basic operating principles of many types of pressure sensors used for the higher pressures are considered. We should be aware of many types of pressure sensors used for the higher pressures are considered. We should be aware that this is not a rigid separation, because we shall find many of these same principles employed in the lower (vacuum) pressure measurement. Measurement of pressure requires techniques for producing the displacement and means for converting such displacement into a proportional electrical signal.

3.5.2.1 Diaphragm

One common element used to convert pressure information into a physical displacement is the diaphragm shown in figure 3.17. If a pressure $p_1$exists of one side of the diaphragm and p_2 on the other, then a net force is exerted given by:

$$F = (p_2 - p\ )A$$

Where, A= Diaphragm area in m^2

p_1, p_2=pressure in N/ m^2

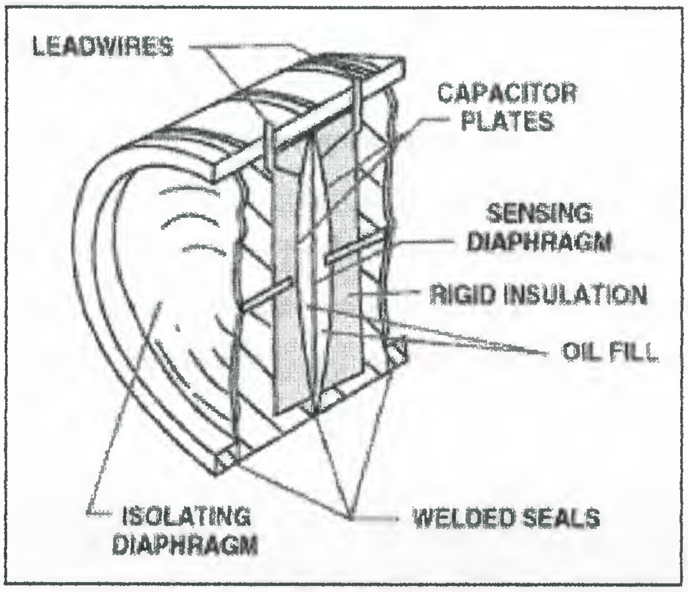

Figure 3.17: A diaphragm is used in many pressure sensors. Displacement varies with pressure difference.

A diaphragm is like a spring, and therefore extends or contracts until a Hook's law force is developed that balances the pressure difference force.

3.5.2.2 Bourdon tube

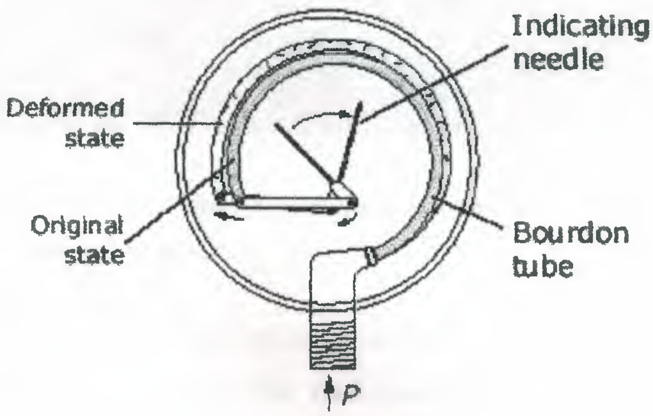

Figure 3.18: A bourdon tube is a common transducer for converting pressure of displacement.

A common pressure-to-displacement conversion is accomplished by a specially constructed tube, shown in figure 3.18. If a section of tubing is partially flatted and coiled as shown, then the application of pressure inside the tube causes the tube to uncoil. This then provides a displacement that is proportional to pressure.

3.5.2.3 Electronic Conversions

Many techniques are used to convert the displacements generated in the previous example into electronic signals. The simplest technique is to use mechanical linkage connected to a potentiometer. In this fashion, pressure is related to a resistance change. Other methods of conversion employ strain gauges directly on a diaphragm. LVDTs and other inductive devices are used to convert bellows or bourdons tube motions into proportional electrical signals.

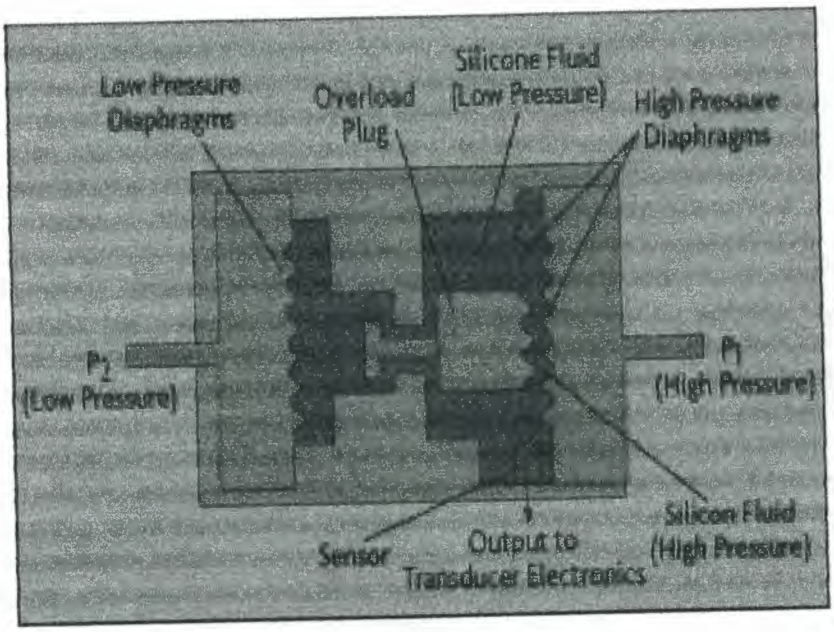

Figure 3.19: A differential pressure (DP) cell measures pressure difference with a diaphragm. A feedback system minimizes actual diaphragm motion.

Often, pressure measurement is accomplished using a diaphragm in a special feedback configuration, shown in figure 3.19. The feed back system keeps the diaphragm from moving, using an induction motor. The error in the feedback system provides an electrical measurement of the pressure.

