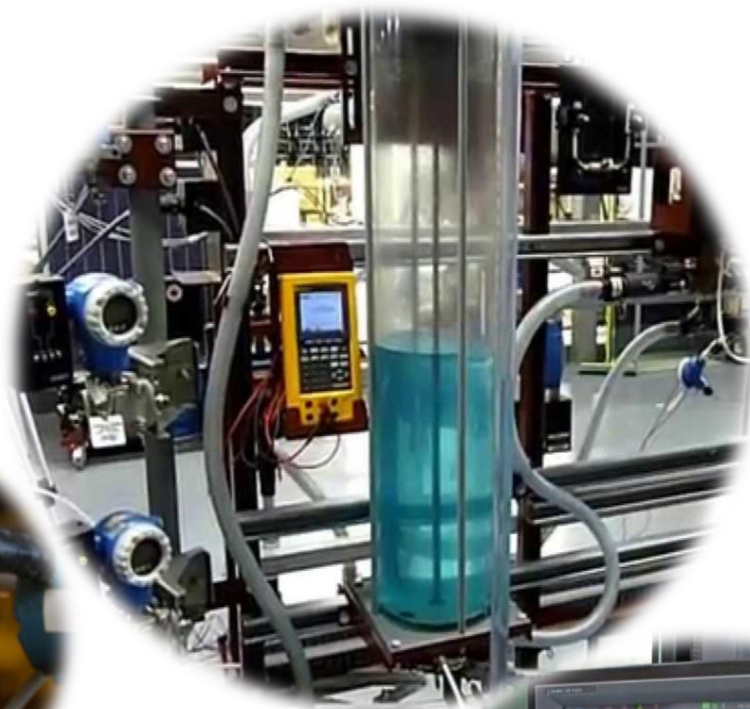
INSTRUMENTATION AND PROCESS CONTROL



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Instrumentation and Process Control

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Lesson 1

FUNCTIONS OF INSTRUMENTS AND MEASUREMENT SYSTEM

1.1 Introduction

Dairy processing unit operations mainly involve heating, cooling, separating, drying or freezing of the products. These unit operations are carried out under varying conditions of temperatures, pressures, flows and physical compositions. The measurement and control of these variable factors at the various stages of processing call for the accurate and efficient instruments, in addition to the dependence upon human skills. With the advent of large scale milk handling plants the automatic operation and control through efficient instrumentation and automation has become even more necessary. Utilities such as steam, water, electricity air, fuel etc. have to be measured and controlled at appropriate points in the plant. Automatic control instruments are employed to measure and control the temperature, pressure, flow and level of these utilities. The overall aim of the instrumentation/ automation is to improve the product quality and enhance the plant efficiency for better economic returns.

1.2 Variable

A characteristic number or quantity that increases or decreases over time, or takes different values in different situations is known as Variable. It is a factor that can be assigned a measurable dimension of some kind that varies, e.g., length, diameter, area, flow, weight, cost or life-span etc. A dependent variable is any measurable factor whose behavior is controlled by another variable. An independent variable is any measurable factor that produces change or reaction in another variable. A variable is something that is changed or altered in an experiment. In processing of food products the variables involved could be temperature and pressure of steam, processing time, flow rate of various streams etc. For example, to determine the effect of temperature and humidity on storage of a food product will provide evidence on the shelf life of product in different storage conditions. Variable is liable to change, may have a range of possible values and is liable to deviate from an established extension type.

1.3 Measurement

When we decide to study a variable we need to devise some way to measure it. Some variables are easy to measure and others are very difficult. The values of variables are made meaningful by quantifying them into specific units. For example, instead of saying that a particular fluid is hot, we can specify a measurement and specify that the fluid is having a temperature of 80°C. Measurement is collection of quantitative data. A measurement is made by comparing a quantity with a standard unit. An example of measurement means the use of a ruler to determine the length of a piece of paper.

Measurement is thus essentially an act or the result of comparison between the quantity (whose magnitude is unknown) and a predefined standard. Since both the quantities are compared, the result is expressed in numerical values. In the physical sciences, quality assurance, and engineering, measurement is the activity of obtaining and comparing physical quantities of real-world objects and events. Established standard objects and events are used as units, and the process of measurement gives a number relating the item under study and the referenced unit of measurement.

There are two essential requirements of the measurements, in order to make the results meaningful;

(i) The standard used for comparison purposes must be accurately defined and should be commonly accepted.

(ii) The apparatus used and the method adopted must be provable.

1.4 Unit of Measurement

A unit of measurement is a definite magnitude of a physical quantity, defined and adopted by convention and/or by law, that is used as a standard for measurement of the same physical quantity. Any other value of the physical quantity can be expressed as a simple multiple of the unit of measurement. For example, length is a physical quantity. The metre is a unit of length that represents a definite predetermined length. When we say 10 metres (or 10 m), we actually mean 10 times the definite predetermined length called "metre".

The definition, agreement, and practical use of units of measurement have played a crucial role in human endeavour from early ages up to this day. Different systems of units used to be very common. Now there is a global standard, the International System of Units (SI), the modern form of the metric system.

The International System of Units (abbreviated as SI from the French language name *Système International d'Unités*) is the modern revision of the metric system. It is the world's most widely used system of units, both in everyday commerce and in science. The SI was developed in 1960 from the metre-kilogram-second (MKS) system, rather than the centimetre-gram-second (CGS) system, which, in turn, had many variants. During its development the SI also introduced several newly named units that were previously not a part of the metric system. The original SI units for the six basic physical quantities were:

- metre (m) : SI unit of length
- second (s) : SI unit of time
- kilogram (kg) : SI unit of mass
- ampere (A) : SI unit of electric current
- degree kelvin (K) : SI unit of thermodynamic temperature
- candela (cd) : SI unit of luminous intensity

The mole was subsequently added to this list and the degree Kelvin renamed the kelvin.

There are two types of SI units, base units and derived units. Base units are the simple measurements for time, length, mass, temperature, amount of substance, electric current and light intensity. Derived units are constructed from the base units, for example, the watt, i.e. the unit for power, is defined from the base units as $m^2 \cdot kg \cdot s^{-3}$. Other physical properties may be measured in compound units, such as material density, measured in kg/m^3.

1.5 Significance of Measurements

Science is based on objective observation of the changes in variables. The greater our precision of measurement the greater can be our confidence in our observations. Also, measurements are always less than perfect, i.e., there are errors in them. The more we know about the sources of errors in our measurements the less likely we will be to draw erroneous conclusions. With the progress in science and technology, new phenomena and relationships are constantly being discovered and these advancements require newer developments in measurement systems. Any invention is not of any practical utility unless it is backed by actual measurements. The measurements thus confirm the validity of a given hypothesis and also add to its understanding. This is a continuous chain that leads to new discoveries with new and more sophisticated measurement techniques. While elementary measurements require only ordinary methods of measurement, the advanced measurements are associated with sophisticated methods of measurement. The advancement of Science and Technology is therefore dependent upon a parallel progress in measurement techniques. It can be safely be said that, the progress in Science and Technology of any country could be assessed by the way in which the data is acquired by measurements and is processed.

In R&D applications the design of equipments and processes require the basic engineering design data on the properties of the input raw materials and processed products. The operation and maintenance of equipments for optimal processing variables to achieve best quality product and energy efficient equipment utilization require the monitoring and control of several process variables. Both these functions require measurements. The economical design, operation and maintenance require a feedback of information. This information is supplied by appropriate measurement systems.

1.6 Function of Instrumentals and Measurement Systems

The measurement systems and the instruments may be classified based upon the functions they perform. There are four main functions performed by them: indicating, signal processing, recording and control.

i). **Indicating Function:** This function includes supplying information concerning the variable quantity under measurement. Several types of methods could be employed in the instruments and systems for this purpose. Most of the time, this information is obtained as the deflection of a pointer of a measuring instrument.

ii). **Recording Function:** In many cases the instrument makes a written record, usually on paper, of the value of the quantity under measurement against time or against some other variable. This is a recording function performed by the instrument. For example, a temperature indicator / recorder in the HTST pasteurizer gives the instantaneous temperatures on a strip chart recorder.

iii). **Signal Processing:** This function is performed to process and modify the measured signal to facilitate recording / control.

iv). **Controlling Function:** This is one of the most important functions, especially in the food processing industries where the processing operations are required to be precisely controlled. In this case, the information is used by the instrument or the systems to control the original measured variable or quantity.

Thus, based on the above functions, there are three main groups of instruments. The largest group has the indicating function. Next in line is the group of instruments which have both indicating and or recording functions. The last group falls into a special category and perform all the three functions, i.e., indicating, recording and controlling.

In this lesson only those instruments would be discussed whose functions are mainly indicating and recording, especially those instruments which are used for engineering analysis purposes. The process control functions and the related instruments are discussed in Lesson 27.

1.7 Basic Requirements of a Measurement System / Instrument

The following are the basic requirements of a good quality measurement system / instrument:

a) Ruggedness
b) Linearity

c) No hysteresis
d) Repeatability
e) High output signal quality
f) High reliability and stability
g) Good dynamic response

1.8 Applications of Measurement Systems

Before discussing the instrument characteristics, construction and working, it is pertinent to understand the various ways in which the measuring instruments are put in use. Different applications of the instruments and measurement systems are:

i). Monitoring a process/operation
ii). Control a process/operation
iii). Experimental engineering analysis

i). Monitoring a Process/Operation

There are several applications of measuring instruments that mainly have a function of monitoring a process parameter. They simply indicate the value or condition of parameter under study and these readings do not provide any control operation. For example, a speedometer in a car indicates the speed of the car at a given moment, an ammeter or a voltmeter indicates the value of current or voltage being monitored at a particular instant. Similarly, water and electric energy meters installed in homes and industries provide the information on the commodity used so that its cost could be computed and realized from the user.

ii). **Control a Process/Operation**

Another application of instruments is in automatic control systems. Measurement of a variable and its control are closely associated.

To control a process variable, e.g., temperature, pressure or humidity etc., the prerequisite is that it is accurately measured at any given instant and at the desired location. Same is true for all other process parameters such as position, level, velocity and flow, etc. and the servo-systems for these parameters.

A block diagram of a simple process control system is shown in Fig. 1.1.

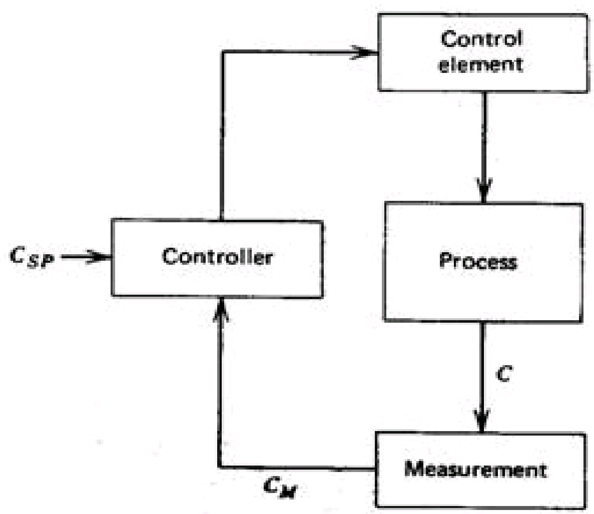


Fig. 1.1 Process control system

Let us assume that the output variable to be controlled is non-electrical quantity and the control action is through electrical means. Since the output variable is a non-electrical quantity, it is converted into a corresponding electrical form by a transducer connected in the feedback loop. The input to the controller is reference which corresponds to the desired value of the process parameter. The output process variable is compared with the reference or desired value with the help of a comparator. In case the desired value and the process variable differ, there is a resultant error signal. This error signal is amplified and then fed to an actuator, which produces power to drive the controlled circuitry.

The corrective action goes on till the output is at the same level as the input which corresponds to the desired output. At this stage, there is no error signal and hence there is no input to the actuator and the control action stops.

Common examples of this application are the domestic appliances, such as, refrigerator, air conditioner or a hot air oven. All of these employ a thermostatic control. A temperature measuring device (often a bimetallic element) measures the temperature in the room, refrigerated chamber or in the oven and provides the information necessary for appropriate functioning of the control system in these appliances.

iii). Experimental Engineering Analysis

Experimental engineering analysis is carried out to find out solution of the engineering problems. These problems may be theoretical designs or practical analysis. The exact experimental method for engineering analysis will depend upon the nature of the problem. The analysis could be grouped into following categories:

1. Obtaining solutions of mathematical relationships with the help of analogies.
2. Formulating the generalized empirical relationships in the cases where no proper theoretical backing exists.
3. Testing the validity of theoretical predications.
4. Generating the basic engineering design data on the properties of the input raw materials and processed products for R&D application.
5. Design of process equipments for specific applications.
6. Optimization of machine / system parameters, variables and performance indices.

Lesson 2

ELEMENTS OF GENERALIZED MEASUREMENT SYSTEM

2.1 Introduction

Scientists, engineers and other humans use a vast range of instruments to perform their measurements. These instruments may range from simple objects such as ruler scales and stopwatches to electron microscopes and particle accelerators used by scientists and engineers.

An *instrument* is as a device or a system which is designed to maintain a functional relationship between prescribed properties of physical variables being measured. It provides the means of communication to a human observer or the operator of a machine or equipment. The above stated functional relationship remains valid, only as long as the static calibration of system remains constant. The performance of an instrument of a measurement system is usually described in terms of a set of its *static and dynamic characteristics*. These characteristics have been described in detail in lessons 6 and 7.

2.2 Functional Elements of a Measurement System

To understand a measuring instrument/system, it is important to have a systematic organization and analysis of measurement systems. The operation of a measuring instrument or a system could be described in a generalized manner in terms of functional elements. Each functional element is made up of a component or groups of components which perform required and definite steps in the measurement. The functional elements do not provide the intricate details of the physical aspects of a specific instrument or a system. These may be taken as basic elements, whose scope is determined by their functioning rather than their construction.

The main functional elements of a measurement system are:

i) Primary sensing element
ii) Variable conversion element
iii) Variable manipulation element
iv) Signal conditioning element
v) Data transmission element
vi) Data presentation element.

2.2.1 Primary sensing element

The quantity or the variable which is being measured makes its first contact with the primary sensing element of a measurement system. The measurement is thus first detected by primary sensor or detector. The measurement is then immediately converted into an analogous electrical signal. This is done by a transducer. Though a transducer in general, is defined as a device which converts energy from one form to another. But in measurement systems, this definition is limited in scope. A transducer is defined as a device which converts a physical quantity into an electrical quantity. The output of the sensor and detector element employed for measuring a quantity could be in different analogous form. This output is then converted into an electrical signal by a transducer. This is true of most of the cases but is not true for all. In many cases, the physical quantity is directly converted into an electrical quantity by a detector transducer. The first stage of a measurement system is known as a detector transducer stage.

2.2.2 Variable conversion element

The output signal of the variable sensing element may be any kind. It could be a mechanical or electrical signal. It may be a deflection of elastic member or some electrical parameter, such as, voltage, frequency etc. Sometimes, the output from the sensor is not suited to the measurement system. For the instrument to perform the desired function, it may be necessary to convert this output signal from the sensor to some other suitable form while preserving the information content of the original signal. For example, suppose the output from the sensing element is in the form of very small displacement which is difficult to measure mechanically, it is converted in to corresponding electrical signal with the help of transducer called stain gauge for further processing. Also if the output at one stage is analogue form and the next stage of the system accepts input signal only in digital form. In such cases, we will have to use as Analogue /Digital converter.

In many instruments variable conversion element is not required. Some instruments/measuring systems may require more than one element.

2.2.3 Variable manipulation element

Variable manipulation means a change in numerical value of the signal. The function of a variable manipulation element is to manipulate the signal presented to this element while preserving the original nature of the signal. For example, a voltage amplifier acts as a variable manipulation element. The amplifier accepts a small voltage signal as input and produces an output signal which is also voltage but of greater magnitude. The variable manipulation element could be either placed after the variable conversion element or it may precede the variable conversion element.

2.2.4 Signal conditioning element

The output signal of transducers contains information which is further processed by the system. Many transducers develop usually a voltage or some other kind of electrical signal and quite often the signal developed is of very low voltages, may be of the order of mV and some even μV. This signal could be contaminated by unwanted signals like noise due to an extraneous source which may interfere with the original output signal. Another problem is that the signal could also be distorted by processing equipment itself. If the signal after being sensed contains unwanted contamination or distortion, there is a need to remove the interfering noise / sources before its transmission to next stage. Otherwise we may get highly distorted results which are far from its true value.

The solution to these problems is to prevent or remove the signal contamination or distortion. The operations performed on the signal, to remove the signal contamination or distortion, is called Signal Conditioning. The term signal conditioning includes many other functions in addition to variable conversion and variable manipulation. Many signal conditioning processes may be linear, such as, amplification, attenuation, integration, differentiation, addition and subtraction. Some may be non-linear processes, such as, modulation, filtering, clipping, etc. The signal conditioning processes are performed on the signal to bring it to the desired form for further transmission to next stage in the system. The element that performs this function in any instrument or instrumentation system is known as Signal Conditioning Element.

2.2.5 Data transmission element

There are several situations where the elements of an instrument are actually physically separated. In such situations it becomes necessary to transmit data from one element to another. The element that performs this function is called a Data Transmission Element. For example satellites or the air planes are physically separated from the control stations at earth. For guiding the movements of satellites or the air planes control stations send the radio by a complicated telemetry systems. The signal conditioning and transmission stage is commonly known as Intermediate Stage.

2.2.6 Data presentation element

The function of data presentation element is to convey the information about the quantity under measurement to the personnel handling the instrument or the system for monitoring, control, or analysis purposes. The information conveyed must be in a convenient form. In case data is to be monitored, visual display devices are needed. These devices may be analogue or digital indicating instruments like ammeters, voltmeters, etc. In case the data is to be recorded, recorders like magnetic tapes, high speed camera and T.V. equipment; storage type C.R.T., printers, analogue and digital computers may be used. For control and analysis purpose computers and the control elements are used. The final stage in a measurement system is known as terminating stage.

Figure 2.1 below presents the block diagram of functional elements of a generalized measuring system / instrument. One must understand the difference between functional elements and the physical elements of measuring system. Functional element indicates only the function to be performed. Physical elements are the actual components or parts of the system. One physical element can perform more than one function. Similarly one function could be performed by more than one physical element. This is more suitably illustrated in the example of a measuring instrument described below.

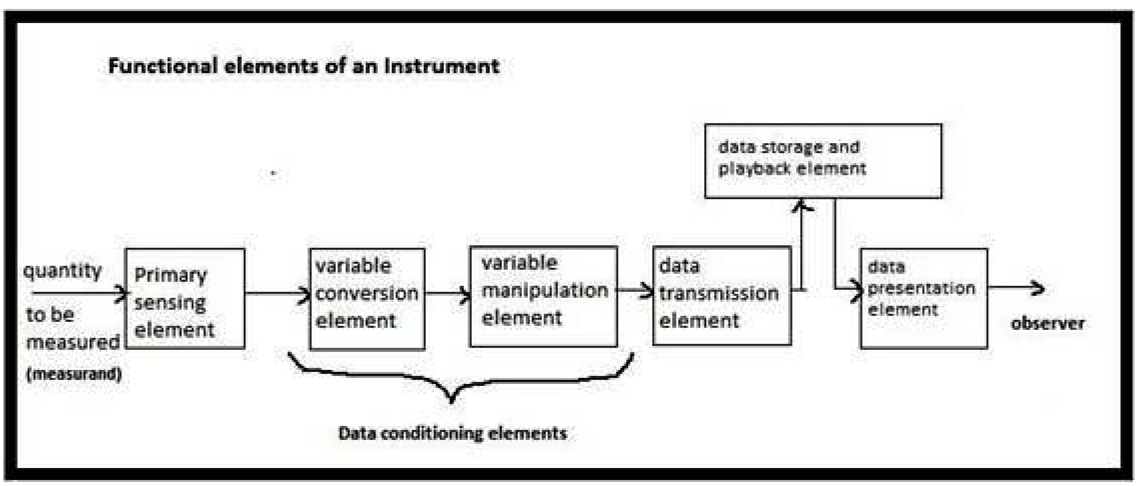


Fig. 2.1 Block diagram of functional elements of a measurement System / Instrument

2.3 Functional Elements of a Bourdon Pressure Gauge

As an example of a measurement system, consider the simple Bourdon tube pressure gauge as shown in Fig. 2.2. This gauge offers a good example of a measurement system. In this case, the Bourdon tube acts as the primary sensing element and a variable conversion element. It senses the input quantity (pressure in this case). On account of the pressure the closed end of the Bourdon tube is displaced. Thus, the pressure is converted into a small displacement. The closed end of the Bourdon tube is connected through mechanical linkage to a sector-pinion gearing arrangement. The gearing arrangement amplifies the small displacement and makes the pointer to rotate through a large angle. The mechanical linkage thus acts as a data transmission element while the gearing arrangement acts as a data manipulation element. The dial scale on the gauge body plays the function of data presentation element and conveys the information about the quantity being measured. The information conveyed by this device is in analogue form.

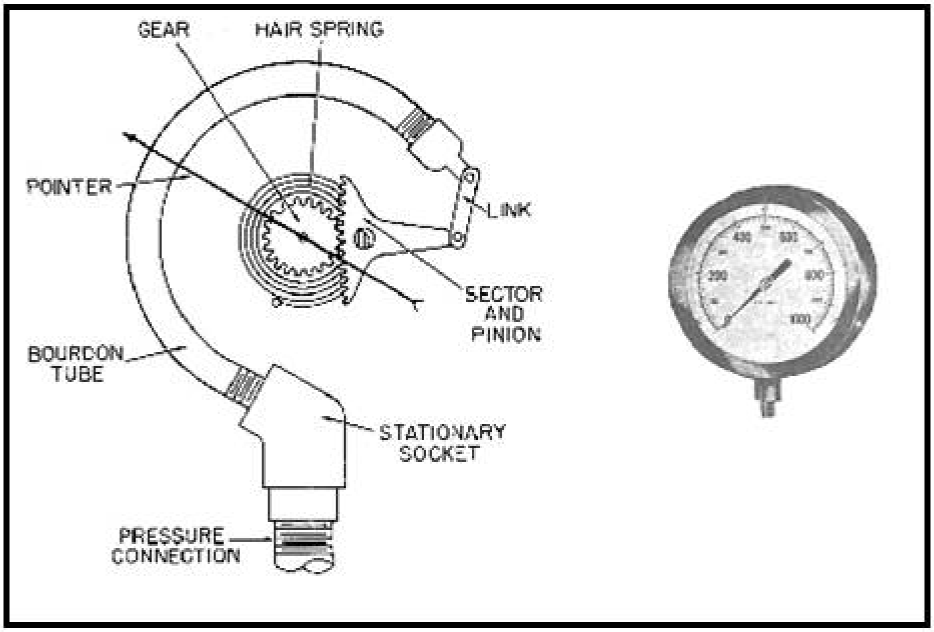


Fig. 2.2 Bourdon Pressure gauge, the pressure measuring instrument

2.4 Functional Elements of a Clinical Thermometer

As another example of a measurement system, let us consider the simple clinical thermometer shown in Fig. 2.3. In this case, the thermometer bulb containing mercury acts as the primary sensing element as well as a variable conversion element. It senses the input quantity, the temperature. On account of the increase in temperature the mercury in bulb expands and its volume is increased. The temperature signal is converted into volume displacement. As the mercury expands it move through the capillary tube in the thermometer stem, integrated to the bulb. The cross section area of the capillary being constant, the volume signal is thus converted into linear distance signal. The capillary thus has the role of signal manipulation and data transportation elements. The final data presentation stage consists of the scale on the thermometer stem, which is calibrated to give the indication of the temperature signal applied to the thermometer bulb. A restriction bend is provided in the clinical thermometers at the junction of the bulb and the capillary, which does not allow the back flow of mercury to the bulb once it has expanded to the capillary. Thus the restriction in the capillary acts as the data storage function of the instrument.

Fig. 2.3 Clinical thermometer, the temperature measuring instrument

If the measurement is done to control a parameter / process then a control device is integrated at the final measurement stage. In such cases, it is necessary to apply some feedback to the input signal to accomplish the control objectives. The control stage compares the signal representing the measured variable provided by the measurement system with a reference signal of the same form. This reference signal has a value to which the measured signal should be controlled. If the measured signal agrees with the reference value, the controller does nothing. However, if there is a difference between the measured value and the reference value, an error signal is generated. Thus, the controller sends a signal to a device which acts to alter the value of the measured signal.

Suppose the measured variable is flow of a liquid, then the control device is a motorized valve placed in the flow system. The measurement system measures the flow rate. In case the measured flow rate is too low than the desired preset flow rate, then the controller would make the valve to open more, thereby increasing the flow rate. If on the other hand, the flow rate is too high, the valve is closed to the require position. The operation of closing or opening of valve will cease when the output flow rate is equal to preset value of flow rate.

Lesson 3

CLASSIFICATION OF INSTRUMENTS

3.1 Introduction

In the physical scsssssiences, process engineering and product quality assurance, measurement is the activity of obtaining and comparing physical quantities of real-world objects and events. Established standard objects and events are used as units, and the process of measurement gives a number relating the item under study and the referenced unit of measurement. Measurement generally involves using an instrument as a physical means of determining a quantity or variable. The instrument serves as an extension of human faculties and enables the man to determine the value of an unknown quantity which unaided human faculties cannot measure. An instrument may be defined as a device for determining the value or magnitude of a quantity or variable. Measuring instruments, and formal test methods which define the instrument's use, are the means by which the variables and the relations between variables are obtained

The instruments may be classified as follows:

i) Mechanical, electrical and electronic instruments
ii) Absolute and secondary instruments
iii) Manual and automatic instruments
iv) Analogue and digital instruments
v) Self operated and power operated instruments
vi) Self contained and remote indicating instruments

3.2 Mechanical, Electric and Electronic Instruments

3.2.1 Mechanical instruments

The first instruments were mechanical in nature and the principles on which these instruments worked are even in vogue today. The earliest scientific instruments used the same three essential elements as our modern instruments do. These elements are a detector, an intermediate transfer device and an indicator, recorder or a storage device.

These instruments are very reliable for static and stable conditions. There is a large number of possibilities of mechanical instruments. It could be calipers, micrometers, scales, measuring tapes, lasers, etc. for measuring distances, a pressure gauge for measuring pressure, strain gauges for measure how much a part is stretched or compressed when a load is applied, tachometer for measuring the rotational speed, multimeter for measuring electrical voltages and currents.

However, the mechanical instruments suffer from a disadvantage that they are unable to respond rapidly to measurements of dynamic and transient conditions. These instruments have several moving parts that are rigid, heavy and bulky and consequently have a large mass. The mass presents inertia problems and hence these instruments cannot follow the rapid changes which are involved in dynamic measurements. Another disadvantage of mechanical instruments is that most of them are a potential source of noise and cause pollution of silence.

Mechanical instruments are simple in design and application. They are more durable and relatively cheaper. No external power source is required for the operation of mechanical instruments. They are quite reliable and accurate for measurements under stable conditions.

3.2.2 Electrical instruments

Electrical methods of indicating and transmitting the output are faster than the respective mechanical methods. However, an electrical system normally depends upon a mechanical pointer movement as an indicating device. Thus owing to the inertial of mechanical movements these instruments have a limited time and frequency response. For example, some electrical recorders can give full scale response in 0.2 seconds; while the majority of industrial recorders have response time of 0.5 to 24 seconds. Some of the galvanometers can follow 50 Hz variations, but as per present day requirements of fast measurements these are also considered to be slow.

Electrical instruments are light and compact. Amplification produced is greater than that produced by mechanical means. They provide greater flexibility and are lighter in construction. These instruments consume less power and hence cause lesser load on the system.

3.2.3 Electronic instruments

Majority of the modern scientific and industrial measurements require very rapid responses. The mechanical and electrical instruments and systems cannot fulfil these requirements. There is a requirement of decreasing the response time and also the detection of dynamic changes in certain parameters. The monitoring time could be of the order of milli seconds (ms) and many a times, micro seconds (μs). This has led to the design of today's electronic instruments and their associated circuitry. These instruments involved vacuum tubes or semi-conductor devices. The present day practice is to use semi-conductor devices owing to their many advantages over their vacuum tube counterparts. Since in electronic devices the only movement involved is that of electrons and the inertia of electrons being very small, the response time of these devices is extremely small. For example, a C.R.O. is capable of following dynamic and transient changes of the order of a few nano seconds (10^{-9} s).

Electronically controlled power supplies are used to provide stable voltages for studies in the field of chemical reactions and nuclear instrumentation. Electronic instruments are steadily becoming more reliable on account of improvements in design and manufacturing processes of semi-conductor devices. Another advantage of using electronic devices is that very weak signals can be detected by using pre-amplifiers and amplifiers. The foremost importance of the electronic instruments is the power amplification provided by the electronic amplifiers. Additional power may be fed into the system to provide an increased power output beyond that of the input. This has been only possible through the use of electronic amplifiers, which have no important mechanical counterpart. This is particularly important where the data presentation devices use stylus type recorders, galvanometers, cathode ray oscilloscopes and magnetic tape recorders.

It is a fact that hydraulic and pneumatic systems may be used for power amplification of signals. However, their use is limited to slow acting control applications like servo-systems, chemical processes and power systems. Electronic instruments find extensive use in detection of electro-magnetically produced signals such as radio, video, and microwave. Electrical and electronic instruments are particularly useful in the intermediate signal modifying stage. Electronic instruments are light compact and have a high degree of reliability. Their power consumption is very low.

Electronic instruments make it possible to build analogue and digital computers without which the modern developments in science and technological are virtually impossible. Computers require a very fast time response and it is only possible with use of electronic instruments. The mathematical processing of signal, such as, summation, differentiating and integrating is possible with electronic measurements. With these instruments non contact or remote measurements are also possible.

3.3 Absolute/primary and Secondary Instruments

Electrical measurements of different parameters like current, voltage, power, energy, etc. are most essential in any industry. These are among the oldest of all measurements. The various electrical instruments may be broadly divided into two categories:

1) Absolute instruments
2) Secondary instruments

3.3.1 Absolute/primary instruments

Absolute/primary instruments are those which give the value of electrical quantity to be measured in terms of the constants of the instruments and their deflection only e.g. tangent galvanometer. These instruments are rarely used except in standard laboratories, especially for calibration of secondary instruments.

3.3.2 Secondary instruments

Secondary instruments are those in which the values of electrical quantity to be measured can be determined from the deflection of the instruments only when they have been pre-calibrated by comparison with an absolute instrument. Without calibration, the deflection of such instruments is meaningless.

Working with absolute instruments for routine work is time consuming since every time a measurement is made, it takes a lot of time to compute the magnitude of the quantity under measurement. It is the secondary instruments which are most generally used in everyday work, the use of the absolute instruments being merely confined within laboratories as standardizing instruments. A voltmeter, a glass thermometer and a pressure gauge are typical examples of secondary instruments.

Secondary type of measuring instruments has been classified in the following categories:

3.3.2.1 Indicating instruments

Indicating instruments are those which indicate the instantaneous value of the variables being measured, at the time at which it is being measured. Their indications are given by pointers moving over calibrated dials or scales, e.g., ammeter, voltmeter and wattmeter. This movement of pointer or the deflection is not constant but depends on the quantity it measures. As the needle deflects and indicates the amount of current, voltage or any quantity, these are called deflection type of instruments.

3.3.2.2 Recording instruments

Recording instruments are those which give a continuous record of variations of the measured variable over a selected period of time. The moving system of the instrument carries an inked pen which rests tightly on a graph chart. These instruments will go on recording on a graph sheet fixed on the instrument all the variations of the quantity in the time it is connected in the circuit. Normally these recordings will be for one day and the recorded sheets are kept as a record of variation of the quantity with time.

3.2.2.3 Integrating instruments

These are the instruments which will add up the quantity as the time passes or in other words will give a total account of quantity spent in a given time for which it is connected in a circuit. For example, an electric meter measure and register, by a set of dials and pointers, either the total quantity of electricity (in ampere-hours) or the total amount of electrical energy (in watt-hours or kilowatt-hours) supplied to a circuit over a period of time and are known as ampere-hour meters, watt hour meters, energy meters, etc. Another example is house hold water meter. Deflecting type instruments are again classified as follows:

a) Depending upon working principle, such as, moving coil, moving iron, dynamometer, electrostatic type, induction type
b) Depending upon the quantity it measures, such as, voltmeter, ammeter, ohm meter, power factor meter, energy meter etc.
c) Depending upon the shape of the instruments, such as, portable, panel board type with flush mounting or surface mounting.

Deflection is normally with in 90^{o}, but circular scale instruments are also available which give about 250^{o} deflection. All the deflecting instruments are marked on scale to indicate its working principle by symbols.

3.4 Manual and Automatic Instruments

Manual require the services of an operator, where as in automatic instruments the operator is not required. For example, measurement of rotational speed by a hand operated tachometer an operator is required to make the contact of the instrument with the rotating shaft. For measurement of temperature by a resistance thermometer by Wheat stone bridge in its circuit an operator is required to indicate the temperature being measured. Where as, in measurement of temperature by mercury-in-glass thermometer, no operator is required.

3.5 Self Operated and Power Operated Instruments

A self operated instrument does not require any external power source for its operation. In such instruments the output energy is supplied by the input signal e.g. a dial indicator or mercury-in-glass type thermometer.

In power operated instruments some auxiliary power source is required for its operation. This external power source could be electricity, compressed air etc. In such cases the input signal supplies only the insignificant portion of the output power e.g. an electro-mechanical measurement system.

3.6 Self Contained and Remote Indicating Instruments

A self contained instrument has all the physical elements in one assembly e.g. an analog ammeter or a mercury-in-glass thermometer etc. Whereas, in a remote indicating instrument has primary sensory element and the secondary indicating element are located at two different locations linked by transmitting element. These locations could be long distance apart. In modern instrumentation technology such type of arrangement is quite necessary and vogue.

3.7 Contact Type and Non-Contact Type Instruments

In contact type instruments the sensing element of the instrument contacts the control medium for the measurements, for example mercury-in- glass thermometer. Where as in non-contact type instruments the sensor does not contact the control medium. The non-contact type measurement includes optical, radioactive or radiation measurements. Such as, radiation or optical pyrometer, non-touch tachometer etc. The Secondary instruments working on analog and digital mode of operation are discussed in Lesson 4.

Lesson 4

ANALOG AND DIGITAL MODES OF OPERATION

4.1 Introduction

Working with absolute instruments for routine work is time consuming since every time a measurement is made, it takes a lot of time to compute the magnitude of the quantity under measurement. It is the secondary instruments which are most generally used in everyday work, the use of the absolute instruments being merely confined within laboratories as standardizing instruments. Secondary instruments work in two modes, the Analog mode and the Digital mode.

4.2 Analog or Analogue Signal

Analog signals are those which vary in a continuous fashion and take on infinity of values in any given range. The devices which produce these signals are called analog devices. Analog is usually thought of in an electrical context; however, mechanical, pneumatic, hydraulic, and other systems may also convey analog signals. An analog signal uses some property of the medium to convey the signal's information. For example, an aneroid barometer uses rotary position as the signal to convey pressure information. Electrically, the property most commonly used is voltage followed closely by frequency, current, and charge. The devices that produce such signals are called analog devices.

Any information may be conveyed by an analog signal. Often such a signal is a measured response to changes in physical phenomena, such as temperature, pressure, sound or position and is achieved using a transducer. An analog signal is one where at each point in time the value of the signal is significant. For example, in sound recording, fluctuations in air pressure (that is to say, sound) strike the diaphragm of a microphone which induces corresponding fluctuations in the current produced by a coil in an electromagnetic microphone, or the voltage produced by a condenser microphone.

4.3 Digital Signal

In contrast the analog signals which vary in a continuous fashion and take on infinity of values in any given range, the digital signals vary in discrete steps and thus take up only finite different values in a given range. The devices that produce such signals are called digital devices.

Analog and Digital signals are presented in Fig. 4.1 (a) and (b). In an analog system, the function varies continuously. On the other hand, the digital values are discrete and vary in equal steps. The figure below illustrates how both an analog voltage and a digital voltage vary with time.

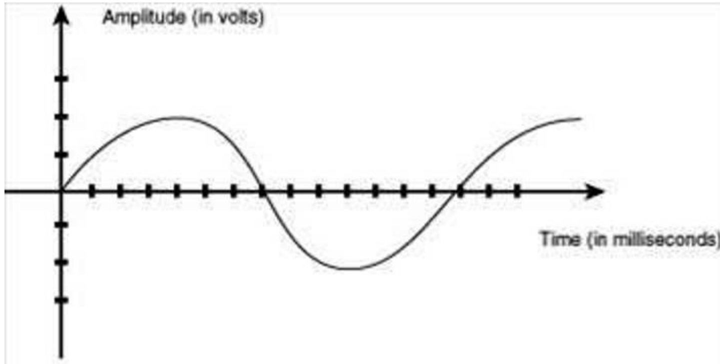


Fig. 4.1(a) Analog signal

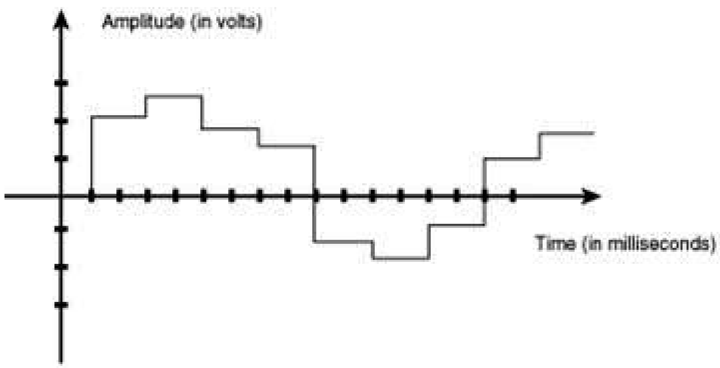


Fig. 4.1(b) Digital signal

4.4 Analog Versus Digital Modes

An analog signal is one where at each point in time the value of the signal is significant, where as a digital signal is one where at each point in time, the value of the signal must be above or below some discrete threshold. The display of the quantity to be measured in analog instruments is in terms of deflection of a pointer, where as digital instruments indicate the value to be measured in terms of decimal number. The main advantage of the analog signal is its fine definition which has the potential for an infinite amount of signal resolution. Compared to digital signals, analog signals are of higher density.

Another advantage with analog signals is that their processing may be achieved more simply than with the digital equivalent. An analog signal may be processed directly by analog components, though some processes aren't available except in digital form. The analog instruments are less costly and simple in design as compared to their digital counter parts.

The primary disadvantage of analog signaling is that any system may have noise, that is, random unwanted variation. As the signal is copied and re-copied, or transmitted over long distances, these apparently random variations become dominant. Electrically, these losses can be diminished by shielding, good connections, and several cable types such as coaxial or twisted pair. The effects of noise create signal loss and distortion. This is impossible to recover, since amplifying the signal to recover attenuated parts of the signal amplifies the noise (distortion/interference) as well. Even if the resolution of an analog signal is higher than a comparable digital signal, the difference can be overshadowed by the noise in the signal.

The digital devices have high speed and they also eliminate the human error. With increasing use of digital computers for data handling and automatic process control, the importance of digital instrumentation is increasing. It has become necessary to have both analog to digital converter at input to the computers and digital to analog converters at the output of the computers.

In order to convert an analog quantity into a digital number, the vertical displacements in Fig.4.2 are divided into equal parts. If we divide the vertical quantities into 10 equal parts with each part having a length of 1 unit. While dealing with digital numbers, a quantity between 0 to 0.5 are considered as 0, while a quantity between 0.5 to 1.5 is 1 and similarly a quantity between 1.5 to 2.5 is 2. It is apparent that if we adopt digital system, the errors will be involved. But if we further divide each of the steps into 2 equal parts, we get 20 steps instead of 10. And if these 20 steps are further divided into 2 parts each, we will have 40 steps. By doing this we can get much better accuracy in converting analogue quantities into digital numbers. We can go on subdividing each step further and further, till the desired accuracy is achieved. However, it should be remembered that a digital number is still a sum of equal units. And in a digital system, magnitudes lying within one of these steps lose their identity and are all defined by the same number. For example, if we have ten steps, all the numbers lying between 2.5 to 3.5, that is, 2.6, 2.7, 2.8, 2.9, 3.0, 3.1, 3.2, 3.3, 3.4, would all be read as 3.

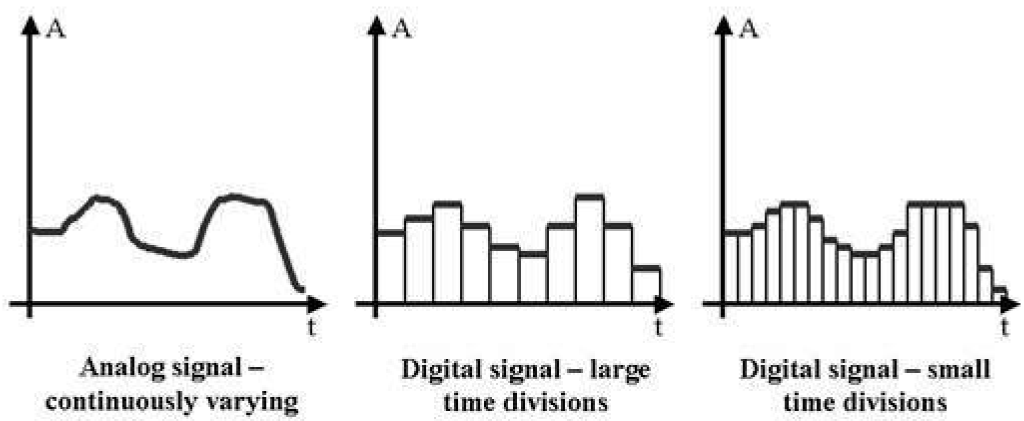


Fig. 4.2 Analog to digital conversion of signal

From the above discussion we concluded that the difference between analogue and digital information is that the analogue output is a continuous function while the digital output is a discrete number of units. The last digit of any digital number is rounded to ±0.5 of the last digit. It should also be marked that the magnitude of the digital quantity is measured only at the instant the reading is taken. One reading persists till another reading is taken (unlike the analogue quantity which is a continuous function).