3.5.3 Pressure sensors ($p < 1$ atm)

Measurements of pressure less than 1 atm are most conveniently made using purely electronic methods. There are three common methods of electronic pressure measurements. The first two devices are useful for pressure less than1 atm, down to about 10^{-3}atm. They are both based on the rate at which heat is conducted and radiated away from a heated filament placed in the low pressure environment. The heat loss is proportional to the number of gas molecules per unit volume, and thus, under constant filament current, the filament temperature is proportional to gas pressure. We have thus transduced a pressure measurement to a temperature measurement.

3.5.3.1 Pirani gauge

This gauge determines filament temperature through a measure of filament resistance. Filament excitation and resistance measurement are both performed with a bridge circuit. The response of resistance versus pressure is highly nonlinear.

3.5.3.2 Thermocouples

A second pressure transducer or gauge measures filament temperature using a thermocouple directly attached to the heated filament. In this case, ambient room temperature serves as a reference for the thermocouple, and the voltage output, which is proportional to pressure, is highly nonlinear. Calibration of both Pirani and thermocouple gauges depends on the type of the gas for which the pressure is being measured.

3.6 Flow Sensors

The measurement and control of flow can be said to be very heart of process industries. Continuously operating manufacturing processes involve the movement of raw materials, products and waste throughout the process. All such functions can be considered as flow, whether automobiles through an assembly line or methyl chloride through a pipe. It would be unreasonable to try to present every type of flow sensor, and in this case we shall consider flow on three broad fronts—solid, liquid and gas.

3.6.1 Solid Flow Meters

The most common solid flow measurement occurs when material in the form of small particles, such as crushed material or powder, is carried by the conveyer belt system or by some other host material. For example, if the solid is suspended in a liquid host, the combination is called slurry, which is then pumped through pipes like a liquid. We shall consider the conveyor system and leave slurry to be treated as liquid flow.

Conveyer Flow Concept

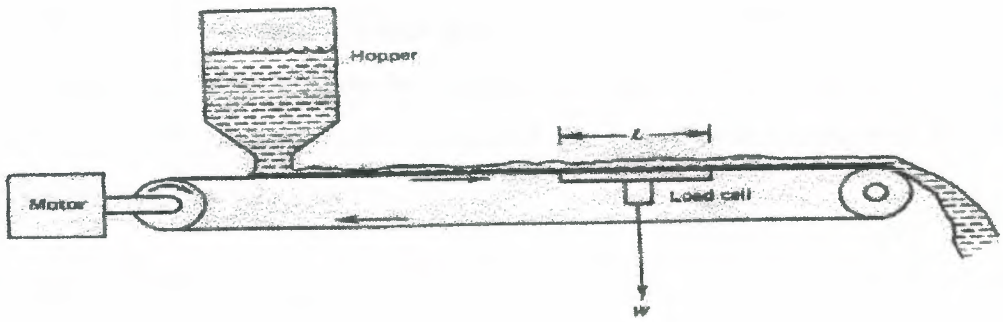

Figure 3.20: Conveyor system for illustrating solid flow measurement.

For solid objects, the flow is usually described by a specification of the mass or weight per unit time that is being transported by the conveyor system. The units will be in many forms, for example, Kg/min or lb/min. To make a measurement of flow, it is only necessary to weight the quantity of material on the some fixed length of the conveyor system. Knowing the speed of the conveyer allows calculation of the material flow rate.

In figure 3.20, a typical conveyor system is shown where material is drawn from the hopper and transported by the conveyor system. Assuming that the material can flow freely from the hopper, the faster the conveyor is moved, the faster material will flow from the hopper, and the greater the material flow rate on the conveyor. In this case, flow rate can be calculated from:

$$Q = \frac{WR}{L}$$

Where, Q= flow in Kg/min

W= weight of material on section of length L

R= conveyor speed in m/min

L= length of weighing plate-form in m

In this example with which we are working in figure 3.20, it is evident that the flow sensor is actually the assembly of conveyor, hopper opening and weighing plate-form. It is the actual weighing plate-form that performs the measurement from which flow rate is determined. We see that flow measurement becomes weight measurement. In this case, we have suggested that this weight is measured by means of a load cell, which is then a strain gauge measurement. Another popular device for weight measurement of moving systems like this is a LVDT that measures the droop of the conveyor at the point of measurement because of the material that it carries.

3.6.2 Liquid flow Meters

The measurement of liquid flow is involved in nearly every facet of the process industry. The conditions under which the flow occurs and the vastly different types of the material that flow result in a great many types of flow measurement methods.

Flow Units

1. Volume flow rate: Expressed as a volume delivered per unit time. Typical units are Gallons/min, m^3/hr, ft^3/hr.
2. Flow velocity: Expressed as the distance, the liquid travels in the carrier per unit time. Typical units are m/min. This is related to the volume flow rate by:

$$V = \frac{Q}{A}$$

Where, V= Flow velocity

Q= Volume flow rate

A= Cross-sectional area of flow carrier (pipe and so on)

3. Mass or weight flow rate: Expressed as mass or weight flowing per unit time. Typical units are Kg/hr, lb/hr. This is related to the volume flow rate by:

$$F=\rho Q$$

Where, F= Mass or weight flow rate

ρ= Mass density or weight density

Q= Volume flow rate

Pipe Flow Principle

The flow rate of liquids in pipes is determined primarily by the pressure that is forcing the liquid through the pipe. The concept of pressure head or simply head is often used to describe this pressure, because it is easy to relate the forcing pressure to that produced by a depth of liquid in a tank from which the pipe exit. In figure 3.21, flow through pipe p is driven by the pressure in the pipe, but this pressure is caused by the weight of liquid in the tank of height h (head). Many other factors affect the actual flow rate produced by this pressure, including liquid velocity, pipe size, pipe roughness (friction), turbulence of flowing liquid and others.

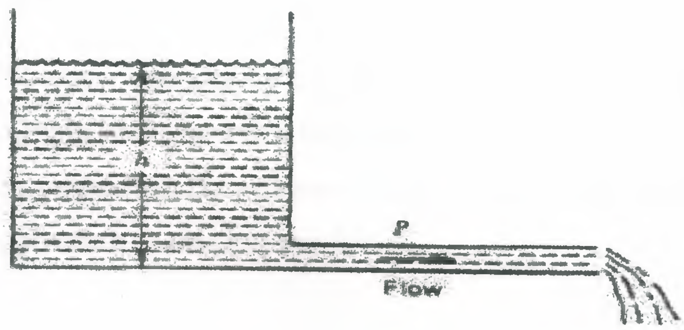

Figure 3.21: Flow through pipe P is determined in part by the pressure due to head h.

Restriction Flow Sensors

One of the most common methods of measuring the flow of liquids in pipes is given by introducing a restriction in the pipe and measuring the pressure drop that results across the restriction. When such a restriction increases, the pressure in the restriction is decreases. We find that there is relationship between the pressure drop and the rate of flow such that as the flow increases, the pressure drops. In particular, one can find an equation of the form:

$$Q = K\sqrt{\Delta p}$$

Where, Q= Volume flow rate

K= A constant for the pipe and liquid type

Δp = Drop in pressure across the restriction

The constant K depends on many factors, including the type of liquid, size of pipe, velocity of flow, temperature and so on. The type of restriction employed also will change the value of the constant used in this equation. The flow rate is linearly dependent not on the pressure drop but on the square root. Thus, if the pressure drop in a pipe is increased by a factor of 2 when the flow rate was increased, the flow rate will have increased only by a favor of 1.4 (the square root of 2). Certain standard types of restriction are employed in exploiting the pressure-drop method of measuring flow.

Obstruction Flow Sensor

Another type of flow sensor operates by the effect of flow in an obstruction placed in the flow stream. If the turbine is attached to a tachometer, a convenient electrical signal can be produced. In all these methods of flow measurement, it is necessary to present a substantial obstruction into the flow path to measure the flow.

Magnetic Flow Meter

if can be shown that if charged particles move across a magnetic field, a potential is established across the flow, perpendicular to the magnetic field. Thus, if the flowing liquid is also a conductor (even if not necessarily a good conductor) of electricity, the flow can be measured by allowing the liquid to flow through a magnetic field and measure the transverse potential produced. The pipe section in which this measurement is made must be insulated and a conductor itself, or the potential produced will be cancelled by currents in the pipe. A diagram of this type of flow meter is presented in figure 3.22. This type of sensor produces an electrical signal directly and is convenient for process control applications involving conducting fluid flow.

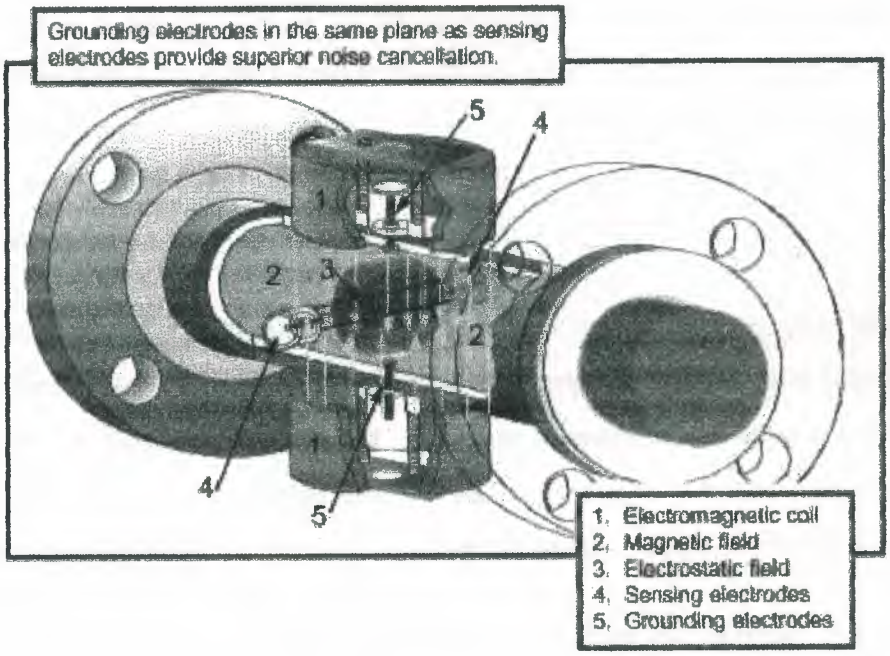

Figure 3.22: A magnetic flow meter will work only with conducting fluid.

4. OPTICAL SENSORS

4.1 Introduction

A desirable characteristic of sensors is that they have negligible effect on the measured environment, that is, the process. When electromagnetic (EM) radiation is used to perform process variable measurements, transducers that do not affect the system measured emerge. Such systems of measurements are called nonlinear or non-contact because no physical contact is made with the environment of the variable. Non-contact characteristic measurements often can be made from a distance.

In process control, EM radiation is either the visible or infrared light band is frequently use in measurement applications. The techniques of such applications are called optical because such radiation is close to visible light. A common example of optical transduction is measurement of an object's temperature by its emitted EM radiation. Another example involves radiation reflected off the surface to yield a level or displacement measurement.

Optical technology is a vast subject covering a span from geometrical optics, including lenses, prisms, gratings and the like to physical optics with lasers, parametric frequency conversion and nonlinear phenomena. These subjects are all interesting but all that is required for our purposes is a familiar with optical principles and knowledge of specific transduction and measurement methods.

4.2 Fundamentals of EM radiation

We are familiar with EM radiation as visible light. Visible light is all around us. EM radiation is also familiar in other forms, such as radio or TV signals and ultraviolet or infrared light.

This section covers a general method of characterizing EM radiation. Although much of what follows is valid for the complete range of radiation, particular attention is given to the infrared, visible and ultraviolet, because most sensor applications are concerned with these ranges.

4.2.1 Nature of EM Radiation

EM radiation is a form of energy that is always in motion, that is, it propagates through space. An object that releases or emits such radiation loses energy. One that absorbs radiation gains energy.