4.5 Analog Measuring Device

An analog device is one in which the output or display is a continuous function of time and bears a constant relation to its input. The analog instruments find extensive use in present day applications although digital instruments are increasing in number and applications. The areas of application which are common to both analog and digital instruments are fairly limited at present. Hence, it can safely be predicted that the analog instruments will remain in extensive use for a number of years and are not likely to be completely replaced by digital instruments for certain applications.

4.5.1 Classification of analog instruments

Broadly, the analog instruments (and for that matter digital instruments) may be classified according to the quantity they measure. For example, an instrument meant for measurement of current is classified as an Ammeter while an instrument that measures voltage is classified as a Voltmeter. Thus we have wattmeters, power factor meters, frequency meters, etc. Electrical instruments may also be categorized as per the kind of current that can be measured by them, such as, direct current (d.c.), alternating current (a.c.), and direct and alternating current (d.c. / a.c.). As discussed earlier, there are three categories of instruments; on the same pattern analog instruments could also be classified as indicating, recording, integrating type.

Indicating instruments are those instruments which indicate the magnitude of a quantity being measured. They generally make use of a dial and a pointer for this purpose. Ordinary voltmeters, ammeters and wattmeters belong to this category. The analog indicating instruments may be further divided into two groups, the *electromechanical* instruments, and the *electronic* instruments. Electronic instruments are constructed by addition of electronic circuits to electromagnetic indicators in order to increase the sensitivity and input impedance.

Recording instruments give a continuous record of the quantity being measured over a specified period. The variations of the quantity being measured are recorded by a pen (attached to the moving system of the instrument; the moving system is operated by the quantity being measured) on a sheet of paper carried by a rotating drum. For example, we may have a recording voltmeter in a sub-station which keeps record of the variations of supply voltage during the day.

Integrating instruments totalise events over a specified period of time. The summation, which they give, is the product of time and an electrical quantity. Ampere hour and watt hour (energy) meters are examples of this category. The integration (summation value) is generally given by a register consisting of a set of pointers and dials.

On the basis of method used for comparing the unknown quantity (measured) with the unit of measurement the analog instruments may also be grouped into two categories of instruments:

i) **Direct Measuring Instruments:** These instruments convert the energy of the measurand directly into energy that actuates the instruments and the value of the unknown quantity is measured or displayed or recorded directly. The examples of this class of instruments are ammeters, voltmeters, wattmeters and energy meters.

ii) **Comparison Instruments:** These instruments measure the unknown quantity by comparison with a standard. The examples of comparison type instruments are d.c. and a.c. bridges.

Direct measuring instruments are the most commonly used in engineering practice because they are the most simple and inexpensive. Also their use makes the measurement possible in the shortest time.

4.6 Digital Measuring Device

A digital measuring device is that in which the value of the measured physical quantity is automatically represented by a number on a digital display or by a code, that is, a set of discrete signals. Digital measuring devices can be divided into digital measuring instruments and digital measuring transducers. Digital measuring instruments are self-contained devices that automatically present the value of the measured quantity on a digital display. Digital measuring transducers lack a digital display; and the measurement results are converted into a digital code for subsequent transmission and processing in measuring systems. The most common types of digital measuring devices are those used to measure electrical quantities, such as current, voltage, and frequency. These devices may be used to measure nonelectrical quantities—such as pressure, temperature, speed, and force—if the nonelectrical quantity is first converted into an electrical quantity. For example there are digital multimeters, digital thermometers, digital flow meters etc.

The operation of digital measuring devices is based on the digitization, that is, quantization with respect to level and coding of the value of the measured physical quantity. The coded signal is fed either to a digital display or to a data transmission and processing system. In a digital display the coded measurement result is converted into a number expressed by numerals, usually in the decimal number system. The most widely used digital displays give two to nine digits. Digital measuring instruments may use electric, cathode-ray, gas-discharge, or liquid-crystal displays.

4.7 Analogue to Digital (A/D) Conversion

The majority of present day instruments are analogue type. The importance of digital instruments is increasing, mainly because of the increasing use of digital computers in both data reduction and automatic control systems. Since digital computer works only with digital signals, any information supplied to it must be in digital form. The computer's output is also in digital form. Thus working with a digital computer at either the input or the output, we must use digital signals.

However, most of our present day measurement and control apparatus produces signals which are of analogue nature, it is thus necessary to have both Analogue to Digital (A/D) Converters at the input to the computer and Digital to Analogue (D/A) Converters at the output of the computer.An analog-to-digital converter is a device that converts a continuous quantity to a discrete time digital representation. The reverse operation is performed by a digital-to-analog converter. Typically, an A/D is an electronic device that converts an input analog voltage or current to a digital number proportional to the magnitude of the voltage or current. However, some non-electronic or only partially electronic devices, such as rotary encoders, can also be considered ADCs. The digital output may use different coding schemes. Typically, the digital output will be a binary number that is proportional to the input, but there are other possibilities.

An analog to digital converter (Fig. 4.3) inputs an analog electrical signal such as voltage or current and outputs a binary number. In block diagram form, it can be represented as below:

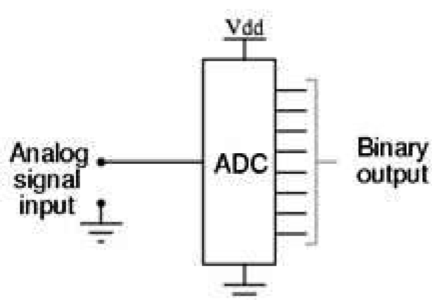


Fig. 4.3 Analog to digital converter

A digital to analog converter (Fig.4.4) on the other hand, inputs a binary number and outputs an analog voltage or current signal. In block diagram form, it looks like this:

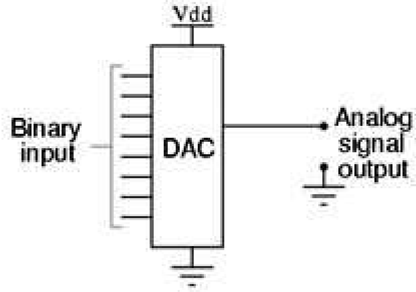


Fig. 4.4 Digital to analog converter

Lesson 5

INSTRUMENT SELECTION CRITERIA AND INSTALLATION PROCEDURES

5.1 Introduction

The availability of several types of sophisticated instruments and automatic process control techniques has greatly helped in improving not only the product quality in the food processing industries but also in achieving the reduction in cost of processing. Automation has become the essential component of technological and industrial development. A large number of specialized instruments have been developed to measure the variety of process variables. They generally give a range of measurement accuracy and sensitivity and vary vastly in cost factor. Choice between the various types of instruments is available and several alternatives are there with the entrepreneur.

5.2 Instrument Selection Criteria

The selection of an instrument for a specific application is an iterative process, carried out as a joint effort of a process technologist and an instrument engineer. Following are the points that should be considered while choosing the instrument for particular application

1. Identify all operating cases, such as normal operation at minimum, normal and maximum flow, alternative operating modes, start-up, commissioning and emergency operation.
2. Collect all relevant process data for each operating case. Data pertaining to processing fluids, such as, fluid name and phase, physical properties, corrosiveness and toxicity , presence of solids or contaminants, special risks such as fouling, plugging and deposition need to be delineated. Quantify the process operating data, such as, flow rate, pressure, temperature, density and viscosity etc. Specify the application aspects, such as, continuous/batch operation, pulsating flow, unidirectional or bi-directional flow, backflow risk, vibration and hydraulic noise.
3. Specify the environmental conditions that the instrument will be subjected to. As some conditions will immediately either eliminate the possibility of using certain types of instrument or else will create a requirement for expensive protection of instrument. One point to be remembered is that the protection of instruments reduces the performance of some instruments, especially in terms of their dynamic characteristics. For example sheaths protecting thermocouples and resistance thermometers reduce their speed of response. Instrument should be chosen that are as insensitive as possible to operating environment.
4. The extent to which the measuring system will be disturbed during the measuring process is another important factor in instrument choice. For example significant pressure loss can be caused to measured system in some techniques of flow measurement.
5. Consideration of durability, maintainability and consistency of performance are also very important during selecting the appropriate instrument.
6. Published literature is of considerable help in the choice of suitable instrument for a particular measurement situation. It is important to keep abreast of latest developments through appropriate technical publications.
7. Select suitable instrument makes and types for each measurement option from the ‘List of Selected Instrument Vendors’ as prepared for each project. The types of instruments already installed at the

Principal's site should be taken into consideration, for the sake of variety control.

Instrument choice is a compromise between it's performance characteristics, ruggedness, durability, maintenance requirements and purchase cost. To carry out such an evaluation properly, the instrument engineer must have a wide knowledge of range of instruments available for measuring particular physical quantities, and he/she must also have deep understanding of how instrument characteristics are affected by particular measurement situations and operating conditions.

Cost is very strongly correlated with the performance characteristics of an instrument. Increasing the accuracy or resolution of an instrument, for example, can only be done at the penalty of increasing its manufacturing cost. Instruments choice therefore proceeds by specifying the minimum characteristics required by a measurement situation and finding an instrument whose characteristics match those required. To select an instrument with characteristics superior to those required would only mean paying more than necessary for a level of performance greater than that needed.

5.3 Choice Between Different Types of Instruments

5.3.1 Pressure sensors

Choice between the various types of instruments available for measuring mid-range pressure (1.013-7000bar) is usually strongly influenced by the intended application. Manometers are commonly used when just a visual indication of low pressure level is required. For medium pressure or vacuum sensing a Bourdon tube type pressure gauge is used. Bellows-types instruments are also sometimes used for this purpose, but much less frequently. When an electrical form of output is required, the choice is usually any one of the diaphragm type sensor with strain gauge, capacitive or fiber optics are used. If very high measurement accuracy is required, the resonant-wire devices are popular choice. Deadweight gauges, because of their superior accuracy, are used in calibration procedures of other pressure measuring devices.

In the case of pressure measurement in vacuum ranges, that is, below 1.0132bar, adaptation of most of the types of pressure transducer can be used. Special forms of Bourdon tubes measure pressures down to 0.1mbar, and diaphragms can be designed to measure the pressure down to 0.001mbar. However a number of specialized instruments have also been developed to measure the vacuum pressures. For differential pressure measurement, diaphragm-type sensors are the preferred option, with double-bellows sensors being used occasionally. Manometers are also sometimes used to give the visual indication of differential pressure values especially in the liquid flow rate indicators.

5.3.2 Temperature sensors

Choice between the various types of temperature measuring instruments for a given situation depends mainly on the type of medium to be measured. A good contact is essential between the medium and the sensor transducer. If the medium is solid this choice is restricted to thermocouples, thermopiles, resistance thermometers, thermisters, semiconductor devices and color indicators. For the fluid temperatures can be measured by any of the instruments with the exception of radiation thermometers.

The most commonly used devices in the industry for the temperature measurement is the base-metal thermocouple. Typical inaccuracy is ±0.5% of the full scale over the temperature range -250°C to +1200°C.

Noble metal thermocouples are much more expensive, but are chemically inert and can measure temperature up to 2300°C with an accuracy of ±0.2% of full scale.

Resistance thermometers are also in common use within the temperature range -270°C to +650°C, with a measurement inaccuracy of ±0.5%. They have a smaller temperature range than thermocouples. Thermisters are other commonly used sensors. They are small and cheap. They give a fast outputs response to temperature changes with good measurement sensitivity, but their measurement range is quite limited. Dual diverse devices are new development that includes a thermocouple and a resistance thermometer inside the same sheath.

Semiconductor devices have better linearity than thermocouples and resistance thermometers and similar level of accuracy. Thus they are viable alternative to these in many applications. For non contact, non invasive mode of measurement radiation thermometers or optical pyrometers could be used. They are used to monitor temperature above 600°C in industrial furnaces etc. The instruments working on the thermal expansion principle, such as bimetallic thermometers, are used as temperature indicating devices as well as components within automatic control system.

5.3.3 Flow sensors

The number of relevant factors to be considered when specifying a flow meter for a particular application is very large. These include the temperature and pressure of the fluid, its density, viscosity, chemical properties and abrasiveness, whether it contains particle, whether it is liquid or gas, etc. This narrows the field to a subset of instruments that are physically capable of making the measurement. Next, the required performance factors of accuracy, range ability, acceptable pressure drop, output signal characteristics, reliability and service life must be considered. Accuracy requirements vary widely across different applications and range from ±0.5% to ±5%. Finally, the economic viability must be assessed and this must take account not only of purchase cost, but also of reliability, installation difficulties, maintenance requirements and service life.

Where only a visual indication of flow rate is needed, variable-area meter is popular. Where a flow measurement in the form of an electrical signal is required, the choice of available instrument is very large. It ranges from an orifice plate, various forms of differential pressures meter and electromagnetic flow meters. The currently trend in flow measurement is limiting the use of rotating devices such as turbine meters and positive displacement meters and at the same time increased use of ultrasonic and vortex meters.

5.4 Installation Requirements of Instruments

Every instruments manufacture provides a set of instrument manufacturer's instructions for installation of that equipment. It is mandatory to comply with such instructions. It is to be ensured that the instruments that are flow direction sensitive e.g. Control Valves, Regulators, Vortex meters, Magnetic Flow meters, Orifice Plates, Corrosion Coupons, Pitot Tubes, Venturi Tubes etc. are checked with marking on instruments before installation. Ensure that dummy holes on instruments supplied with temporary protection for transportation etc (e.g. extra taps on venture tube supplied with plastic plugs etc.) are blocked with properly rated valves, plugs or blinds

5.4.1 Pressure instruments

Pressure gauges should have a high quality block valve, followed by a bleed valve and then followed by the gauge. If the instrument is located at a significant distance from the process piping location, the pressure takeoffs installations should have a double block and bleed arrangement between the process piping and the instrument. The bleed valve shall be so located that it may act as the vent valve if the instrument impulse line must be flushed or filled with a sealing fluid like glycol or a purging fluid. The block valve immediately upstream of the instrument should be part of a manifold assembly to facilitate mounting the instrument. When a sealing fluid is required, a drain valve downstream of the instrument is needed to be installed to allow flushing the tubing or filling the tubing with the isolating fluid.

5.4.2 Temperature instruments

The sensor should be located at a place where it will have limited exposure to direct or reflected sunlight and open night sky. It should be placed at least 2 metres from man-made sources of heat because the heat from this surface may affect air temperature readings in the vicinity.

Keep the sensor away from AC power lines. Sensor and most of the cable should be at least 3m from 220 V A.C. 50 Hz power supply. Do not run the sensor cable parallel to house wiring. Mount the sensor at least 10 m from high-voltage power lines and transformers.

5.4.3 Flow instruments

The flow meter must be installed according to the manufactures written instructions. The meter must be installed in the correct direction to flow. It must be ensured that there are no air pockets in the section of the pipe and the pipe runs full of water or fluid. A meter approved for operation in full flowing pipes shall be installed so that it is completely filled with fluid under all conditions during operation. If it is likely that air will become entrapped near the meter, an air valve must be installed upstream of the meter.

Appropriate liquid filtering device must be installed on the intake side of the meter. Suitable backflow preventer must be installed on the discharge side of the meter. If the meter is of electro-magnetic type, it is essential that the meter is earthed correctly as per the manufacture’s specifications. Where the meter is to be fitted above ground to plastic, PVC or polythene pipelines, it must be suitably supported to ensure its stability. The meter must be mounted in such a way that it allows for both easy access and reading of display unit.

Lesson 6

STATIC CHARACTERISTICS OF MEASURING INSTRUMENTS - I

6.1 Introduction

When considering a measurement instrument, it is important to have a clear understanding of all the parameters involved in defining the characteristics of the measurement device. By knowing the accuracy and resolution requirements for your application, you can compute the total error in the measurement device you are considering and verify that it satisfies your needs. There are number of important performance parameters discussed in the following text, but they should not be considered the ultimate or only parameters to take into account. It is worthwhile to ask the instruments supplier to clarify the meaning of the specifications in the instrument data sheet. Not knowing the true performance of your instrument could lead you to incorrect readings, and the cost of this error could be very high.

The performance characteristics of instruments and measurement systems can be divided into two distinct categories, viz., the Static characteristics, and the Dynamic characteristics. Some applications involve the measurement of quantities that are either constant or vary very slowly with time. Under these circumstances, it is possible to define a set of criteria that gives a meaningful description of quality of measurement without interfering with dynamic descriptions that involve the use of differential equations. The characteristics in this set of criteria are called *Static Characteristics.* Thus the static characteristics of a measurement system are those which must be considered when the system or instrument is used under a condition not varying with time.

However, many measurements are concerned with rapidly varying quantities. In such cases we must examine the dynamic relations which exist between the output and the input. This is normally done with the help of differential equations or other methods. Performance criteria based upon dynamic relations constitute the *Dynamic Characteristics*.

6.2 Static Calibration

All the static performance characteristics are obtained in one form or another by a process called static calibration. The calibration procedures involve a comparison of the particular characteristic with either a primary standard, a secondary standard with a higher accuracy than the instrument to be calibrated, or an instrument of known accuracy. It checks the instrument against a known standard and subsequently to errors in accuracy. Actually all measuring instruments must be calibrated against some reference instruments which have a higher accuracy. Thus reference instruments in turn must be calibrated against instrument of still higher grade of accuracy, or against primary standard, or against other standards of known accuracy. It is essential that any measurement made must ultimately be traceable to the relevant primary standards.

6.3 Static Characteristics

The main static characteristics include:

(i) Accuracy, (ii) Sensitivity, (iii) Reproducibility,
(iv) Drift, (v) Static error, and (vi) Dead zone

The qualities (i), (ii) and (iii) are desirable, while qualities (iv), (v) and (vi) are undesirable. The above characteristics have been defined in several different ways and the generally accepted definitions are presented here. Some more quantities have to be defined here which are essential in understanding the above characteristics.

6.3.1 Scale range and scale span

In an analogue indicating instrument, the measured value of a variable is indicated on a scale by a pointer. The choice of proper range of instruments is important in measurement. The region between the limits with in which an instrument is designed to operate for measuring, indicating or recording a physical quantity is called the range of the instruments. The *Scale Range* of an instrument is thus defined as the difference between the largest and the smallest reading of the instrument. Supposing the highest point of calibration is X_{max} units while the lowest is X_{min} units and the calibration is continuous between the two points, then the instrument range is between X_{min} and X_{max} . Many times it is also said that the instrument range is X_{max}. The instrument span is the difference between highest and the lowest point of calibtaration. Thus

$$\text{Span} = X_{max} - X_{min}$$

For example for a thermometer calibrated between 100°C to 400°C, the range is 100°C to 400°C (or 400°C) but the span is 400 – 100 = 300°C.

The same is true of digital instruments. There is another factor that must be considered while determining the range of the instrument. This is the *Frequency Range,* which is defined as frequencies over which measurements can be performed with a specified degree of accuracy. For example a moving iron instrument may have a 0-250 V range and 0-135 Hz frequency range.

6.3.2 True value

The true value of variable quantity being measured may be defined as the average of an infinite number of measured values when the average deviation due to the various contributing factors tends to zero. Such an ideal situation is impossible to realize the practice and hence it is not possible to determine the true value of a quantity by experimental means. The reason for this is that there are several factors such as lags, loading effects, wear or noise pick-up etc. Normally an experimenter would never know that the value or quantity being measured by experimental means is the 'true value' of the quantity or not.

6.3.3 Accuracy

Accuracy is the closeness with which an instrument reading approaches the true value of the quantity being measured. Thus accuracy of a measurement means conformity to truth. The accuracy of an instrument may be expressed in many ways. The accuracy may be expressed as point accuracy, percent of true value or percent of scale range. Point accuracy is stated for one or more points in the range, for example, the scale of length may be read with in ± 0.2 mm. Another common way is to specify that the instrument is 'accurate to within ±x percent of instrument span' at all points on the scale. Another way of expressing accuracy is based upon instrument range.

Accuracy is many a time confused with Precision. There is difference in these two terms. The term 'Precise' means clearly or sharply defined. For example an ammeter will possesses high degree of precision by virtue of its clearly legible, finely divided, distinct scale and a knife edge pointer with mirror arrangements to remove parallax. As an example of the difference in meaning of the two terms, suppose above ammeter can read up to 1/100 of an ampere. Now if its zero adjustment is wrong, every time we take a reading, the readings taken with this ammeter are not accurate, since they do not confirm to truth on account of its faulty zero adjustment. Though the ammeter is as precise as ever and readings are consistent and clearly defined and can be down to 1/100 of an ampere. The instrument can be calibrated remove the zero error. Thus the accuracy of the instrument can be improved upon by calibration but not the precision.