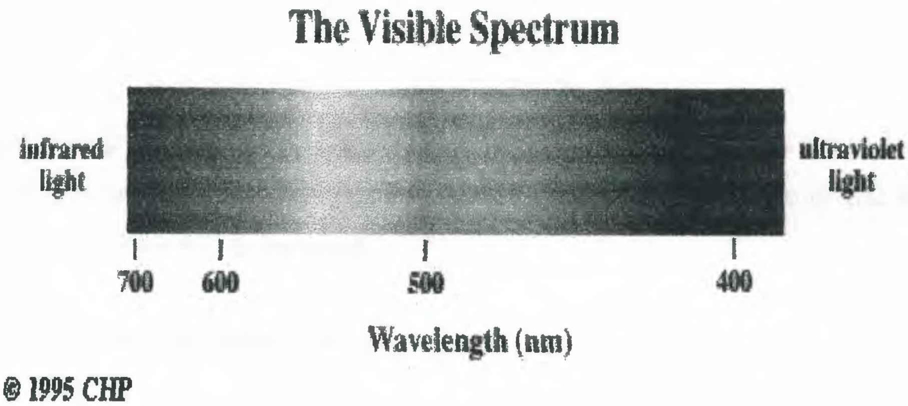

Figure 4.1: It covers everything of the electromagnetic radiation spectrum from very low frequency (VLF) radio to X-rays and beyond.

Figure 4.1 sows the range of EM radiation from very low frequency to very high frequency, together with the associated wavelength in meters and how the bands of frequency relate to our world.

Visible Light

The small band of radiation between approximately 400nm and 760nm represents visible light. This radiation band covers those wavelengths to which our eyes (or radiation detectors in our heads) are sensitive.

Infrared light

The longer wave radiation band that extends from the limit of eye sensitivity at 0.7µm to approximately 100µm is called infrared (IR) radiation. In some cases, the band is further subdivided so that radiation of wavelength 3 to 100µm is called far infrared.

4.3 Photo-detectors

An important part of any application of light to an instrumentation problem is how to measure or detect radiation. In most process control related applications, the radiation lies in the range from IR through visible and sometimes UV bands. The measurement sensors generally used are called photo-detectors to distinguish them from other spectral ranges of radiation such as RF detectors in radio frequency (RF) applications.

The particular characteristic related to EM radiation detection is the spectral sensitivity. This is given as graph of sensor response relative to the maximum as a function of radiation wavelength. Obviously, it is important to match the spectral response of the sensor to the environment in which it is to be used.

4.3.1 Photo-conductive Detectors

One of the most common detectors is based on the change in conductivity of a semiconductor material with radiation intensity. The change in conductivity appears as a change in resistance, so that these devices also are called photo-resistive cells.

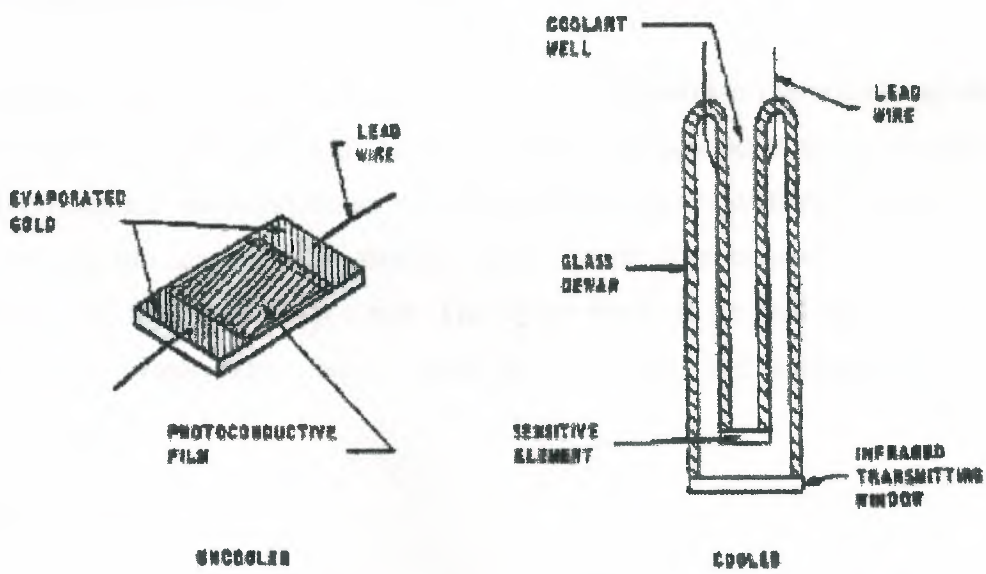

Figure 4.2: Photoconductive cell has a structure to maximize exposure and minimize resistance.

Principle

In a semiconductor photo-detector, a photon is absorbed and thereby excited into the conduction band, the semiconductor resistance decreases, making the resistance an inverse function of radiation intensity. For the photon to provide such an excitation it must carry at least as much energy as the gap.

Following equation shows the maximum wavelength as:

$$E_p = \frac{hc}{\lambda_{max}} = \Delta W_g$$

$$\lambda_{max} = \frac{hc}{\Delta W_g}$$

Where, h= Plank's constant

ΔW_g= Semiconductor energy gap (J)

λ_{max} = Maximum detectable radiation wavelength (m)

Any radiation with a wavelength greater than that predicted by the equation cannot cause any resistance change in the semiconductor.

It is important to note that the operation of a thermistor involves thermal energy excitation electrons in the conduction band. To prevent the photoconductor from showing similar thermal effects, it is necessary either to operate the devices at a controlled temperature or to make the gap too large for the thermal effects to produce conduction electrons. Both approaches are employed in practice. The upper limit of the cell spectral response is determined by many other factors, such as reflectivity and transparency to certain wavelengths.

Cell Characteristics

Two common photo-conductive semiconductor materials are cadmium sulfide (CdS) and cadmium selenide (SdSe). The characteristics of photo-conductive detectors vary considerably when different semiconductor materials are used as the active element.

Signal Conditioning

Various Op. Amp. Circuits using the photoconductor as a circuit element are used to convert the resistance change to a current or voltage change. It is important to note that the cell is a variable sensor, and therefore has some maximum power dissipation that cannot be exceeded. Most cells have dissipation from 50 to 500 mW, depending on size and construction.

4.3.2 Photovoltaic Detectors

Another important class of photo-detectors generates a voltage that is proportional to incident EM radiation intensity. These devices are called photovoltaic cells because of their voltage generating characteristics. They actually convert the EM energy into electrical energy. Applications are found as both EM radiation detectors and power sources converting solar radiation into electrical power. The emphasis of our consideration is on instrumentation type applications.

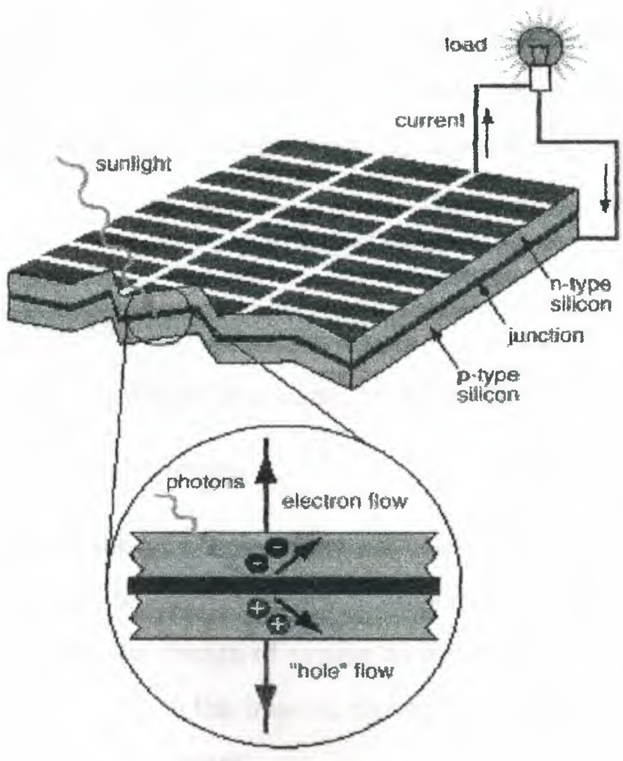

Figure 4.3: A photovoltaic solar cell is a giant pn junction diode.

Principle

Operating principles of the photovoltaic cell are best described by figure 4.3. We see that the cell is actually a giant diode that is constructed using a pn junction between appropriately doped semiconductors. Photons, striking the cell, pass through the thin p-diode upper layer and are absorbed by electrons in the n-layer, which cause formation of conduction electrons and holes. The depletion-zone potential of the pn junction then separates these conduction electrons and holes, which causes a difference of potential to develop across the junction. The upper terminal is positive and the lower negative. It is also possible to build a cell with a thin n-doped layer on top so that all polarities are opposite.

Photovoltaic cells also have a range of spectral response within which a voltage will be produced. Clearly, if the frequency is too small, the individual photons will have insufficient energy to create an electron-hole pair and no voltage will be produced. There is also upper limit to the frequency because of the optical effects such as radiation penetration through the cell.

Since the photovoltaic cell is a battery, it can be modeled as an ideal voltage source, Vc, in series with an internal resistance Rc as shown in figure 4.4. It turns out that the voltage source varies with light intensity in an approximately logarithmic fashion:

$$V_c = V_o \log_e(1 + I_R)$$

Where, Vc= Open-circuit cell voltage

Vo= Constant, dependant on cell material

I_R= light intensity

The internal resistance of the cell also varies with light intensity. At low intensity the resistance may be thousands of ohms, whereas at higher intensities it may drop to less than fifty ohms. This complicates the design of system to derive maximum power from the cell, since the optimum load is equal to the internal resistance. Fortunately, at higher intensities the internal resistance is nearly constant.

Signal Conditioning

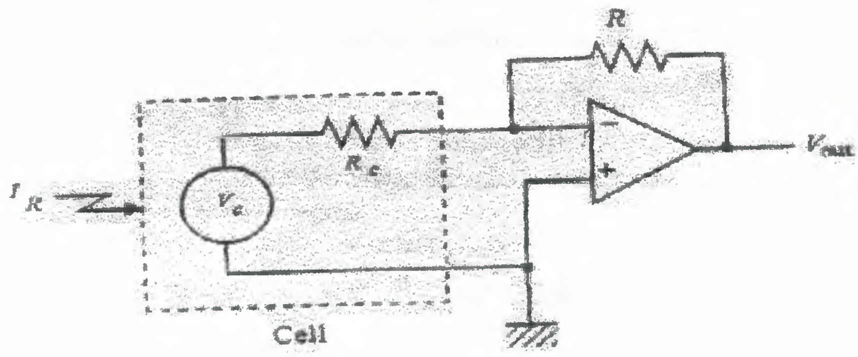

Figure 4.4: This circuit allows conversion of the cell short circuit current into a proportional voltage.

Since the short circuit current Isc is nearly related to radiation intensity, it is preferable to measure this current when using the cell in measurement and instrumentation.

Figure 4.4 shows how Isc can be obtained by connecting the cell directly to an Op Amp. Since the current to the Op Amp input must be zero, the feedback current through R must equal Isc. Therefore, the output voltage is given by:

$$V_{out} = RI_{SC}$$

Since the current is linearly proportional to light intensity, so it is the output voltage.

Cell Characteristics

The properties of photovoltaic cell depend on the material employed for the cell and the nature of the doping used to provide the n and p layer. Some cells are used only at low temperatures to prevent thermal effects from obscuring radiation detection. The silicon photovoltaic cell is probably the most common.

4.3.3 Photodiode Detectors

The previous section showed one way that the pn junction of a diode is sensitive to EM radiation, the photovoltaic effect. A pn diode is sensitive to EM radiation in another way as well, which gives rise to the fact that photodiodes as sensors.

The photodiode effect refers to the fact that photon impinging on the pn junction also alter the reverse current-versus-voltage characteristics of the diode. In particular, the reverse current will be increased almost linearly with light intensity. Thus, the photodiode is operated in the reverse-bias mode.

One of the primary advantages of the photodiode is its fast response, which can be in the nanosecond range. Generally, photodiodes are very small, like regular diodes, so that a lens must be used to focus light on the pn junction. Often, the lens is built into photodiode casing, as shown in the figure 4.5.