6.3.4 Static error

Measurements done with an instrument always involve errors. No measurement is free from errors. If the precision of the equipment is adequate, no matter what its accuracy is, a discrepancy will always be observed between two measured results. Since the accuracy of an instrument is measured in terms of its error, an understanding and evaluation of the errors is thus essential.

Static error is defined as the difference between the best measured value and the true value of the quantity. Then:

$$E_s = A_m - A_t$$

Where, E_s = error,

A_m = measured value of quantity, and

A_t = true value of quantity.

E_s is also called the absolute static error of quantity A. The absolute value of error does not indicate precisely the accuracy of measurement. For example, an error of ±2 A is negligible when the current being-measured is of the order of 1000 A while the same error highly significant if the current under measurement is 10 A. Thus another term relative static error is introduced. The *relative static error* is the ratio of absolute static error to the true value of the quantity under measurement. Thus the relative static error E_r is given by:

$$E_r = \frac{E_s}{A_t}$$

Percentage static error % $E_r = E_r$ x 100

Static Correction

It is the difference between the true value and the measured value of the quantity, or

$$\delta C = A_t - A_m$$

6.4 Numericals

1. A meter reads 115.50 V and the true value of the voltage is 115.44 V. Determine the static error, and the static correction for this instrument.

Solution:

The error is: $E_s = A_m - A_t = 115.50 - 115.44 = +0.06$ V

Static correction $\delta C = A_t - A_m = -0.06$ V.

2. A thermometer reads 71.5 °C and the static correction given is +0.5°C. Determine the true value of the temperature.

Solution:

True value of the temperature

$A_t = A_m + \delta C = 71.5 + 0.5 = 72.0°C$.

3. A thermometer is calibrated for the range of 100°C to 150°C. The accuracy is specified within ±0.25 percent. What is the maximum static error?

Solution:

Span of thermometer = 150 – 100 = 50°C

$\therefore$ Maximum static error = $\frac{\pm 0.25\ x\ 50}{100} = \pm 0.125^{\circ}C$

4. An analogue indicating instrument with a scale range of 0 – 2.50 V shows a voltage of 1.46 V. A voltage has a true value of 1.50 V. What are the values of absolute error and correction? Express the error as a fraction of the true value and the full scale deflection.

Solution:

Absolute error $= A_m - A_t$

$= 1.46 - 1.50 = -0.04$ V

Absolute correction $\delta C = \delta A = +0.04$ V

Relative error $\varepsilon_r = \frac{-0.04}{1.50} x100 = -2.66\%$

Relative error expressed as a percentage of full scale division

$= \frac{-0.04}{2.5} x100 = -1.60\%$

5. A pressure indicator showed a reading as 22 bar on a scale range of 0-25 bar. If the true value was 21.4 bar, determine:

i) Static error
ii) Static correction
iii) Relative static error

Solution:

i) Static error = 22 – 21.4 = + 0.6 bar
ii) Static correction = - (+0.6) = - 0.6 bar
iii) Relative error = 0.6 / 21.4 = 0.028 or 2.8 %

Lesson 7

STATIC CHARACTERISTICS OF MEASURING INSTRUMENTS - II

7.1 Scale Readability

This indicates the closeness to with which the scale of an analog type of instrument can be read. The readability of an instrument depends upon following factors:

i) Number of graduations
ii) Spacing between the graduations
iii) Size of the pointer
iv) Discriminating power of the observer

The readability is actually the number of significant figures in the instrument scale. The higher the number of significant figures, the better would be the readability.

7.2 Repeatability and Reproducibility

Repeatability is the degree of closeness with which a given value may be repeatedly measured. It is the closeness of output readings when the same input is applied repetitively over a short period of time. The measurement is made on the same instrument, at the same location, by the same observer and under the same measurement conditions. It may be specified in terms of units for a given period of time. Reproducibility relates to the closeness of output readings for the same input when there are changes in the method of measurement, observer, measuring instrument location, conditions of use and time of measurement. Perfect reproducibility means that the instrument has no drift. Drift means that with a given input the measured values vary with time.

Reproducibility and Repeatability are a measure of closeness with which a given input may be measured over and over again. The two terms cause confusion. Therefore, a distinction is made between the two terms. Reproducibility is specified in terms of scale readings over a given period of time. On the other hand, Repeatability is defined as the variation of scale reading and is random in nature.

7.3 Drift

Drift is a departure in the output of the instrument over the period of time. An instrument is said to have no drift if it produces same reading at different times for the same variation in the measured variable. Drift is unrelated to the operating conditions or load. The following factors could contribute towards the drift in the instruments:

i) Wear and tear
ii) Mechanical vibrations
iii) Stresses developed in the parts of the instrument
iv) Temperature variations
v) Stray electric and magnetic fields
vi) Thermal emf

Drift can occur in the flow meters due to wear of nozzle or venturi. It may occur in the resistance thermometer due to metal contamination etc.

Drift may be of any of the following types;

a) Zero drift: Drift is called zero drift if the whole of instrument calibration shifts over by the same amount. It may be due to shifting of pointer or permanent set.

b) Span drift: If the calibration from zero upwards changes proportionately it is called span drift. It may be due to the change in spring gradient.

c) Zonal drift: When the drift occurs only over a portion of the span of the instrument it is called zonal drift.

Drift is an undesirable quality in industrial instruments because it is rarely apparent and cannot be easily compensated for. Thus, it must be carefully guarded against by continuous fields can be prevented from affecting the measurements for proper shielding. Effect of mechanical vibrations can be minimized by having proper mountings. Temperature changes during the measurement process should be preferably avoided or otherwise be properly compensated for.

7.4 Static Sensitivity

The static sensitivity of an instrument or an instrumentation system is the ratio of the magnitude of the output signal or response to the magnitude of input signal of the quantity bring measured. Its units depend upon the type of input and output. If the output is in mm and the input is in micro ampere then the units would be mm per micro-ampere.

Sometimes the static sensitivity is also expressed as the ratio of the magnitude of the measured quantity to the magnitude of the response. Thus the sensitivity expressed this way has the units of micro-ampere per mm. It is reciprocal of the sensitivity as defined above. This ratio is defined as the inverse sensitivity or defection factor. Many manufacturers define the sensitivity of their instruments in terms of inverse sensitivity and still call it sensitivity.

The sensitivity is expressed as the slope of the calibration curve if the ordinates are expressed in actual units. When a calibration curve is linear the slope of the calibration curve is constant. For this case the sensitivity is constant over the entire range of the instrument. However, if the curve is not a straight line, the sensitivity varies with the input.

In general, the static sensitivity at the operating point is defined as:

$$Static\ sensitivity = \frac{infinitesimalchange\ in\ output}{nfinitesimalchange\ in\ input} = \frac{\Delta q_o}{\Delta q_i}$$

Similarly,

$$Inverse\ sensitivity\ or\ defection\ factor = \frac{\Delta q_i}{\Delta q_o}$$

The sensitivity of an instrument should be high and therefore the instrument should not have a range greatly exceeding the value to be measured. However, some margin should be kept for any accidental overloads.

7.5 Numericals

1. A pressure gauge which has a linear calibration curve has a radius of scale line as 120 mm and pressure of 0 to 50 Pascal is displayed over an arc of 300^{o}. Determine the sensitivity of the gauge as a ratio of scale length to pressure.

Solution:

$$300^{o} = 300 \times \frac{\pi}{180} = \frac{5\pi}{3}$$

$$Full\ scale\ deflection = \frac{5\pi}{3}\ rad.$$

$$Length\ of\ scale = \frac{5\pi}{3} \times 120 = 200\pi\ mm$$

$$Sensitivity = \frac{200\pi}{50} = 4\pi\ mm/Pa$$

2. A Wheatstone bridge requires a change of 7.000 Ω is the unknown arm of the bridge to produce a change in deflection of 3.000 mm of the galvanometer. Determine the sensitivity. Also determine the deflection factor.

Solution:

$$Sensitivity = \frac{magnitude\ of\ output\ response}{magnitude\ of\ output} = \frac{3.000\ mm}{7.000\ \Omega} = 0.429 mm/\Omega$$

It may be noted that

i) A sensitive instrument can quickly detect a small change in measurement.

ii) Measuring instruments that have smaller scale parts are more sensitive.

iii) Sensitive instruments need not necessarily be accurate.

7.6 Linearity

When the input-output points of the instrument are plotted on the calibration curve and resulting curve may not be linear. This would be only if the output is proportional to input. Linearity is the measure of maximum deviation of these points from the straight line (Fig. 7.1). The departure from the straight line relationship is non-linearity, but it is expressed as linearity of the instrument. This departure from the straight line could be due to non-linear elements in the measuring system or the elastic after effects of the mechanical system.

Linearity is expressed in many different ways:

i) Independent Linearity: It is the maximum deviation from the straight line so placed as to minimize the maximum deviation (Fig. 7.1).

ii) Zero based linearity: It is the maximum deviation from the straight line joining the origin and so placed as to minimize the maximum deviation.

iii) Terminal based linearity: It is the maximum deviation from the straight line joining both the end points of the curve.

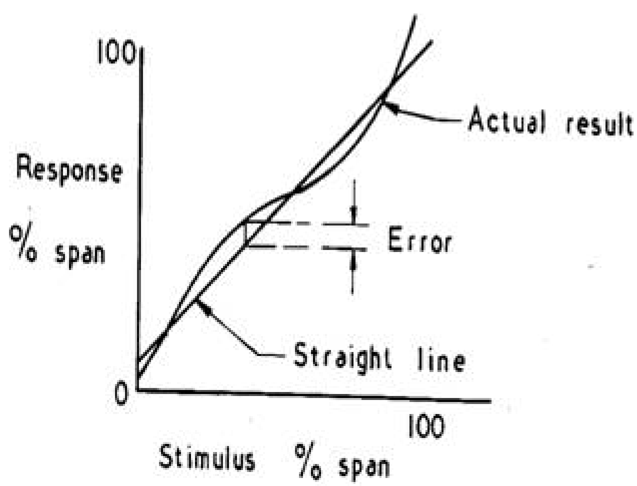


Fig. 7.1 Independent linearity

Linearity of out-input relation is considered to be one of the best characteristics of the measurement system, because of the convenience of scale reading. The non linear relation does not lead to any inaccuracy, but it is better to keep the linearity as small as possible, by choosing the operating range instrument in such a way that the input-output relation is linear. Lack of linearity thus does not necessarily degrade sensor performance. If the nonlinearity can be modelled and an appropriate correction applied to the measurement before it is used for monitoring and control, the effect of the non-linearity can be eliminated.

7.7 Dead Band and Dead Time

Dead band, sometimes called a neutral zone, is an area of a signal range or band where no action occurs, that is, the system is dead e.g. 10 g weight on a 10 kg balance. It is the largest change in the physical variable to which the measuring instrument does not respond. In other words it is defined as the range of input values over which there is no change in output value. It has also been referred to as Dead space or Dead zone. In the analog instruments, it may occur due to friction in the instrument which does not allow pointer to move till sufficient force is developed to overcome the frictional loss. It is shown in the figure 7.2.

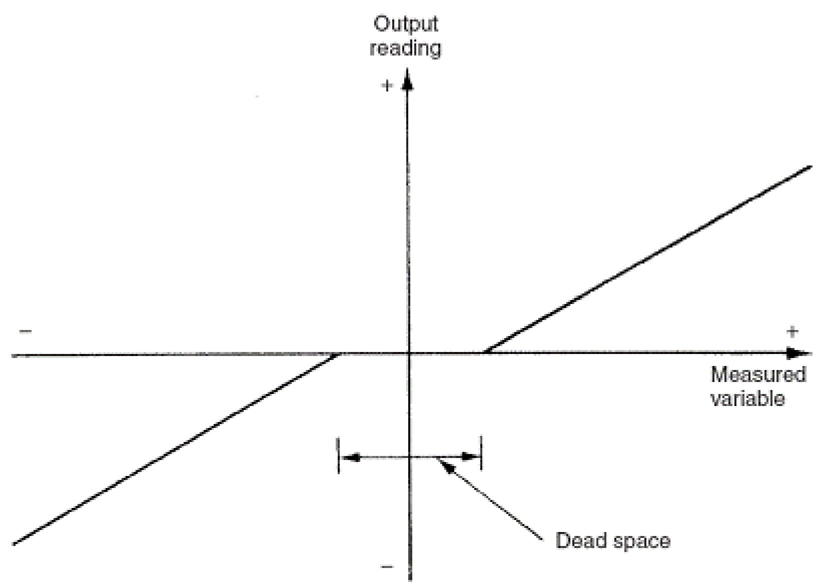


Fig. 7.2 Dead band or dead space of measuring instruments

Dead zone is specified by indicating it as the percent of span range. For example, if the calibration range of a thermometer is 100 to 300°C and the dead zone is specified as 0.1% of the span, then the change in temperature that must occur before it is detected by the instrument would be:

$$(300 - 100) \times 0.1 / 100 = 0.2°C$$

Dead band is different from hysteresis. Dead band is purposefully used in voltage regulators and other controllers to prevent oscillation or repeated activation-deactivation cycles.

Dead time is the time required by measuring instrument to begin to respond to a change in the measured variable. It represents the time before the instrument begins to respond after the measured variable has changed. The units of dead zone are the units of the variable, whereas, the units of the Dead time are the units of time.

Lesson 8

STATIC CHARACTERISTICS OF MEASURING INSTRUMENTS - III

8.1 Hysteresis

Hysteresis is a phenomenon under which the measuring instrument shows different output effects during loading and unloading. Hysteresis results from the inelastic quality of an element or device. It is the maximum difference between corresponding upscale and downscale outputs for any single test cycle, that is, the maximum difference in output at any given value of the measured variable within the specified range when approaching that point first with increasing the input and then decreasing the input. Figure 8.1 illustrates the hysteresis phenomenon.

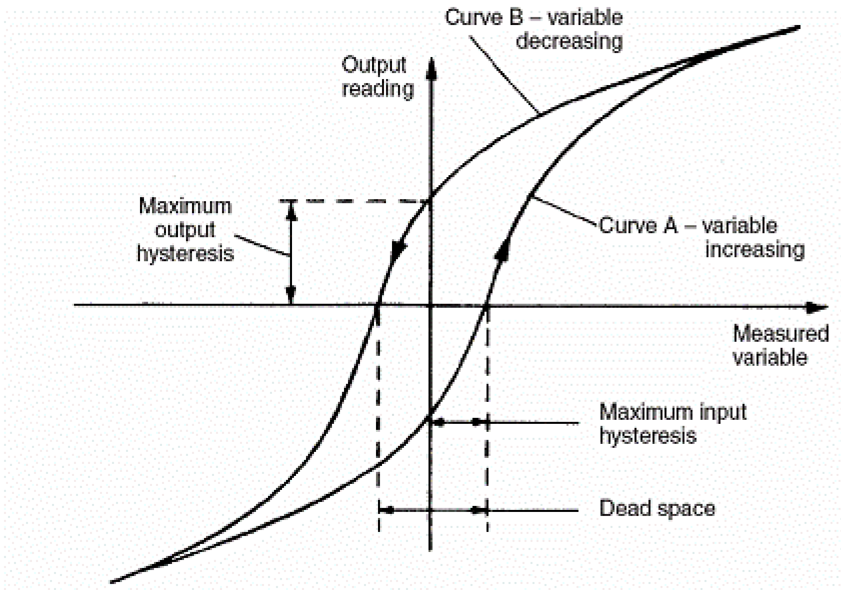


Fig. 8.1 Input and output hysteresis

The numerical value of hysteresis is specified in terms of output or input values. The sum of the two effects of dead band and the hysteresis is determined directly from the deviation values of a number of test cycles. Hysteresis is determined by subtracting the value of dead band from the corresponding value of hysteresis plus dead band for a given input. The maximum difference in the readings is reported as hysteresis. The difference may be expressed as a percent of ideal output span. For example, the hysteresis is reported as 0.2% of output span. Hysteresis results due to the presence of several factors, such as, mechanical friction, motion in bearings, magnetic and thermal effects. This could also be due to a free play or looseness in the mechanisms.

8.2 Threshold and Resolution

8.2.1 Threshold

Threshold of a measuring instrument is the minimum value of input signal that is required to make a change or start from zero. This is the minimum value below which no output change can be detected when the input is gradually increased from zero. In digital system, the out put is displayed in incremental digits. Thus, in digital instruments the threshold is the minimum input signal which is necessary to produce at least one significant digit of output to indicate on the display.

8.2.2 Resolution

When an instrument is showing a particular output reading, there is a lower limit on the magnitude of the change in the input measured quantity that produces an observable change in the instrument output. That means, when the input is slowly increased from some arbitrary input value, which is non-zero, the output does not change at all until certain increment is exceeded. This increment is called resolution or discrimination of the instrument. Thus, the resolution refers to the smallest change of input for which there will be a change output.

In the analog instruments, the resolution is also determined by the observer's ability to judge the position of pointer on the scale. One of the major factors influencing the resolution of an instrument is how finely its output scale is divided into subdivisions. Using a car speedometer as an example again, this has subdivisions of typically 20 km/h. This means that when the needle is between the scale markings, we cannot estimate speed more accurately than to the nearest 5 km/h.

The difference between threshold and the resolution of the measuring instrument could be understood this way. *Threshold* defines the smallest measureable input, while the *resolution* defines the smallest measureable input change. Both of these values may be expressed in terms of an actual value or as a fraction / percentage of the full scale value.

8.2.2.1 Numericals

1. Determine the resolution of a voltmeter which has a range readout scale with 100 divisions and a full-scale reading of 100 V. If one tenth of a scale division can be read certainty, determine the resolution of the voltmeter.

Solution:

100 scale division = 100V
One scale division = 100 /100 = 1V
Resolution = 1 x 1/10
= 0.1 V

2. A transducer measures a range of 0-200 N force with a resolution of 0.20 percent of full scale. What is the smallest change in the force which can be measured by this transducer?

Solution:

Range of force = 0-200 N
Resolution = 0.20 % of full scale
Smallest change in force which can be measured = 200 x 0.20 / 100
= 0.4 N

8.3 Noise

Noise is a random fluctuation in an electrical signal, a characteristic of all electronic circuits. Noise generated by electronic devices varies greatly, as it can be produced by several different effects. In general noise is an error or undesired random disturbance of a useful information signal, introduced before or after the detector and decoder. The noise is a summation of unwanted or disturbing energy from natural and sometimes man-made sources. The quality of a signal is often expressed quantitatively as the *signal-to-noise ratio*.

Noise may be defined as any signal that does not convey any useful information. Extraneous disturbances generated in the measuring system itself or coming from outside, frequently constitute a background against which a signal may be read.

There are many sources of noise. Noise may originate at the primary sensing device, in a communication channel or other intermediate links. The noise may also be produced by indicating elements of the system.

The common sources of noise are given below:

i). Stray electrical and magnetic fields present in the neighbourhood of the instruments produce extraneous signals which tend to distort the original signal. The effects of these stray fields can be minimized by adequate shielding or relocation of the components of the instruments.

ii). Mechanical shocks and vibrations are another source of trouble. Their effect can be eliminated by proper mounting devices.

8.4 Loading Effect

An ideal measuring instrument should not change or distort the original signal. The sensing element should not draw the process or current from the circuit, thereby resulting in the true measurement of parameters being measured. Unfortunately, in the real world, all instruments draw current and invariably draw energy from the system. This is referred to as the 'loading effect'. This causes parameters being measured to change in value.

The loading effects may occur due to both electrical and mechanical elements. The loading effects of an Instrument are the alternations that are caused in the circuit conditions such as voltage, current etc. when the instrument is introduced in the circuit for the purpose of measurement. In simple terms, loading effects of an instrument ends up distorting the signal they are supposed to measure in the form of attenuation or phase shift. The instrument therefore reads the altered value of the quantity and thus an erroneous measurement is resulted. These loading effects can be better explained by the following examples.

Let a voltage has to be measured across a resistance R in the circuit. For this purpose, a voltmeter V is connected across the resistor R in parallel. We know that a voltmeter has a very high resistance value. But since this value is finite, a fraction of the total current passing through R will pass through the Voltmeter V. This will lead to power dissipation in the Voltmeter. The voltmeter extracts this power out of the circuit and thus end up varying the values of the circuit parameters on being introduced. Another example of loading effects is found in the measurement of current by an Ammeter. An ammeter is a very low resistance device that is connected in series in a circuit for the measurement of current. When current passes through it, because of the low finite resistance of the ammeter, there is a small voltage drop across the ammeter which results in power dissipation. This power is again borrowed from the circuit and therefore affects the circuit parameters.

So to minimize this 'loading effect', the best you can do is to use a measuring instrument that has very high impedance so that the current it draws is minimal.

But practically an infinite or zero impedance in an instrument is not possible. So a condition of minimum loading effects is tried to be reached by making the values of the impedances of instruments very high or very low according to their use. That is why Voltmeters always have very high while Ammeters always have very low impedance values.