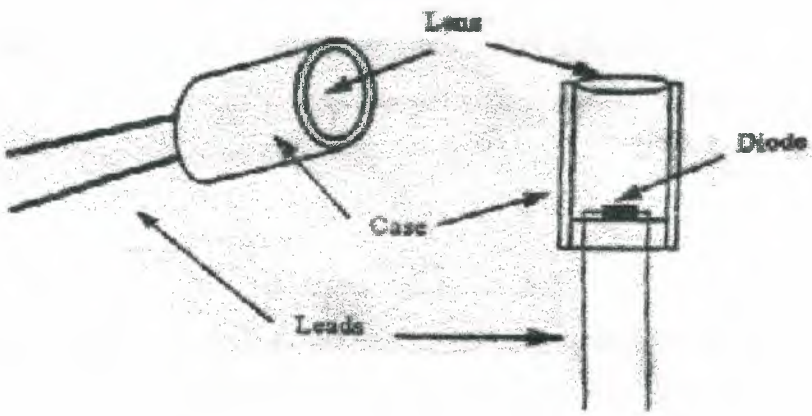

Figure 4.5: Photodiodes are very small and often use an internal lens to focus light on the junction.

Spectral response of photodiode is typically peaked in the infrared, but with usable response in the visible radiation in a broad range of visible to infrared and far-infrared radiation. In some cases a photodiode is operated in the photovoltaic mode, since the output will then be zero when the voltage is zero. In this mode the speed is slower, however, and the short-circuit currents are very small.

Phototransistor

An extension of the photodiode concept is the phototransistor. In this sensor the intensity of EM radiation impinging on the collector-base junction of the transistor acts much like a base current in producing an amplified collector-emitter current.

The phototransistor is not as fast as the photodiode, but still offers response times in microseconds. As usual, there is a limit to the spectral response, with maximum response in the infrared but usable range in the visible band. This device can be used much like a transistor, except that no base current is required. A load line using the collector resistor and supply voltage will show response as a function of light intensity.

Often, the transistor has a built-in lens, like that in figure 4.5, to concentrate radiation on the junction.

4.3.4 Photo-emissive Detectors

This type of photo-detector was developed many years ago, but it is still one of the most sensitive types. A wide variety of spectral ranges and sensitivity can be selected from many types of photo-emissive detectors available.

Principles

To understand the basic operational mechanism of photo-emissive devices, let us consider the two-element vacuum photo-tube as shown in figure 4.6. Such photo-detectors have been largely replaced by the other detectors in modern measurements.

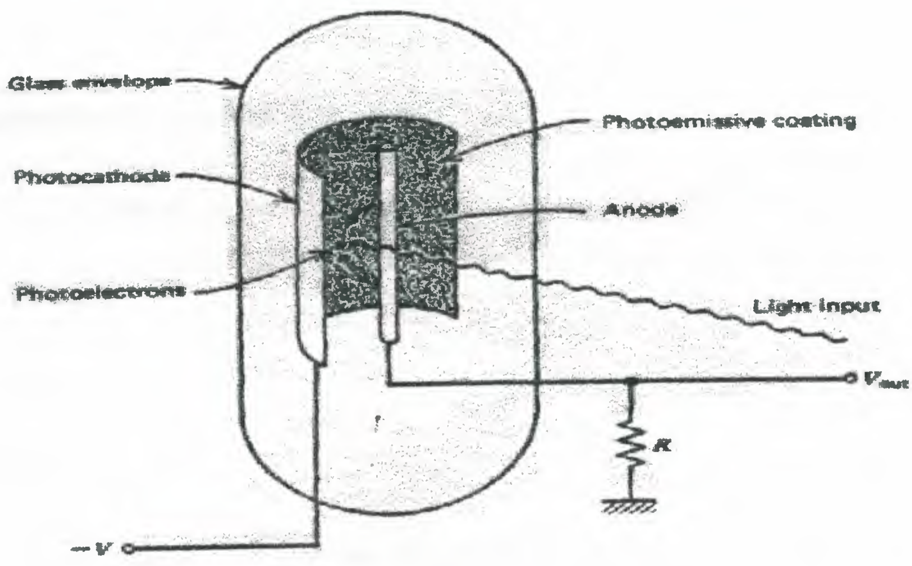

Figure 4.6: Structure of the basic photoemissive diode.

In figure 4.6, we note that the cathode is maintained at some negative voltage with respect to the wire of anode that is grounded through resistor R. The inner surface of the cathode is a metal for which electrons are easily detached from the metal surface.

In particular, then, a photon can strike the surface and impart sufficient energy to an electron to eject it from this coating. The electron will then be driven from the cathode to the anode by the potential, and thence through resistor R. Thus, we have a current that depends on the intensity of light striking the cathode.

4.4 Optical Sources

One limitation in the application of EM radiation devices to process control has been the lack of convenient characteristics of available optical sources. Often, complicated collimating lens systems are required, heat dissipation may be excessive, wavelength characteristics may be undesirable, or a host of other problems may arise. The development of sources relying on light amplification by stimulated emission of radiation (LASER) has provided EM radiation sources having good characteristics for application to process control measurements. In this section we shall consider the general characteristics of both conventional and laser light sources and their applications to measurement problems. Our discussion is confined to sources in the visible or IR wavelength bands, although it should be noted that many applications exists in other regions of the EM radiation spectrum.

4.4.1 Conventional Light Sources

Before the development of the laser, two primary types of light sources were employed. Both of these are fundamentally distributed, because radiation emerges from a physically distributed source. They also are divergent, incoherent, and often not particularly monochromatic.

Incandescent Sources

A common light source is based on the principle of thermal radiation. Thus, if a fine current-carrying wire is heated to a very high temperature by I^2R losses, it emits considerable EM radiation in the visible band. A standard lamp is an example of this type of source, as are flashlight lamps, automobile headlights and so on.

4.4.2 Laser Principles

The basic operation of the laser depends on a principle formulate by Albert Einstein regarding the emission of radiation by excited atoms. He found that if several atoms in a material are excited to the some level and one of the atoms emits its radiation before the others, then the passage of this radiation by such excited atoms can also stimulate them to de-excite.