Lesson 9

DYNAMIC CHARACTERISTICS OF MEASURING INSTRUMENTS

9.1 Dynamic Response

When an input is applied to an instrument or a measurement system, the instrument or the system cannot take up immediately its final steady state position. It goes through a transient state before it finally settles to its final 'steady state' position. Some of the measurements are made under such conditions as to allow the sufficient time for the instrument or the measurement system to settle to its final steady state conditions. Under such conditions the study of behaviour of the system under transient state, known as 'transient response' is not of much of importance. However, in many areas of measurement systems applications it becomes necessary to study the response of the system under both transient as well as steady state conditions. In many applications, the transient response of the system, i.e., the way system settles down to its final steady state conditions is more important than the steady state response.

The transient response in the instruments is on account of the presence of energy storage elements in the system, such as, electrical inductance and capacitance, mass, fluid and thermal capacitances etc. The systems exhibit a characteristic of sluggishness on account of presence of these elements. However many a times in several applications the measurement systems are subjected to inputs which are not static but dynamic in nature, which means the inputs vary with time. Since the input varies from instant to instant, so does the output. The behaviour of the system under such conditions is described by the dynamic response of the system and the characteristics of the measuring system under such conditions are known as dynamic characteristics.

Dynamic characteristics of a measuring instrument refer to the case where the measured variable changes rapidly. As has been discussed earlier the sensors in control system cannot react to a sudden change in measured variable immediately. A certain amount of time is required before the measuring instrument in control system technology can indicate any output based on the input received by the measuring instrument. The amount of time depends on resistance, capacitance, mass and dead time of the measuring instrument. Step response, ramp response, frequency response of the measuring instrument determines the dynamic characteristics of the measuring instrument in control system technology.

The dynamic characteristics of any measurement system are:

(i) Speed of response and Response time

(ii) Lag

(iii) Fidelity

(iv) Dynamic error

Out of the above four characteristics the Speed of Response and the Fidelity are desirable in a dynamic system, while Lag and Dynamic error are undesirable.

9.2 Speed of Response and Response Time

Speed of Response is defined as the rapidity with which an instrument or measurement system responds to changes in measured quantity.

Response Time is the time required by instrument or system to settle to its final steady position after the application of the input. For a step input function, the response time may be defined as the time taken by the instrument to settle to a specified percentage of the quantity being measured, after the application of the input. This percentage may be 90 to 99 percent depending upon the instrument. For portable instruments it is the time taken by the pointer to come to rest within ±0.3 percent of final scale length and for switch board (panel) type of instruments it is the time taken by the pointer to come to rest within ±1 percent of its final scale length.

9.3 Measuring Lag

As discussed earlier, an instrument does not react to a change in input immediately. The delay in the response of an instrument to a change in the measured quantity is known as *measuring lag*. Thus it is the retardation delay in the response of a measurement system to changes in the measured quantity. This lag is usually quite small, but this small lag becomes highly important when high speed measurements are required. In the high speed measurement systems, as in dynamic measurements, it becomes essential that the time lag be reduced to minimum.

Measuring lag is of two types

i) **Retardation type:** In this type of measuring lag the response begins immediately after a change in measured quantity has occurred.

ii) **Time delay:** In this type of measuring lag the response of the measurement system begins after a dead zone after the application of the input.

9.4 Fidelity

Fidelity of a system is defined as the ability of the system to reproduce the output in the same form as the input. It is the degree to which a measurement system indicates changes in the measured quantity without any dynamic error. Supposing if a linearly varying quantity is applied to a system and if the output is also a linearly varying quantity the system is said to have 100 percent fidelity. Ideally a system should have 100 percent fidelity and the output should appear in the same form as that of input and there is no distortion produced in the signal by the system. In the definition of fidelity any time lag or phase difference between output and input is not included.

9.5 Dynamic Error

The dynamic error is the difference between the true value of the quantity changing with time and the value indicated by the instrument if no static error is assumed.

However, the total dynamic error of the instrument is the combination of its fidelity and the time lag or phase difference between input and output of the system.

9.6 Overshoot

Moving parts of instruments have mass and thus possess inertia. When an input is applied to instruments, the pointer does not immediately come to rest at its steady state (or final deflected) position but goes beyond it or in other words ‘overshoots’ its steady position.

The overshoot is evaluated as the maximum amount by which moving system moves beyond the steady state position. In many instruments, especially galvanometers it is desirable to have a little overshoot but an excessive overshoot is undesirable.

9.6.1 Overshoot response graph

A typical overshoot response graph can be shown as the response time stated in terms of rise time, peak percentage overshoot and settling time. Such an under damped graph in control system technology of a measuring instrument is shown in Fig. 9.1.

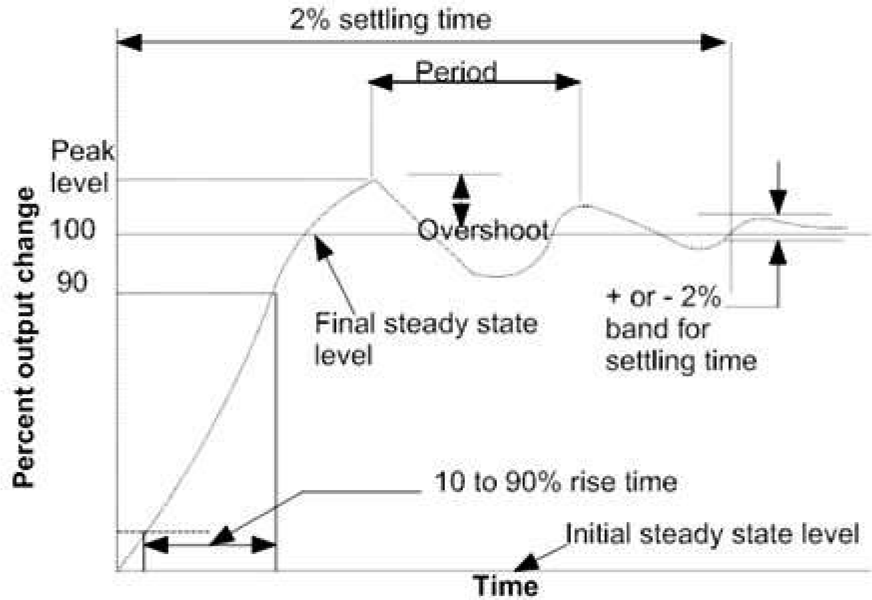


Fig. 9.1 Overshoot response graph

9.6.2 Numerical

1. A step input of 5 A is applied to an ammeter. The pointer swings to a voltage of 5.18 A and finally comes to rest at 5.02 A. (a) Determine the overshoot of the reading in ampere and in percentage of final reading. (b) Determine the percentage error in the instrument.

Solution:

(a) Overshoot = 5.18 – 5.02 = 0.16 A

(b) $\text{Percentage overshoot} = \frac{0.16}{5.02} x100 = 3.2\%$

(b) $\text{Percentage error} = \frac{5.02-5.0}{5.0} x100 = 0.4\%$

9.7 Standard Signals

The measurement systems may be subjected to any type of input. Since in majority of the applications the signals are random in nature and the type of input signals cannot be known ahead of time, it becomes difficult to express the actual input signals mathematically by simple equations. To study the dynamic behaviour of measurement systems, certain standard signals are employed for which the mathematical equations have been developed. These standard signals are:

(i) Step input, (ii) Ramp input, (iii) Parabolic input, and (iv) Impulse input.

The above signals are used for studying dynamic behaviour in the time domain and the dynamic behaviour of the system to any kind of inputs can be predicted by studying its response to one of the standard signals. The standard input chosen for this purpose is a step input.

9.8 Step Response

When the measured variable of a measuring instrument in control system technology encounters changes from one steady state value to a second steady state value it is a step signal and the response shown by the output of a measuring instrument is called the step response. For example, when you change the temperature of the probe of a measuring instrument by shifting it from ice water to boiling water, a sudden temperature change could be observed in the output of the measuring instrument. The step response of such a measuring instrument is stated in terms of response time and rise time for over damped or critically damped situation. Where as for under damped situation the terms used for the measuring instrument are rise time, peak percentage overshoot and setting time. Typical step response curve for an over damped or critically damped measuring instrument is shown in Fig 9.2.

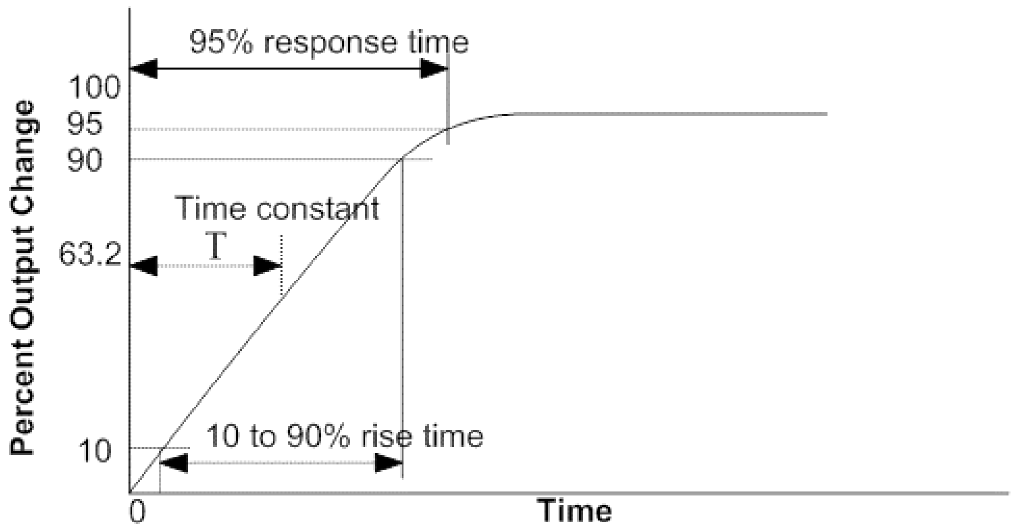


Fig. 9.2 Typical step response curve

Response time is the time required for output to reach a designated percentage of the total change in a measuring instrument. The 95% response time shown in typical step response graph is the time required for output to reach 95% of the total change. 63.2% response time in control system technology of the typical step response graph shown above is the time constant.

9.8 Ramp Response

In the ramp signal the value of signal changes slowly with time. The typical ramp response curve of a temperature measuring instrument is shown in the figure 9.3 below. The measured temperature lagged behind the input temperature, then caught up the input after a certain period of time. This figure allows us to view two response curves, the dynamic error and dynamic lag.

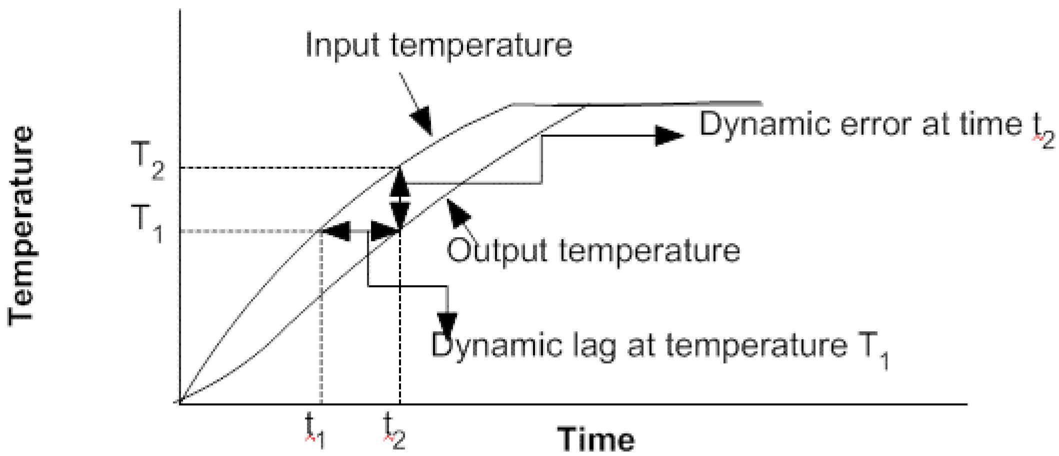


Fig. 9.3 Typical ramp response curve

Dynamic lag of a measuring instrument is the amount of time that passes between the time the input reaches a certain temperature and the output that follows input reaches also at the same temperature. A horizontal line at T_1 on the dynamic response graph intersects with input curve at time t_1 and the output curve at time t_2. The difference between these two times is defined as the dynamic lag at temperature T_1.

Dynamic error of a measuring instrument is the difference between input temperature and output temperature at a given time. It is the vertical line at a time t_2 on the ramp response graph that intersects the output curve at temperature T_1 and the input curve at temperature T_2. The difference between these two temperatures is the dynamic error at time t_2.

Lesson 10

ESSENTIALS OF INDICATING INSTRUMENTS

10.1 Introduction

The main purpose of any measuring system is to provide information concerning the physical variable being measured. The last stage of a measuring system is the data presentation stage,. The results of the measurement are displayed for the instant by a display device or for storage for observation at a later stage by a recorder. The data presentation devices are also known as output devices. The choice between the display devices and the recorders depend upon the information content of the output and the expected use of the output. In this section we will discuss certain features which are common to all electrical measuring instruments.

10.2 Electrical Indicating Instruments

The electrical instruments are widely used for measurement of current, voltage, resistance and power. These instruments are classified as Analog and Digital type of instruments. These principles of operation of such instruments have already been discussed in Lesson 4. The output of measuring instruments could be categorized

i) Single number output devices
ii) Time domain output devices.

The single number output devices indicate the value of the variable quantity when such values are not to be taken as a function of time, thus a single number will represent the measurement. Indicating instruments and digital display units belong to this category. A good display is one which permits the best combination of speed, sensitivity and accuracy when transferring the necessary information from the instrument to the operator. When the values of the quantity are to be taken as a function of time, the indicating instruments or digital display units do not serve this purpose. For keeping the permanent record of the variation of output with time, direct writing recorders, strip chart recorders, magnetic recorders etc. are used.

10.3 Pointer-Scale Indicating Instruments

As discussed above the analog instruments indicate the value of the measured parameter by positioning an indicator pointer on a calibrated scale. For this purpose several following arrangements can be made and the option can be exercised depending upon the requirement, feasibility and the convenience.

10.3.1 Single point indicators

This involves fixed scale and the movable pointer indicator. There are several such arrangements are available, such as, circular scale, circular scale with part circle, straight horizontal or vertical scale, arc or segmental scale etc. There could also be fixed pointer and movable scale indicators. The readability of graduated dials is influenced by shape and length of pointer, number, spacing and thickness of scale markings and size & design of numerals.

10.3.2 Multi point indicators

This type of indicators have more than one number of pointers and above each point the identification number of the medium being measured is marked. Generally this arrangement is followed in recorders.

10.3.3 Multi range indicators

Such instruments have different scales for different ranges. The choice of a particular scale is made by selector switch e.g. electrical multimeter.

10.4 Essentials of Indicating Instruments

Indicating instruments consist essentially of a pointer which moves over a calibrated scale and which is attached to a moving system pivoted in jewelled bearings. We will first consider various torques acting on its moving system. In an indicating instrument, it is essential that the moving system is acted upon by three distinct torque (or forces) for satisfactory working. The moving system is subjected to the following 3 torques:

1) Deflecting torque or operating torque
2) Controlling torque or restoring torque
3) Damping torque

10.4.1 Deflecting torque

The deflecting or operating torque (Td) is produced by utilizing one or other effects, e.g., magnetic, electrostatic, electrodynamic, thermal or inductive. The actual method of torque production depends on the type of instrument. The deflecting torque causes the moving system (and hence the pointer attached to it) to move from its zero position.

10.4.2 Controlling torque (Tc)

It is the torque which controls the movement of the pointer on a particular scale according to the quantity of the electricity, passing through it. The controlling forces are required to control the deflection or rotation and bring the pointer to zero position when there is no force, or stop the rotation of the disc when there is no power. Without such a torque, the pointer would swing over to the maximum deflected position irrespective of the magnitude of current or voltage being measured. In indicating instruments, the controlling torque, also called restoring or balancing torque, is obtained by two methods which are discussed below:

i) Spring Control

In the spring control method, a hair spring usually of phosphor bronze, attached to the moving system is used. With the deflection of the pointer, the spring is twisted in the opposite direction. This twist in the spring produces restoring torque which is directly proportional to the angle of deflection of the moving system. The pointer comes to a position of rest (or equilibrium) when the deflecting torque (Td) and the controlling torque (Tc) are equal. For example in permanent magnet moving coil type of instruments, the deflection torque is proportional to the current passing through them.

$$Td \propto I$$

And for spring control $Tc \propto \theta$

As $Tc = Td$

$$\theta \propto I$$

Since deflection θ is directly proportional to current I, the spring-controlled instrument have a uniform or equally-spaced scales over the whole of their range.

ii) Gravity Control

Gravity control is obtained by attaching a small adjustable weight to some part of the moving system such that the two exert torques in the opposite directions.

As shown in the figure, the controlling or restoring torque is proportional to the sine of the angle of deflection, i.e., Tc α Sin θ.

The degree of control is adjusted by screwing the weight up or down the carrying system.

$$\text{If } Td \; \alpha \; I$$

Then for position of rest

$$Td = Tc$$

$$\text{Or } I \; \alpha \; \text{Sin } \theta$$

Hence in gravity control instruments, the scales are not uniform but are cramped or crowded at their lower ends.

10.4.3 Damping torque

Damping torque is one which acts on the moving system of the instrument only when it is moving and always opposes its motion. Such damping force is necessary to bring the pointer to rest quickly, otherwise due to inertia of the moving system, the pointer will oscillate about its final deflected position for quite some time before coming to rest in the steady position. The degree of damping should be adjusted to a value which is sufficient to enable the pointer to rise quickly to its deflected position without over-shooting.

The damping force can be produced by i) air friction, ii) eddy currents, and iii) fluid friction. The method of air-friction damping is shown in the figure 10.1

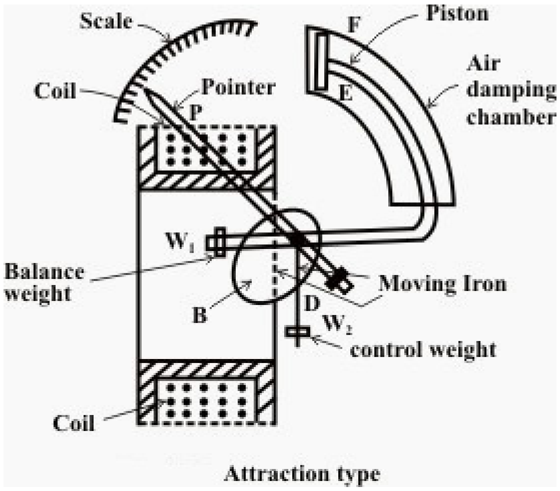


Fig. 10.1 Air-friction damping

The light aluminium piston attached to the moving system of the instrument is arranged to travel with a very small clearance in a fixed chamber closed at one end. The cross-section of the chamber is either circular or rectangular. Damping of the system is affected by the compression and suction actions of the piston on the air enclosed in the chamber. In another method, light aluminium vane is mounted on the spindle of the moving system which moves in air or in a closed sector-shaped box. Fluid-friction is similar is action to the air-friction. Due to greater viscosity of the oil, the damping is more effective. However, oil damping is not much used because of several disadvantages such as objectionable creeping of oil, the necessity of using the instrument always in vertical position and its obvious unsuitability for use in portable instruments.

Eddy current damping is the most efficient type of damping and shown in figure 10.2

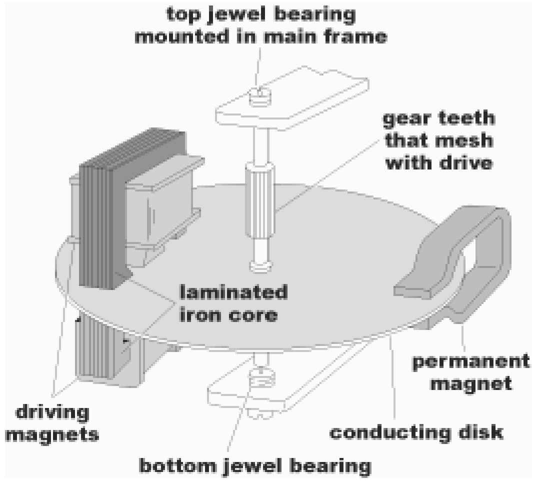


Fig. 10.2 Eddy-current damping

A thin disc of a conducting but non-magnetic material like copper or aluminium is mounted on the spindle. The disc is so positioned that its edges, when in rotation, cut the magnetic flux between the poles of a permanent magnet. Hence eddy currents are produced in the disc which flow and so produce a damping force in such a direction as to oppose the very cause producing them (Lenz's law). Since the cause producing them, is the rotation of the disc, these eddy currents retard the motion of the disc and moving system as a whole.

Lesson 11

PRINCIPLE OF INDUCTION TYPE INSTRUMENTS

11.1 Working Principle of Induction Type Instruments

Consider an aluminum disc placed the between the pole of an electromagnet, as shown in fig. 11.1. Let the flux produced by flow of current of I Amperes through the coil be Φ and this flux will lag behind I, by a small angle β as shown in vector diagram.

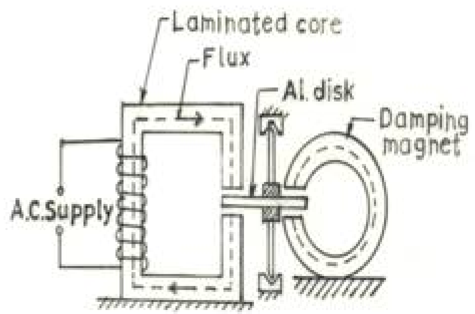


Fig. 11.1 Working principle of induction type instruments

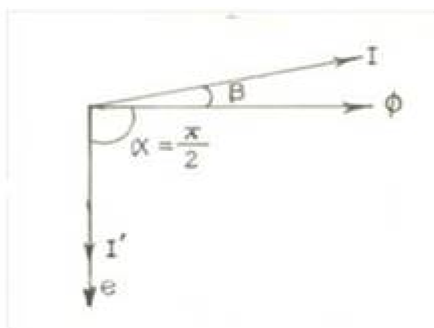


Fig. 11.2 Vector diagram

Since the aluminum disc act as a short circuited secondary of the transformer, therefore, an e.m.f., (say e volts) lagging behind the flux Φ by $\frac{\pi}{2}$ radians will be induced in it. As a result of this induced e.m.f., the eddy current (I') starts flowing in the disc. Since the disk is purely resistive therefore the eddy current will be in phase with induced e.m.f. (e) will lag behind the main flux Φ by $\frac{\pi}{2}$ radians. As the component of eddy current (I') along flux Φ is zero, therefore torque produced is zero. It can be proved as follows.

Let the instantaneous values of flux and eddy current be given by $\Phi = \Phi_{max}$ Sin θ and $i = I_{max}$ Sin (θ – α). Where α is the phase angle between the induced eddy current and flux (Φ).

Instantaneous torque α Φ i

Mean torque, $\alpha \frac{1}{\pi}\int_0^{\pi} \Phi i \, d\theta$

$$\alpha \frac{1}{\pi}\int_0^{\pi} \Phi\text{max Imax } Sin\,(\theta-\alpha)d\theta$$

$$\alpha\ \frac{1}{\pi}\int_0^{\pi}\frac{\Phi max\ Imax}{2}\left[Cos\ \alpha - Cos\ (2\theta-\alpha)d\theta\right] \qquad \alpha\ \frac{1}{\pi}$$

$$*\ \frac{\Phi\ max\ Imax}{\sqrt{2}\ \sqrt{2}}\ *\ \pi\ Cos\ \alpha \quad \alpha\ \Phi i\ Cos\ \alpha$$

Where Φ and i are r.m.s. values.

Since in single phase induction type instruments the angle α between main flux Φ and eddy current I' is $\frac{\pi}{2}$ and Cos $\frac{\pi}{2}$ is zero, therefore torque produced is zero. Hence to obtain the resultant torque it is necessary to produce an eddy current which is either appreciable less than or appreciable more than $\frac{\pi}{2}$ radians, out of phase with the flux which it reacts. Several arrangements are possible but here we will discuss about the descriptions of the two of these.

11.2 Pole Shaded Method

As shown in Fig. 11.3, in this method, the working current is passed through the coil of an electromagnet which has an air gap in one limb. Permanent magnet is used for providing damping torque. The aluminum disc is mounted on pivots and jewel bearings.

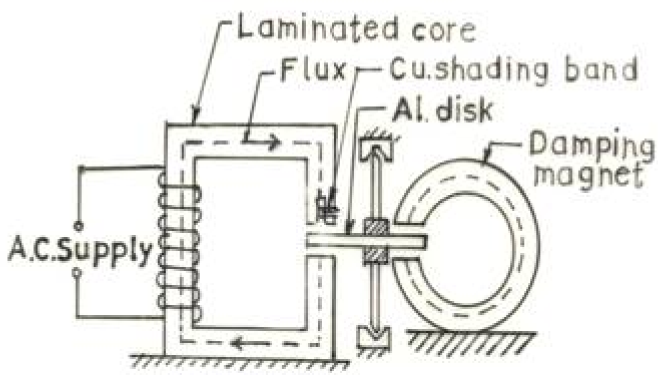


Fig. 11.3 Pole shaded method

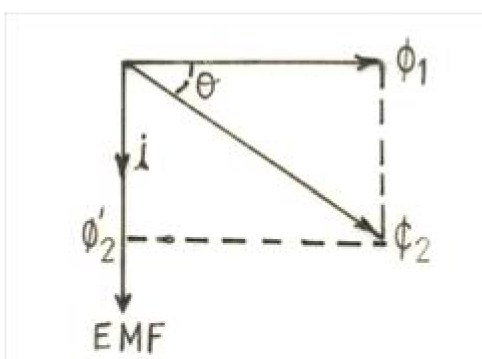


Fig. 11.4 Vector diagram

Two spiral springs are employed to provide controlling torque, wounded in direction opposite to each other if the instrument is used as Voltmeter, Ammeter and Wattmeter etc. One half of the pole face is surrounded by a copper band in order to split the working flux into two different paths. The copper shading band acts as a single turn short circuited secondary winding of the transformer. The spiral springs, pointer and scale etc. have been omitted for simplicity.

11.2.1 Theory

Let the total flux produced in the magnetic core be Φ Weber. Due to shading of pole, this flux will split up into two fluxes i.e. flux through un-shaded portion and other through the shaded portion. Suppose the flux Φ_1 be the flux of the shaded portion of the pole. This flux Φ_1 will induce an e.m.f. in the copper ring, which will lag the flux Φ_1 by 90°, as shown in Fig. 11.4. The induced e.m.f. will force a current say i to flow in the copper ring which will be lagging behind the flux Φ_1 by 90^0. The current flowing in the copper ring will produce its own magnetic field say Φ'_2 in phase with current i. The flux given by the shaded portion of the pole will be the vector sum of Φ_1 and Φ'_2 which is equal to Φ_2 lagging behind flux Φ_1 by an angle θ and its value should be 40^0 to 60^0 for producing effective deflecting torque.

Let the flux Φ_1 and Φ_2 are the fluxes passing through the shaded and un-shaded portions of the pole respectively induce e.m.fs. e_1 and e_2 in the disc, each of which is 90^0 in phase behind the fluxes responsible for inducing it. These induced e.m.fs; will induce eddy currents (say i_1 and i_2) in the disc lagging by a small angle (say α) behind its voltage due to the inductance of the path in the disc.

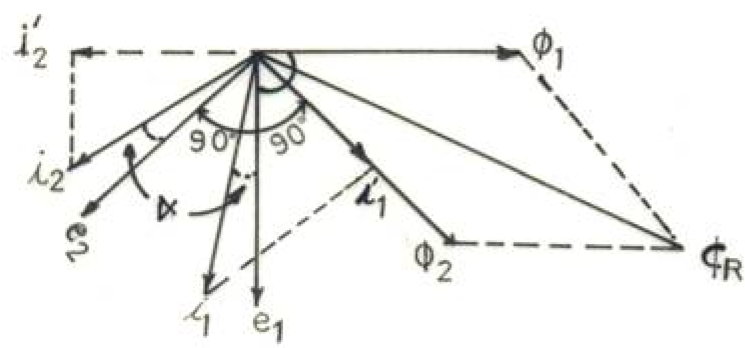


Fig. 11.5 Vector diagram

From Fig. 11.5, it is obvious that each of the current i_1 and i_2 has a component in phase with the other flux such $i_1{}'$ and i_2'. Hence two torques are acting in a directions having angle θ are produced in the instrument. Resultant of these two torques, provides an operating or deflecting torque.

11.3 Two Pole Method

This method is also known as split phase method. In this method, two laminated magnets A and B are placed near to each other with aluminum (Al) disc in between and a non inductive resistance R is connected in series with the magnetizing coil of magnet A and an inductive coil L is connected in series with the magnetizing coil of magnet B, as shown in Fig. 11.6.

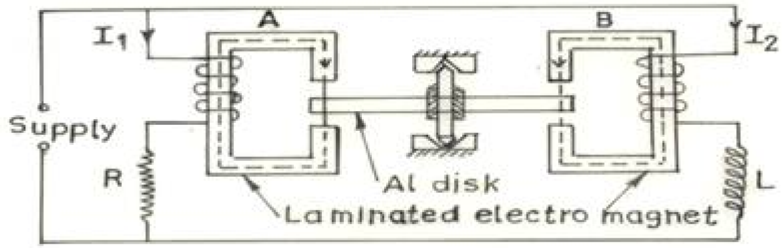


Fig. 11.6 Two pole method (split phase)

Hence there will be two fluxes having phase difference of less than 90° with each other, acting on the disc which will produce a resultant torque in the aluminium disc.

Let the flux produced by the magnet A and B is Φ_1 and Φ_2 respectively. Φ_2 is lagging Φ_1 by an angle θ as shown in Fig. 11.5. Hence an operating or deflecting torque will be produced as explained above in case of shaded pole method.

Lesson 12

INDUCTION TYPE VOLTMETER AND AMMETER

12.1 Shaded Pole Type Votmeter

A volt meter is an instrument used to measure the potential difference between the two points in an electric circuit. In analog voltmeters, the pointer moves over a calibrated scale in proportion to potential difference across the points where as in case of digital voltmeters, it displays numerical values with the help of analog to digital converter. The induction type voltmeter operates on the either shaded pole method or on two pole method's working principle as explained in Lesson 11.

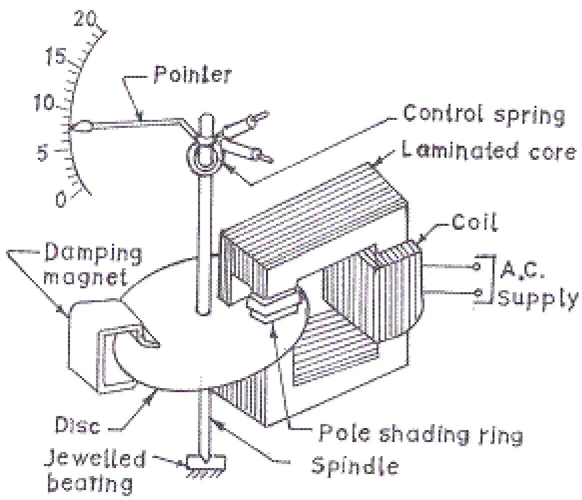


Fig. 12.1 Shaded pole type voltmeter

A non inductive high resistance is also inserted in series with the shunt coil and is connected across the supply, whose potential difference has to be measured. Since the voltmeters are connected across the supply, so the current flowing through coil is very small of the order of 5 to 10 mA. The spindle of aluminium disc is provided with a pointer moving over a calibrated scale in terms of voltage. Spiral springs are provided on both the ends of spindle for providing controlling torque. Permanent magnet (C- magnet) is used to provide damping torque on the spindle. As the instrument is provided with spiral springs, to provide controlling torque, the scale of the instrument is uniform because in such instrument this torque is directly proportional to angle of deflection of the pointer. Spiral springs, pointer and damping magnets are omitted for clear understanding of the figure. For detail working of the instrument, please refer to working principle of induction type instruments described in Lesson 11.

12.2 Split Phase Ammeter

An ammeter is always connected in series with load current directly or through CT (Current Transformer). As shown in Fig. 12.2, both the windings on the two laminated electromagnets A and B are connected in series but winding is shunted by a resistance R with the result of which, the current in this winding lags with respect to the total current (I). Hence the necessary phase angle (α) required between two fluxes is produced by the laminated electromagnets A and B.

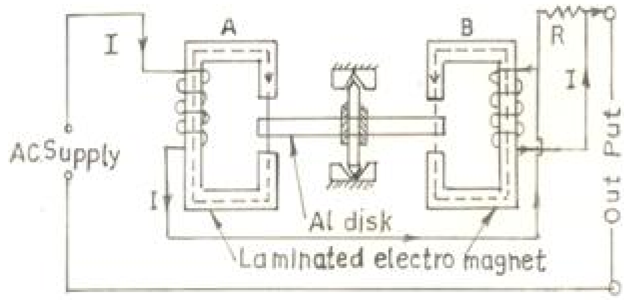


Fig. 12.2 Split phase induction type ammeter

The operating principle of the induction type instrument is based on the two pole method as discussed in Lesson 11. Two fluxes produced by laminated magnet A and B are focused upon the aluminum disc, having a phase angle between them required for producing a resultant torque in the spindle of the moving system. Being a spring control based controlling torque, the scale is uniform and the deflecting torque is directly proportional to square the load current. Eddy current damping is used to provide necessary damping torque by a permanent magnet. Spiral springs, pointer and damping magnets are omitted for clear understanding of the Fig. 12.2.

12.3 Advantages and Disadvantages of Induction Type Instruments

Advantages

(a) Damping is very much effective and efficient.

(b) Full scale deflection more than 200° can be obtained.

Disadvantes

(a) Power consumption is large and hence not recommended where continuous monitoring of ac quantities is required.

(b) Variation in temperature and frequency may cause serious errors if necessary compensations are not provided.

(c) As these instruments are based on principle of induction, they can be used on AC supply only.

12.4 Compensation for Frequency and Temperature Errors

12.4.1 Compensation for variation in frequency

Variation in frequency causes serious errors because deflecting torque is directly proportional to frequency and also the value of impedance (Z) and Cos α depends upon the supply frequency. The error is compensated by use of non inductive shunt in case of an Ammeter, when the frequency increases, the increase in impedance of the winding cause a greater proportion of the total current to flow in the non inductive shunt (whose impedance remains constant for all frequency) and lesser proportion of the total current in flow in the winding and to an extent thus compensate the increase in torque (since T α. f).

In case of voltmeter, the impedance of the winding increases with the increase in frequency, hence smaller current is drawn by the winding, which tends to compensate the increase in torque due to increase in frequency.

12.4.2 Compensation for variation in temperature

Variation in temperature changes the resistance of the eddy current paths, therefore, may result in serious errors. The error is compensated in case of an ammeter, employing a shunt of material having a high temperature coefficient of resistance than the material of the disc. This shunt may be the same one as used for frequency compensation. When the temperature increases, the resistance of the shunt increases, hence the greater portion of the current flows through the coil and decreases in torque due to smaller eddy current in the disc owing to increase in resistance at high temperature is compensated. The combination of shunt and swapping resistance in series with the instrument is often employed to compensate the temperature error in case of voltmeters. Since the frequency errors in induction type instruments are so serious that cannot be compensated satisfactorily. Hence these instruments are used for only constant frequency supplies or where the fluctuation in frequency is very small.

Lesson 13

INDUCTION TYPE WATTMETER, WATT-HOUR METER, AND DYNAMOMETER TYPE POWER FACTOR METER

13.1 Induction Type Wattmeter

These types of watt-meters operate on the same working principle on which the induction type ammeter and voltmeter operates. These instruments can only be used on ac supply while dynamo-meter type watt meters can be used on either ac or dc supply system. Induction type watt-meters are useful only when the supply and frequency remains constant. Since both the coils i.e. current coil and pressure coils are necessary in such instrument, it is not essential to use shaded pole principle. Because for producing a deflecting torque, two fluxes are essential with suitable phase angle and it would be available from these two coils.

13.1.1 Construction

A watt-meter has two laminated electromagnet, one of which is excited by load current or definite fraction of it, and is connected in series with the circuit, known as series magnet and the other is excited by the current proportional to the applied voltage or fraction of it and is always connected across the supply, known as shunt magnet. An aluminum disc is so mounted so that it cuts the fluxes produced by both the magnets. As a result of which, two e.m.f's are produced which induces two eddy currents in the disc. C - Magnet is used to provide necessary damping torque to the pointer, to damp out the oscillations. Deflecting torque is produced due to interaction of these eddy currents and the inducing flux. Copper shading bands are provided either on central limb or on the outer limb of the shunt magnet, and can be so adjusted as to make the resultant flux in the shunt magnet lag behind the applied voltage by 90°. Both the watt-meters are provided with spiral springs A and B, for producing controlling torque to counter balance the deflecting torque. In Fig. 13.2 the spiral spring and damping magnet is omitted for simplicity. The scale of such type instruments is quite uniform and extends over an angle of 300°. Currents up to 100 A can be handled by these watt-meters directly where as beyond this current transformers are used. Two types of induction type watt meters are available. Line diagrams of both of the types are detailed in Fig. 13.1 and 13.2.

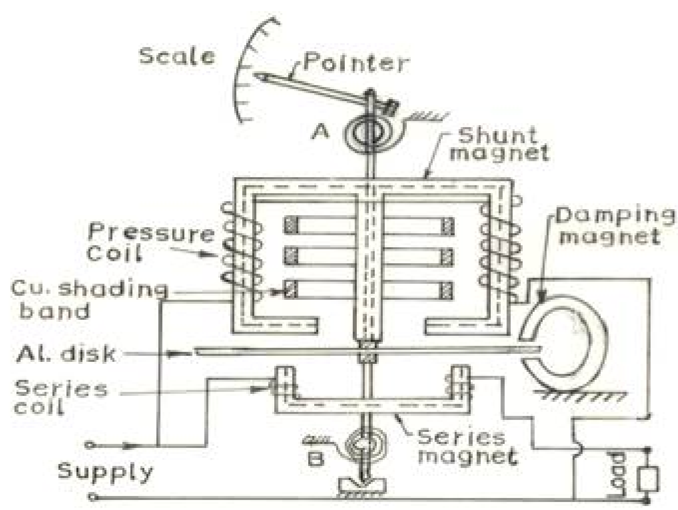


Fig. 13.1 Induction type wattmeter

In the form of the instrument shown in Fig. 13.1, two pressure coils are connected in series in such a way that both of them send flux through the central limb. The series magnet also carries two small current coils connected in series and wound so that they magnetized their respective cores in the same direction. Correct phase displacement between the fluxes produced by series and shunt magnet is obtained by the adjustment of copper shading band on the central limb.

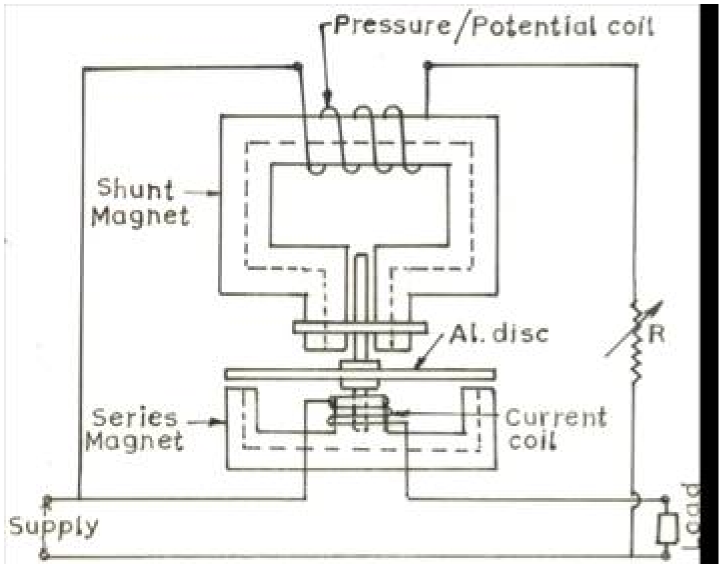


Fig. 13.2 Induction type wattmeter

In Fig. 13.2, there is only one pressure and one current coil. Two projecting poles of shunt magnet are surrounded by a copper shading band whose position can be adjusted for correcting the phase of the flux of this magnet with the applied voltage. The pressure coil circuit of induction type instrument is made as inductive as possible so that the flux of the shunt magnet may lag nearly by 90° behind the applied voltage.

13.1.2 Advantages

The advantages of induction watt meters are the same as those of induction ammeters – long scale, freedom from effects of stray field, and have effective damping torque.

13.1.3 Disadvantages

Following are the disadvantage of the induction type instruments:

a) Change in temperature causes variation in the resistance of the moving element, affects the eddy currents therein, and so the operating torque. The error due to this is in part offset by a balancing effect due to change in temperature of the windings.

b) Change in frequency from that of the calibration value causes variations in both the reactance of the voltage coil circuit, which is highly inductive, and also in the amount of compensation from the phase – compensating circuit. Within the limits of frequency variation met within practice on the mains, this last error in not important.

13.2 Induction Type Single Phase Watt Hour Meter

A watt hour meter is used to sum up the total energy consumed by a consumer during a period so that it can be charged for the actual energy consumed. The working principle, theory and advantage / disadvantages are almost similar to single phase watt meter. The construction of single phase watt hour meter is also almost similar to single phase induction type watt meter as discussed above. The pointer and spiral springs are replaced by wheel-train mechanism for summing up of total energy consumed where as the damping magnet is replaced by braking magnet. The construction of this type of watt hour meter is shown in Fig. 13.3.