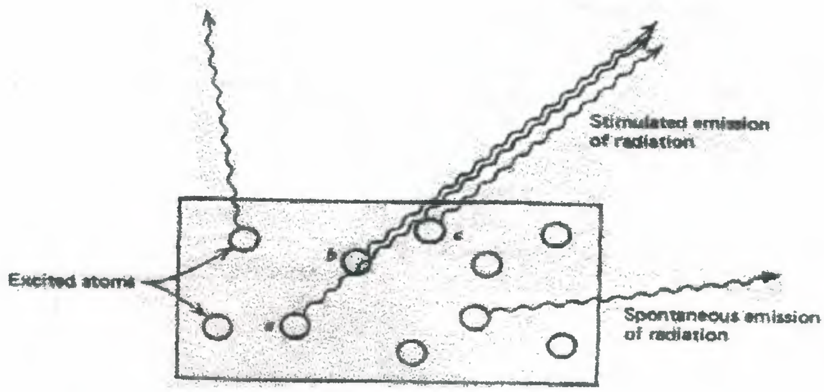

Figure 4.7: Stimulated emission of radiation gives rise to monochromatic, coherent radiation pulses moving in random directions.

It is significant that when stimulated to de-excite, the emitted radiation will be in-phase and in the same direction as the stimulating radiation. This effect is shown in 4.7, where atom "a" emits radiation spontaneously. When this radiation passes by atoms indicated by "b", "c" and so on, they also are stimulated to emit in the same direction and in-phase (coherently). Such stimulated emission is the first requirement in the realization of a laser.

4.5 Applications

Several applications of optical transduction techniques in process control will be discussed. The intention is to demonstrate only the typical nature of such application, and not to design details.

4.5.1 Label Inspection

In many manufacturing processes, a large number of items are produced in batch runs where an automatic process attaches labels to the items. Unavoidably, some items are either missing labels or have the labels incorrectly attached. The system of 4.8 examines the presence and alignment of labels on boxes moving on a conveyor belt system.

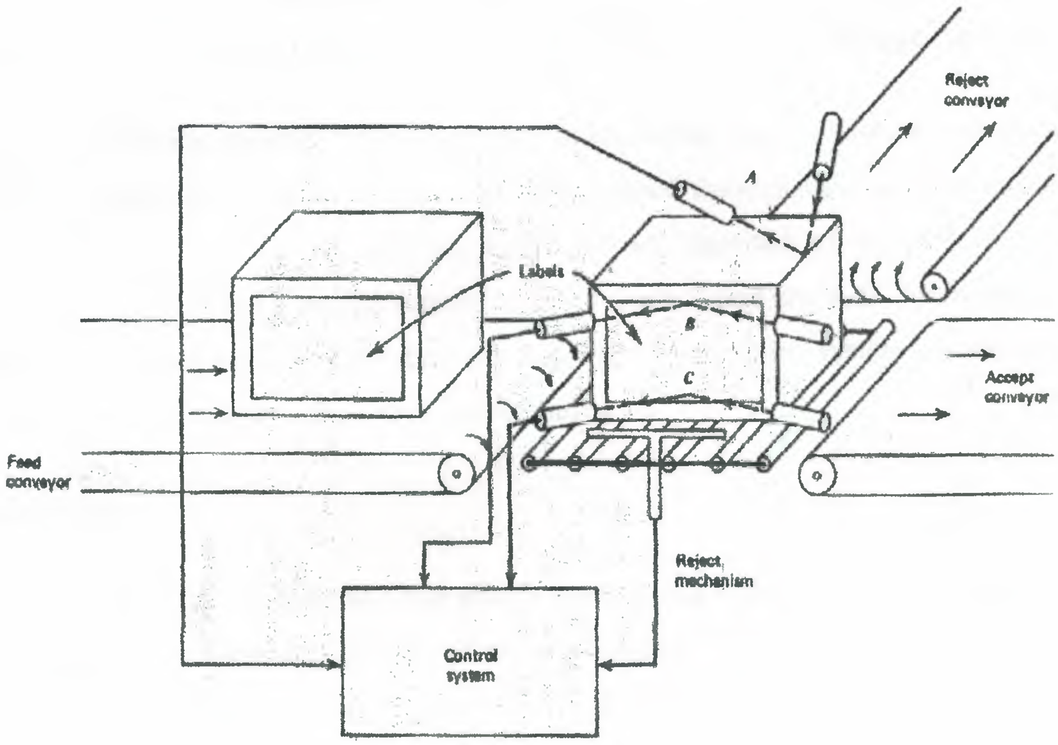

Figure 4.8: Label inspection system as an example of optical technique.

If the label is missing or improperly aligned, the photo-detector signals are incorrect in terms of light reflected from the source, and a solenoid push-out rejects the item from the conveyor.

Source/detector system A detects the presence of a box and initiates measurements by source/detector systems B and C. If the signals received by detectors B and C are identical and at a preset level, the label is correct, and the box moves on to the accept conveyor. In any other instance, a misalignment or missing label is indicated and the box is ejected onto the reject conveyor.

4.5.2 Turbidity

One of the many characteristics of liquids involved in process industries is called turbidity. Turbidity refers to the lack of clarity of a liquid, which can be caused by suspended particular material. Turbidity can be an indication of a problematic condition because of impurities or improperly dissolved products. It also can be intentional as, for example, when some material is suspended in a liquid for ease of transport through pipes. Turbidity can be measured optically because it effects the propagation of light through the liquid.

It is also possible to measure the turbidity of liquids in-line, that is, without taking periodic samples. In this case, a laser beam is split and passed through two samples to matched photo-detectors. One sample is a carefully selected standard of allowed (acceptable) turbidity. The other is an in-line sample of the process liquid itself. If the in-line sample attenuates the light more than the standard, the signal conditioning system triggers an alarm or takes other appropriate action to reduce turbidity.

4.5.3 Ranging

The development of the laser and fast photo-detectors has introduced a number of methods for measuring distances and the rate of travel of objects by non-contact means. Distances can be measured by measuring the time of flight of light pulses scattered off a distant object. Because the speed of light is constant, we use a simple equation to find distance, providing the time of flight T is known. Thus, if a pulse of light is directed at a distant object and the reflection is detected a time T later, then the distance is:

$$D = cT / 2$$

Where, D= Distance to the object (m)

c= Speed of light (m/s)

T= Time for light round trip (s)

This ranging method can be employed for measuring shorter distances limited by time measurement capability and detecting the reflected signal for longer distances. Surveying instruments for measuring distance have been developed by this method. Velocity or rate of motion can be measured by an electronic computing system that records the changing of reflected-pulse travel time and computes velocity.