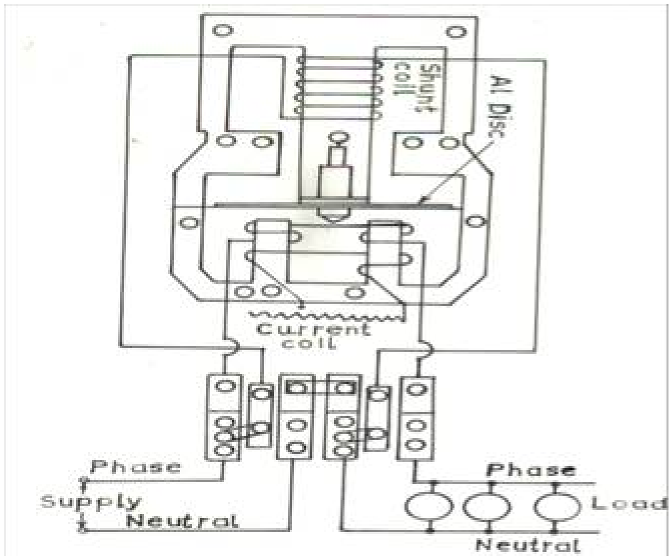


Fig. 13.3 Induction type energy meter

The brake magnet and recording wheel-train being omitted for clear understanding of the diagram. The description of registering mechanism and braking system is detailed below.

13.2.1 Registering or counting system

The registering or counting system essentially consists of gear train, driven either by worm or pinion gear on the disc shaft, which turns pointers that indicate on dials the number of times the disc has turned. The energy meter thus determines and adds together or integrates all the instantaneous power values so that total energy used over a period is thus known. Therefore, this type of meter is also called an **'integrating meter'.**

13.2.2 Braking system

Braking of the disk is provided by a small permanent magnet, located diametrically opposite to the alternating current magnets. The disk moves between the magnet's gaps. The movement of rotating disc through the magnetic field crossing the air gap sets up eddy currents in the disc that reacts with the magnetic field and exerts a braking torque. By changing the position of the brake magnet or diverting some of the flux therefore, the speed of the rotating disc can be controlled. Creep error can be rectified by drilling a small hole in the aluminum disc passing through the magnetic flux of braking magnet.

13.3 Errors and Adjustment in Induction Type Instruments

13.3.1 Phase and speed error

It is necessary that the energy meter should give correct reading on all power factors, which is only possible when the field set up by shunt magnet flux lags behind the applied voltage by 90°. Ordinarily the flux set up by shunt magnet does not lag behind the applied voltage exactly by 90° because of winding resistance and iron losses. The flux due to shunt magnet is made to lag behind applied voltage by 90° with the help of copper shading band provided on the central limb. An error due to incorrect adjustment of shading band will be evident when the meter is tested on a load of power factor less than unity.

An error on the fast side under these conditions can be eliminated by bringing the shading band nearer to the disc and vice versa. An error in the speed of the meter when tested on non inductive load can be eliminated by adjustment of the position of the brake magnet. Movement of the brake magnet in the direction of the spindle will reduce the braking torque and vice versa. Speed of disc is directly proportional to the distance between the disc and brake magnet.

13.3.2 Friction compensation

The two shading bands embrace the flux contained in the two outer limbs of the shunt electromagnet, and thus eddy current are induced in them which cause a phase displacement between the enclosed flux and main gap flux. As a result, a small driving torque is exerted on the disc, this torque being adjusted, by variation of the position of these bands, to compensate for frictional torque in the instrument.

In some energy meter, it is observed that the disc continue to rotate even when the load on the energy meter is zero and potential coil is in excited condition. This defect is known as creeping and is prevented by cutting two holes or slots in the disc on opposite sides of the spindle. The disc tends to remain stationary when one of the holes comes under one of pole of the shunt magnet. In some cases, a small piece of iron wire is attached to the edge of the disc. The force of attraction of the brake magnet upon this wire is sufficient to prevent continuous rotation of the disc under no load condition.

13.3.3 Temperature and frequency errors

The error due to variation in temperature is very small. Since the various effects due to change in temperature tends to neutralize each other on unity power factor if not on low power factor (lagging). Since the meters are used normally on fixed frequency and hence these can be adjusted to have a minimum error at declared supply frequency which is normally 50 cycles / second.

13.4 Single Phase Dynamo-meter Type Power Factor Meter

The power factor meter is used to indicate the instantaneous power factor of the consumer. It consist of two fixed coils CC connected in series carrying the load current (or a definite fraction of it) and two identical moving coils P_1 & P_2 wound with a fine copper wire, fixed at right angle to each other and pivoted on the same spindle. The pressure coils P_1 and P_2 move together and carry a pointer, which indicates the power factor of the circuit directly on the scale.

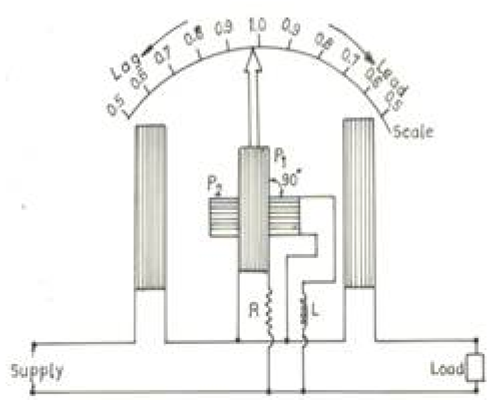


Fig. 13.4 Dynamometer type power factor meter

The pressure coil P_1 is connected across the supply through a non inductive resistance R and pressure P_2 is connected across the supply through a highly inductive choke coil of inductance L. The value of non inductive resistance R and inductance L are so chosen that for the normal frequency, the current in the two pressure coil P_1 and P_2 is same. Thus these coils P_1 and P_2 produce equally strong magnetic field displaced by 90^0 in space as well as in the phase. For measurement of power factor on high voltage system, the current and pressure coils of the instrument may be connected to the main circuit through current and potential transformer respectively.

13.4.1 Theory

While measuring power factor of an installation, there may be three possibilities of installation's power factor, which are described here:

(a) **Power Factor is Unity:** When the circuit is switched on, the current in the potential coil P_1 will be in phase with current in coils CC, where as the current in pressure coil P_2 will lag 90^0 behind the voltage or behind the current in the circuit coli CC. Thus pressure coil P_1 will experience a turning moment so its plane will come in a position parallel to a plane of a current coil CC. The average torque on coil P_2 will be zero but being mechanically coupled to coil P_1, it will follow the rotation of coil P_1. Hence the pointer will in the centre of the calibrated scale and it will show the power factor as unity. The position of coil P_1 is shown in Fig. 13.4 and it will maintain the reading till the load current is in phase with the voltage.

(b) **When Power Factor is Zero (lagging):** In this situation, the current flowing in the pressure coil P_2 will be in phase with load current flowing in the fixed current coil CC, both lagging behind the applied circuit voltage by 90^0 and current in pressure coil P_1 will lead the load current in current coil CC by 90^0. Thus only pressure coil P_2 will experience a turning moment so its plane will come in a position parallel to the plane of current coils CC. At this instant, the pointer will indicate zero power factor lagging.

(c) **When Power Factor Zero (leading):** When the current flowing in fixed coils CC leads the applied voltage by 90° and, therefore, the field of pressure coils P_1 by 90° and that of coil P_2 by 180°. Hence the polarity of field in current coils is the reverse of that considered above. At this instant, the pointer will indicates the power factor as zero leading on the other half of the scale.

For an intermediate power factor, the moving system takes up intermediate position and the pointer makes an angle of (90°- Φ) with the axis of the fixed coils where Φ the phase angle between load current is and applied voltage of the load circuit.

Lesson 14

INTRODUCTION TO SENSORS AND TRANSDUCERS

14.1 Introduction

In a measurement system all the quantities being measured, could not be displayed as such. In such situation, the accurate measurement of a quantity is usually done by converting the related information or signal to another form which is more conveniently or accurately displayed. This is achieved with the help of a device which is known as transducer.

A sensor senses the condition, state and value of the process variable which reflects the output of the instrument. The transducer is a device which provides a usable output in response of corresponding input, which may be physical or mechanical quantity, property or condition. More precisely, '*A TRANSDUCER is a device, which transforms energy from one form to another'*. The transducer may be mechanical, electrical, magnetic, optical, chemical, thermal nuclear, acoustic, or a combination of among of two or more.

All forms of transducers have some merits and demerits but most of the shortcomings have been overcome with the introduction of electrical transducers. The most instrumentation systems having 'Non-Electrical' input quantity and this non-electrical quantity is generally converted into an electrical form by a transducer.

14.2 Basic Requirements of Transducer

The following are the basic requirements of a good quality transducer:

a) Ruggedness
b) Linearity
c) No hysteresis
d) Repeatability
e) High output signal quality
f) High reliability and stability
g) Good dynamic response
h) No deformation on removal of input signal

14.3 Classification of Transducers

The transducers could be classified in several ways. This classification could be on the basis of their application, method of energy conversion, the nature of signal output and according to whether they are self generating or the externally powered units. The transducers can be broadly classified as:

1) Primary transducers and Secondary transducers.
2) Analog transducers and Digital transducers.
3) Active transducers and Passive transducers.
4) Transducers and Inverse transducers

14.3.1 Primary transducers and secondary transducers

The transducer that directly senses the input signal and converts the physical property into the electrical signal is called primary transducer or a sensor. 'Thermistor' is an example of primary transducer. It senses the temperature directly and causes the changes in its resistance with respect to temperature.

On the other hand, if the input signal is sensed first by some detector or sensor and its output, which may be of some other form than the input signal, is given as input to another transducer for conversion into electrical form, then such a transducer is called as secondary transducer.

14.3.2 Analog transducers and digital transducers

The output from the transducer may be a continuous function of time or it may be in discrete function of time. On this basis the transducers may be classified into two categories.

A transducer, which converts input signal into output signal in a continuous function of time is known as Analog transducer. Linear variable differential transformer (LVDT), thermo-couple are the examples of Analog Transducer.

On the other hand, a transducer, which converts input signal into output signal in the form of pulses i.e., it gives discrete output is called a digital transducer. The digital transducers are becoming very popular and useful because the digital signals can be transmitted over a long distance, with minimum distortion due to amplitude variation and phase shift.

Fig 14.1 (a) Analog voltmeter

Fig 14.1 (b) Digital voltmeter

14.3.3 Active and passive transducers

On the basis of methods of energy conversion used the transducers are classified in to following two categories:

A transducer, which develops its output in the form of electrical current or voltage without any auxiliary source, is called active transducer or the self generating transducers. The energy required for this is absorbed from the physical phenomenon which is being measured. This type of transducer draws energy from the system under measurement. Examples are thermocouples, piezo-electric transducers, photovoltaic cell etc. Such transducers normally give very small output and so amplification of the signal becomes essential.

Externally powered transducers are those which derive the power required for energy conversion from an external power source. An electrical transducer, in which electrical parameter like resistance, inductance or capacitance changes with change in the input signal, is called as a passive transducer. They may also absorb a little power from the process variable being measured. Resistive, inductive and capacitive transducers viz., potentiometric devices, differential transformer etc. are known as passive transducers.

14.3.4 Inverse transducers

A transducer is generally defined as a device which converts a non electrical quantity into an electrical quantity. An inverse transducer is a device which converts an electrical quantity into a non-electrical quantity.

A current carrying coil moving in a magnetic field is an inverse transducer, because current by it is converted into a force, which causes translational or rotational displacement. A most useful application of inverse transducers is in feedback measuring systems.

An actuator is an inverse transducer as it is having an electrical input and a low-power non-electrical output. A piezo-electric crystal also acts as an inverse transducer because when a voltage is applied across its surfaces, it changes its dimensions causing a mechanical displacement.

14.4 Characteristics of Transducers

Performance criteria of the transducers are based upon certain set of characteristics that gives a meaningful description of quality of measurement. Normally these characteristics of a measurement system are those that must be considered when the system or instrument is used. All these characteristics have to be taken into account, when choosing a transducer for any application.

The characteristics of transducers are described as:

A) Input characteristics
B) Transfer characteristics
C) Output characteristics

14.4.1 Input characteristics

i). **Type and operating range of Input quantity:** The first consideration for the selection of a transducer is the input quantity which is to be measured and its range of operation. The type of input quantities is generally known in advance. The useful operating range of transducer is an important factor in the choice of a transducer for a particular application. The maximum value or the maximum limit is decided by the transducer capabilities, whereas, the minimum value of range or the lowest limit is normally determined by the unavoidable noise which may originate in the transducer during measurement.
A good resolution is required throughout its operating range of a transducer.

ii). **Loading Effects:** In an ideal transducer, there is no loading effect on the input quantity being measured by the transducer. However, practically it may not be possible. The magnitude of the loading effects is expressed in terms of force, power or energy obtained from the input quantity. Hence the transducer which is selected for a particular application should ideally extract no force, power from the input quantity.

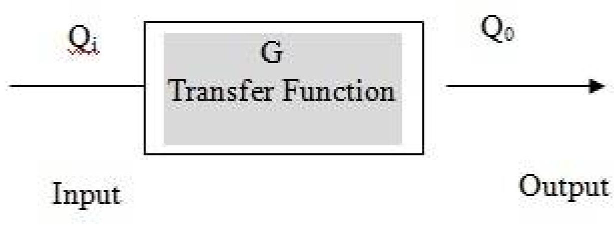
14.4.2 Transfer characteristics

The transfer characteristics involve three separate elements:

i). Transfer function
ii). Sensitivity

iii). Error.

i) Transfer Function: It is defined as relationship between the input quantity and output and describes the input and output behaviour of the system.



$$Q_0 = GQ_i$$

Where, Q_0 and Q_i are respectively output and output of the transducer.

ii) Sensitivity: The sensitivity of a transducer is the ratio of change in output for a given change in input

$$S = \frac{dQ_0}{dQ_i}$$

In general, the sensitivity of transducers is not constant and is dependent upon the input quantity (Q_i). In some cases the relation between output and input becomes linear.

If the sensitivity is constant over the entire range of the transducer it shall be defined as :

$$S = \frac{dQ_0}{dQ_i} = \frac{Q_0}{Q_i}$$

The inverse of sensitivity is called scaled factor.

$$Scale\ factor = \frac{1}{S} = \frac{dQ_i}{dQ_o}$$

iii) Error: Many a times the input-output relationship given by $Q_0 = GQ_i$ is not followed by transducer. In such cases, error is obtained in transducers.

Let at a particular input Q_i, ideally the output will be Q_0 but practically an output $Q_0^{'}$ is obtained, then the error of the instrument is:

$$e = Q_0^{'} - Q_o$$

The error could be due to any of the followings:

a) Scale error.
b) Dynamic error.
c) Error on account of noise and drift.

a) Scale Error: There are four different types of scale errors:

i). **Zero Error:** In such type of error, the output deviates from the original value by a constant factor over the entire range of the transducer.

ii). **Sensitivity Error:** This type of error occurs where the observed output deviates from the correct value by a constant value.

iii). **Hysteresis:** The effect of hysteresis is obtained in all transducers. The output of a transducer not only depends upon the input but also upon input quantities previously applied to it. So, different output is obtained when the same value of input quantity is applied, depending upon whether it is increasing or decreasing.

iv). **Non-Conformity:** When experimentally obtained transfer function deviates from the theoretical transfer function for almost every input

b) **Dynamic Error:** This type of error occurs when the input quantity is varying with time. This type of error occurs where system contains energy storage element and due to this the output cannot follow input exactly. The dynamic error can be made small by having a small time constant.

c) **Noise and Drift Error:** Noise and drift signals originating from the transducers very with time and are superimposed on the output signal.

d) **Error due to Change of Frequency:** A sine wave input in a linear transducer, a sine wave output obtained, as the frequency of the sine wave input is increased, the transducer is required to respond more and more quickly. In this process beyond the range of a particular frequency the transducers can no larger respond with respect to its sinusoidal input is changing. Therefore the output of the transducer becomes smaller as well as the phase shift between the input and output increases. Hence the frequency increases the output of the transducer decreases.

14.4.3 Output characteristics

The output characteristics of a transducer are considered as given below :

i). Type of electrical output.
ii). Output impedance.
iii). Useful output range.

i). Type of Electrical Output: The output of transducer may be a voltage, current impedance or a time function of these amplitudes. The above quantities may or may not be acceptable to the latter stages of the instrumentation system. There is possibility to change their magnitudes or change in their format by signal conditioning equipment for making them drive the different stages of instrumentation system.

ii). Output Impedance: In ideal transducer the value of the output impedance should be zero, but practically it is not possible and, therefore, its value should be kept as low as possible to minimize the loading effects. The output impedance gives the information of amount of power than can be transferred to the further stages of the instrumentation system for a given output signal level. The value of output impedance is low compared to the forward impedance of the system, the transducer behaves as a constant voltage source (provided a voltage is the output of transducer), when the forward impedance is high as compared to the output impedance of transducer, it behaves as constant current source.

iii). Useful Output Range: The output range of a transducer is limited by noise signal at the lower end which may shroud the required input signal. The output range can be increased by adding of amplifier in the transducer in some cases. The addition of amplifier also increases the noise level and therefore in such situation the amplifier should be avoided.

14.5 Factors Affecting the Choice of Transducers

The following is the summary of the factors influencing the choice of a transducer for measurement of a physical quantity:

1. **Operating Principle.** The transducers are so many times selected on the basis of operating principle used by them. The operating principles used in transducer may be resistive, inductive, capacitive, opto-electronic, piezoelectric and so on.
2. **Sensitivity.** The transducer should give a sufficient output signal per unit of measured input in order to yield meaningful data.
3. **Operating Range.** The transducer should maintain the range requirements and have a better resolution over its entire range.
4. **Accuracy.** High degree of accuracy is necessary for measurement.
5. **Error.** The errors inherent in the operation of the transducer itself, but it should maintain the expected input-output relationship as described with its transfer function so as to avoid errors.
6. **Transient and Frequency Response.** The transducer should meet the desired time domain specifications as well as it should ideally have a flat frequency response curve.
7. **Loading Effects.** To avoid loading effect, it is necessary that a transducer has a high input impedance and a low output impedance.
8. **Physical Environment.** The transducer selected should be able to work under specified environmental conditions and maintain its output-input relationship

Lesson 15

MECHANICAL INPUT TRANSDUCERS

15.1 Introduction

A generalized mechanical system consists of a sensing element which responds directly by reacting to the measurand and a transducing element which is responsible for conversion of measurand into analogous driving signal. The sensing element may also serve to transducer the measurand and put it into more convenient form. The unit is then called as detector-transducer. Most of the detector transducer devices employ the devices such as a diaphragm, a Bourdon tube or a bellow. All of these are the elastic elements. The action of these elements is based on elastic deformation brought about by the force resulting from pressure.

15.2 Mechanical Elastic Elements

Mechanical detector-transducer elements are generally elastic elements. These units are frequently employed to furnish an indication of the magnitude of applied pressure/force through a displacement measurement. Operation of the elastic elements is based on one or the combination of following acts:

i) Compression that tends to force the molecules of the solid close together.
ii) Tension that tends to force the molecules further apart.
iii) Torsion that tends to twist the solids.

15.3 Principle of Operation of Elastic Elements

The measurement of force or pressure can be done by converting the applied force or pressure into a displacement by elastic elements which act as primary transducer. This displacement, which is a function of pressure, is then measured by other transducers which act as secondary transducers. The output of the secondary transducer becomes a function of displacement, which in turn is a function of pressure. Mechanical methods are thus used to convert the applied force or pressure into displacement. These devices are also known as Force Summing Devices.

The mechanical elastic elements possess elasticity. When deformed, the stresses developed in the summing device establish equilibrium with the pressure applied on it. As the pressure is removed the elastic element regains its original position. The choice and design of the type of force summing elements depends on the magnitude of the force or pressure to be measured.

15.4 Types of Force Summing Devices

Mechanical input transducers generally use one of the following types of force summing devices:

i) Diaphragm
ii) Bellows
iii) Bourdon tube

15.4.1 Diaphragms

The movement of diaphragm is a convenient way of sensing pressure differential. The diaphragm is a flexible disc made up of sheet metal with precise dimensions. It could be either flat or with concentric corrugations on it.

The edge of the diaphragm is rigidly fixed. When the unknown pressure is applied to one side of the diaphragm, the centre of the diaphragm is displaced. This displacement which is proportional to the applied pressure is measured. Some instruments use the diaphragm as the pressure sensor, while others use it as a basic component of capsular element. The capsules consist of two diaphragms welded together at their peripheries. Evacuated capsules are used for detection of absolute pressure and single element diaphragm for highly sensitive measurement.

The sensitivity of a capsule increases in proportion to its diameter and inversely proportional to the thickness of sheet used. Multiple capsule elements can be built from the capsules. These elements are useful in increasing the output motion resulting from a pressure change.

The diaphragm pressure element, shown in Fig. 15.1 B, employs a thin flexible diaphragm of such material as brass or bronze. The non-metallic-diaphragm pressure element employs a flexible diaphragm of high quality leather or a thin neoprene-like material. 'P_{EXT}' is the external pressure, 'P_{REF}' is the reference pressure and 'w' is the deflection at the centre point of the diaphragm. The extent of this deflection depends upon the pressure applied on the diaphragm. This deflection of the diaphragm operates an indicating or recording type instrument. The resulting displacement of a diaphragm can be multiplied by a suitable linkage and a pointer is made to operate over a scale. Diaphragm gauges are normally employed for low pressure or vacuums up to about 5 psi. Differential pressure can be measured by applying the second pressure to the other side of the diaphragm and using a sealed means of detecting the motion of diaphragm as shown in Fig.15.1 A.