4.5.4 Optical Encoder

An encoder is a device that provides a digital output as a result of a linear or angular displacement. The most popular type of encoder is the optical encoder, which consists of a rotating disk, a light source, and a photo-detector (light sensor). The disk, which is mounted on the rotating shaft, has coded patterns of opaque and transparent sectors. As the disk rotates, these patterns interrupt the light emitted onto the photo-detector, generating a digital or pulse signal output.

The encoding disk is made from:

- Glass, for high-resolution applications (11 to >16 bits)
- Plastic (Mylar) or metal, for applications requiring more rugged construction (resolution of 8 to 10 bits)

Position encoders can be grouped into two categories: incremental encoders and absolute encoders.

4.5.4.1 Incremental Encoders

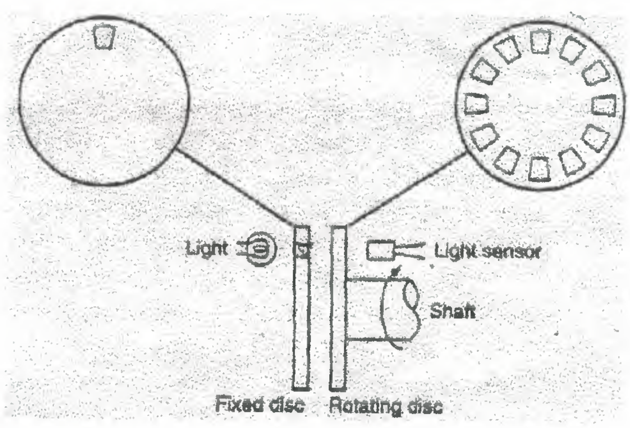

Figure 4.9: Incremental encoder, used to measure the possible speed of the moving object.

These are the most common types used in the industry due to the simplicity of their use. Each encoder is comprised of an optical disc with the required number of lines together with an (HRS) reading system coupled with a single L.E.D. for longer life, reliability and enhanced performance. Either speed or relative position can be determined by monitoring the frequency or the number of pulses generated by the encoder.

The resolution is determined by the number of slots on the disc. Typically the number varies from 60 to over a thousand with multi-tracks having slightly offset slots in each track. With 60 slots occurring with 1 revolution then, since 1 revolution is a rotation of 360°, the resolution is 360/60 = 6° to 0.3° or better.

4.5.4.2 Absolute Encoders

These are commonly used within the industry to measure the precise position as opposed to the relative position measured by incremental encoders. The main feature of absolute encoders is the ability to retain positional data in the event of the absence of power.

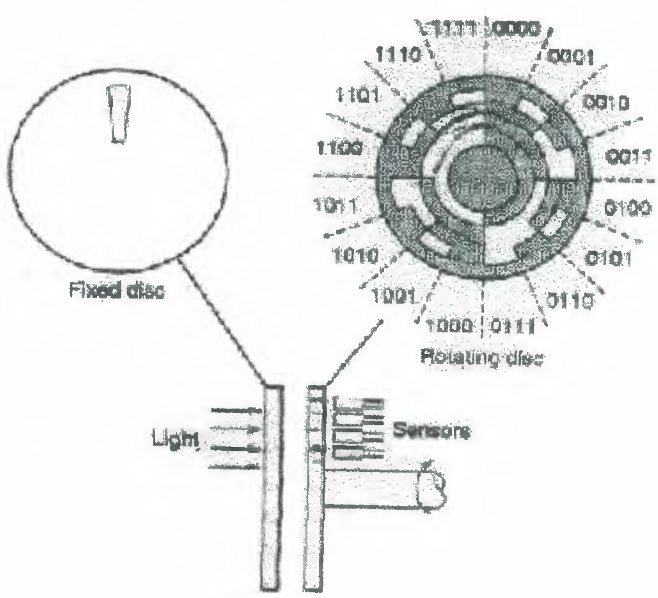

Figure 4.10: Absolute encoder, used for the system to measure the correct position of the object.

The rotating disc has four concentric circles of slots and four sensors to detect the light pulses. The slots are arranged in such a way that the sequential output from the sensors is a number in the binary code. A number of forms of binary code are used. Typical encoders tend to have up to 10 or 12 tracks. The number of bits in the binary number will be equal to the number of tracks. Thus with 10 tracks there will be 10 bits and so the number of position that can be detected is 2^{10}, i.e. 1024, a resolution of $360/1024 = 0.35^{\circ}$.

Difference between an Absolute and an Incremental Encoder

There are a few subtle differences between absolute and incremental rotary encoders. Incremental encoders have output signals that repeat over the full range of motion. It is important to understand that each mechanical position is not uniquely defined. When the incremental encoder is turned on, the position of an incremental encoder is not known since the output signals are not unique to any singular position.

Absolute encoders have a unique value (voltage, binary count, etc) for each mechanical position. When an absolute encoder is turned on, the position of an absolute encoder is known.

5. CONCLUSIONS

The objective of the sensing activity in microelectronics is the search for new engineering solutions for industrial applications inspired by principles, functions, mechanisms and architectures found in living organisms. Currently the focus is on sensor systems featuring an efficient implementation of signal and information processing tasks in Analog and mixed circuitry.

The application scope for sensor systems that include information processing for making decisions or eliciting actions on a local and autonomous basis is quite large. It extends to surveillance, industrial control, robotics, environmental control, the automotive sector, consumer electronics and multimedia applications. Typical requirements for sensor systems in these domains are reliability, real-time processing, compactness, low power consumption (portable, battery operated systems) and finally low-cost.

Many of the results that have been obtained in research are introduced into new industrial developments, such as, for example, a torque sensor designed for electrical power steering in cars.

Introduction to Instrumentation and Measurements makes it easy to make an informed choice among sensors and signal conditioning systems. This excellent reference includes all the general information on instrumentation and measurements as well as the technical details needed to apply the information to problems in the real world.

These are the some of the important features of sensors

- Describes quantum standards for the ohm, volt, and other modem measurement standards
- Includes a detailed treatment of linear and nonlinear analog signal processing
- Evaluates noise and coherent interference
- Presents numerous examples of optoelectronic instrument systems
- Introduces elements of digital signal conditioning used in measurement
- Discusses current industry trends
- Contains challenging problems