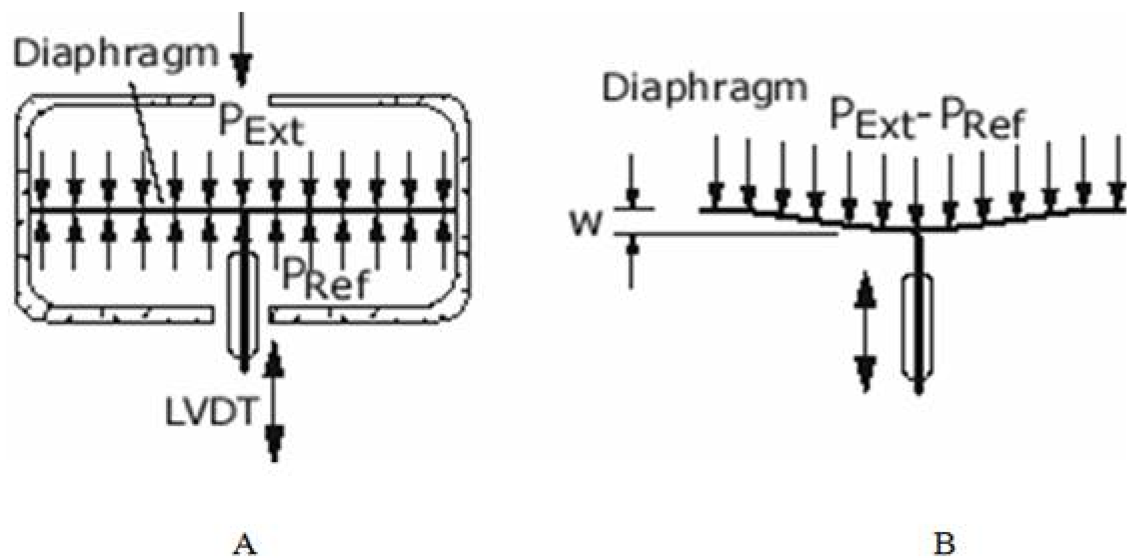


Fig. 15.1 Diaphragm pressure element

15.4.2 Bellows

The bellows pressure sensor is made of a sealed chamber that has multiple ridges like the pleats of an accordion that are compressed slightly when the sensor is manufactured. It is a thin walled tube having a corrugated shape. When pressure is applied to the chamber, the chamber will try to expand and open the pleats. Essentially it is a pressure activated spring. The stiffness or in other words the displacement for a particular pressure depends upon the type and thickness of the material used. The most commonly used material for bellows pressure sensing elements are steel, phosphor bronze and beryllium copper.

The Fig. 15.2 shows an example of a bellows sensor, which uses a spring to oppose the movement of the bellows and provides a means to adjust the amount of travel the chamber which it will have when pressure is applied. In low-pressure bellows sensors, the spring is not required. The travel of the bellows can be converted to linear motion so that a switch can be activated, or it can be connected to a potentiometer. This type of sensor is used in low-pressure applications usually less than 30 psi. The bellows sensor is also used to make a differential pressure sensor. In this application two bellows are mounted in one housing, so that the movement of each bellows opposes the other. This will cause the overall travel of the pair to be equal to the difference of pressure that is applied to them.

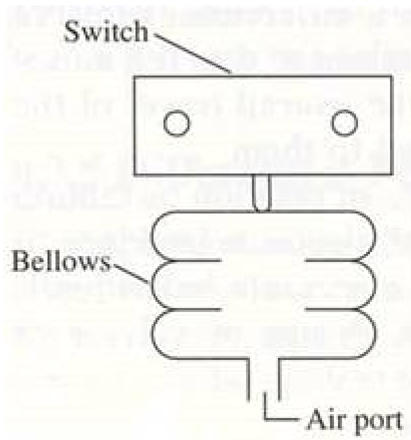


Fig.15.2 Schematic diagram of bellows pressure element

Generally, metallic bellows acting with pressure on one side and a spring on the other is used. The pressure range of the system is determined mainly by the effective area of the bellows and the spring gradient. Often the inside of the entire assembly is tinned for further protection against corrosion. Bellows gauges are generally employed for measuring gauge pressures or vacuums up to 100 psi. Precision bellows are available with minimum error due to drift, friction and elastic hysteresis. Sensitivity of bellows increases as a function of size. In general, it can be said that bellows elements will deliver high forces and can detect slightly higher pressures than the diaphragm capsules. The disadvantages of the bellows element include being subject to work hardening a sensitive to ambient temperature variations.

15.4.3 Bourdon tube

It is most widely used force summing or pressure sensing element. The device was invented by Eugene Bourdon in the year 1849. The basic idea behind the device is that, cross-sectional tubing when deformed in any way will tend to regain its circular form under the action of pressure. The Bourdon pressure gauges used today have a slight elliptical cross-section and the tube is generally bent into a ⊂ or C-shape or arc length of about 27 degrees. The detailed diagram of the Bourdon tube is shown in Fig. 15.3.

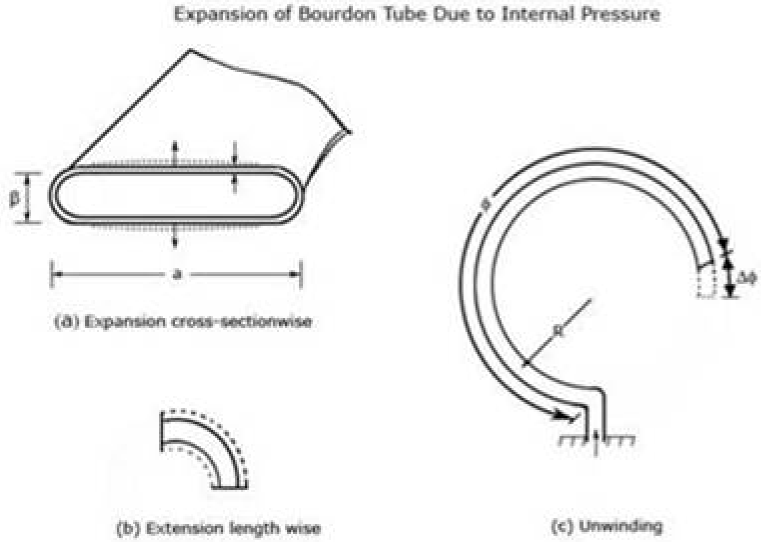


Fig. 15.3 Bourdon tube element

It consists of a narrow bore tube of elliptical cross-section Fig. 15.3 (a), sealed at one end. The pressure is applied at the other end which is open and fixed. The tube is formed into a curve, a flat spiral or a helix. When the pressure is applied, the effect of the forces is to straighten it so that the closed end is displaced.

A '⊂ or C Bourdon tube' as used in direct indicating gauge usually has an arc of 250°. The process pressure is connected to the fixed socket end of the tube while the tip end is sealed. As the fluid pressure enters the Bourdon tube, because of the difference between inside and outside radii, the Bourdon tube presents different areas to pressure, which causes the tube to be reformed, and because of a free tip available, this action causes the tip to travel in free space and the tube unwinds. The resulting tip-motion is non-linear because less motion results from each increment of additional pressure. This non-linear motion has to be converted to linear rotational pointer response. This travel of tip is suitably guided and amplified for the measurement of the internal pressure. But the main requirement of the device is that whenever the same pressure is applied, the movement of the tip should be the same and on withdrawal of the pressure the tip should return to the initial point.

Other than C-type, Bourdon gauges can also be constructed in the form of a helix or a spiral. The types are varied for specific uses and space accommodations, for better linearity and larger sensitivity. For thorough repeatability, the bourdon tubes materials must have good elastic or spring characteristics. The surrounding in which the process is carried out is also important as corrosive atmosphere or fluid would require a material which is corrosion proof. The commonly used materials are phosphor-bronze, silicon-bronze, beryllium-copper, and other C-Cr-Ni-Mo alloys. Like all elastic elements a bourdon tube also has some hysteresis in a given pressure cycle. By proper choice of material and its heat treatment, this may be kept to within 0.1 and 0.5 percent of the maximum pressure cycle.

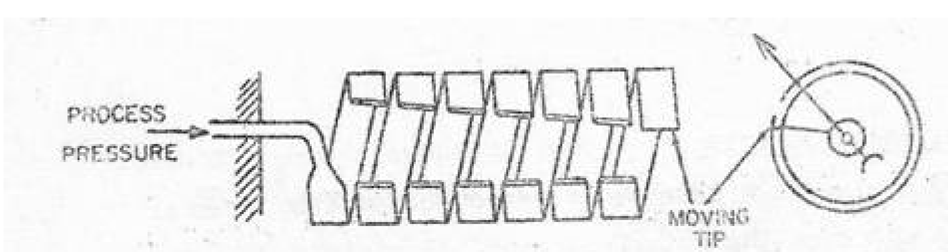


Fig. 15.4 Helical bourdon element

Figure 15.4 shows the construction of a helical Bourdon element. This sensor produces a greater motion of the free end eliminating the need for amplification. Other advantages of this design include the high over range protection available, for example, a 0 to 1000 psig element man safely be exposed to 10,000 psig pressure and it suitable for pressure measurement on continuously fluctuating services. Helical elements can also be used as the element in differential pressure sensors if one of the pressures is acting on the outside surface and the other on the inside of the coil.

The displacement created by the action of the elastic deformation element may also be converted into a change of some electric parameter. The force summing member actuates a transducer which converts the displacement into an output of electrical format. The resistive and inductive transducers have been successfully used as secondary transducers along with a diaphragm for measurement of pressure. Linear Variable Differential Transformer (LVDT) is used as a secondary transducer for measurement of pressure with bellows or Bourdon tube acting as a primary transducer. The pressure is converted into displacement which is sensed by LVDT and transduced into a voltage.

Lesson 16

ELECTRICAL TRANSDUCERS: RESISTIVE TRANSDUCERS

16.1 Introduction

The electrical measurements are used for measurement of electrical quantities but its use in measurement of non electrical quantities is growing. In the measurement of non electrical quantities a detector is used which usually converts the physical quantity in displacement. The displacement actuates an electric transducer, gives an output which is electrical in nature. The electrical quantity so produced is measured by standard methods used for electrical measurements. The resultant electrical output gives the magnitude of the physical quantity being measured. The advantages and limitations of electric measurements have been presented in Lesson 3.

The electrical signal could be a voltage, current or frequency. The production of these signals is based upon the resistive, inductive or capacitive effects. These phenomena may be combined with appropriate primary sensing elements / detectors to produce different types of transducers.

16.2 Resistive Transducers

The resistive transducers or resistive sensors are also called as variable resistance transducers. The variable resistance transducers are one of the most commonly used types of transducers. They can be used for measuring various physical quantities, such as, temperature, pressure, displacement, force, vibrations etc. These transducers are usually used as the secondary transducers, where the output from the primary mechanical transducer acts as the input for the variable resistance transducer. The output obtained from it is calibrated against the input quantity and it directly gives the value of the input.

The variable resistance transducer elements work on the principle that the resistance of the conductor is directly proportional to the length of the conductor and inversely proportional to the area of the conductor.

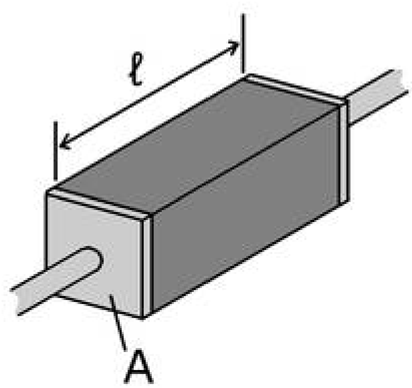


Fig. 16.1 Resistance element

Thus, if ‘L’ is the length of the conductor (m) and ‘A’ is its area (m^2) as shown in Fig.16.1, then its resistance ‘R’ (ohms) is given by:

$$R = \rho L/A$$

Where ‘ρ’ is called as resistivity of the material measured in ‘ohm-m’ and it is constant for the given material.

Some of the popular variable resistance transducers that are being used for various applications are as below:

16.2.1 Sliding contact devices

In the sliding contact type of variable resistance transducers, there is a long conductor whose effective length is variable. One end of the conductor is fixed, while the position of the other end is decided by the slider or the brush that can move along the whole length of the conductor. The slider is connected to the body whose displacement is to be measured. When the body moves the slider also moves along the conductor so its effective length changes, due to which it resistance also changes. The effective resistance is measured as the resistance between the fixed position of the conductor and the position of the sliding contact as shown in Fig. 16.2. The value of the resistance is calibrated against the input quantity, whose value can be measured directly. One of most popular sliding contact type of variable resistance transducer is the potentiometer. These devices can be used to measured translational as well as angular displacement and are shown in Fig 16.2 and 16.3.

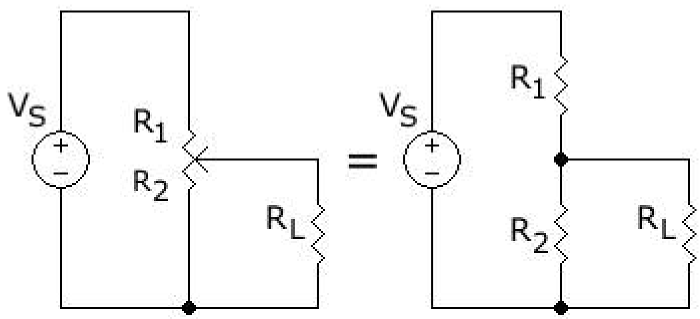


Fig. 16.2 Sliding contact type of variable resistance element

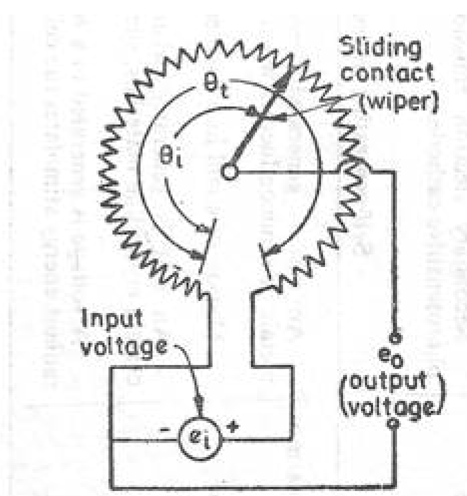


Fig. 16.3 Rotational potentiometer

16.2.2 Wire resistance strain gauge

The strain gauge is a fine wire which changes its electric resistance, when mechanically strained. When an electrical conductor is stretched within the limits of its elasticity such that it does not break or permanently deform, it will become narrower and longer, changes that increase its electrical resistance end-to-end. Conversely, when a conductor is compressed such that it does not buckle, it will broaden and shorten in size, the changes that decrease its electrical resistance end-to-end. A typical strain gauge arranges a long, thin conductive strip, as shown in Fig. 16.3 (a), made in a zigzag pattern of parallel lines such that a small amount of stress in the direction of the orientation of the parallel lines results in a multiplicatively larger strain over the effective length of the conductor Fig. 16.3 (b). The change in resistance of a strain gauge can be measured using a Wheatstone bridge.

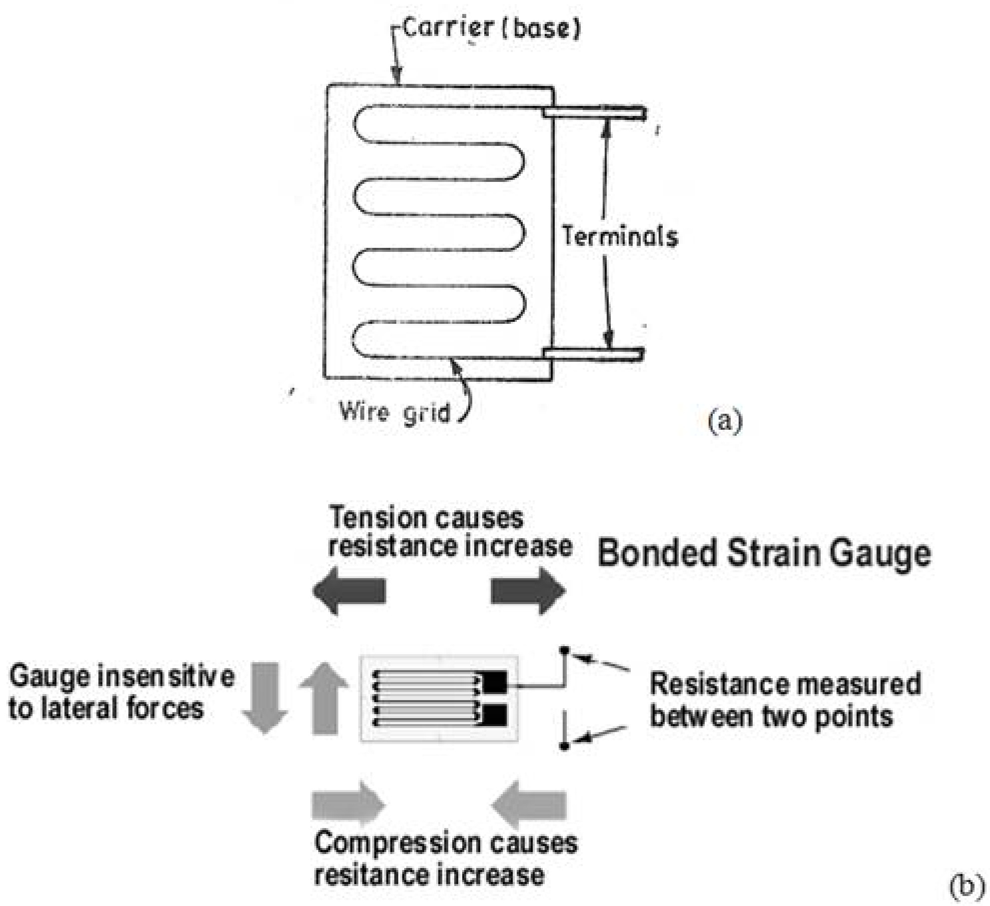


Fig. 16.3 Working principle of strain gauge

A fundamental parameter of the strain gage is its sensitivity to strain. It is expressed quantitatively as the gauge factor (GF). Gauge factor is defined as the ratio of fractional change in electrical resistance to the fractional change in length (strain). The gage factor for metallic strain gages is typically around 2.

$$GF = \frac{\Delta R / R_G}{\varepsilon}$$

Where:

ΔR = change in resistance caused by strain

R_G = resistance of the undeformed gauge

ε = strain

The majority of strain gauges are foil types, available in a wide choice of shapes and sizes to suit a variety of applications. They consist of a pattern of resistive foil which is mounted on a backing material. They operate on the principle that as the foil is subjected to stress, the resistance of the foil changes in a defined way. Foil gauges typically have active areas of about 2–10 mm^2 in size. With careful installation, the correct gauge, and the correct adhesive, strains up to at least 10% can be measured. The strain gauge has been in use for many years and is the fundamental sensing element for many types of sensors, including pressure sensors, load cells, torque sensors, position sensors, etc.

16.2.3 Thermistor

Thermistor works on the principle that resistance of some materials changes with the change in their temperature. When the temperature of the material changes, its resistance changes and it can be measured easily and calibrated against the input quantity. Thermistor has high negative temperature correlation. The commonly used thermistors are made up of the ceramic like semiconducting materials such as oxides of manganese, nickel and cobalt. Thermistor can be used for the measurement of temperature, as electric power sensing devices and also as the controls for various processes. Thermistors are discussed in detail in Lesson 21.

16.2.4 Resistance temperature detector

Resistance Temperature Detector (RTD), commonly referred to generally as resistance thermometers, is a temperature sensor which measures temperature using the principle that the resistance of a metal changes with temperature. RTDs work on a basic correlation between metals and temperature. As the temperature of a metal increases, it’s resistance to the flow of electricity increases. An electrical current is transmitted through a piece of metal, that is, the RTD element or resistor located in proximity to the area where temperature is to be measured. The resistance value of the RTD element is then measured by an instrument. This resistance value is then correlated to temperature based upon the known resistance – temperature characteristics of the RTD element. Thermistors have been discussed in detail in Lesson 20.

Lesson 17

ELECTRICAL TRANSDUCERS: CAPACITIVE TRANSDUCERS

17.1 Capacitive Transducers

A capacitor consists of two conductors (plates) that are electrically isolated from one another by a nonconductor (dielectric). When the two conductors are at different potentials (voltages), the system is capable of storing an electric charge. The storage capability of a capacitor is measured in farads.The principle of operation of capacitive transducers is based upon the equation for capacitance of a parallel plate capacitor as shown in Fig.17.1

$$Capacitance \qquad C = \frac{\varepsilon A}{D}$$

Where, A = Overlapping area of plates; m^2,

d = Distance between two plates; m,

ε = Permittivity (dielectric constant); F/m.

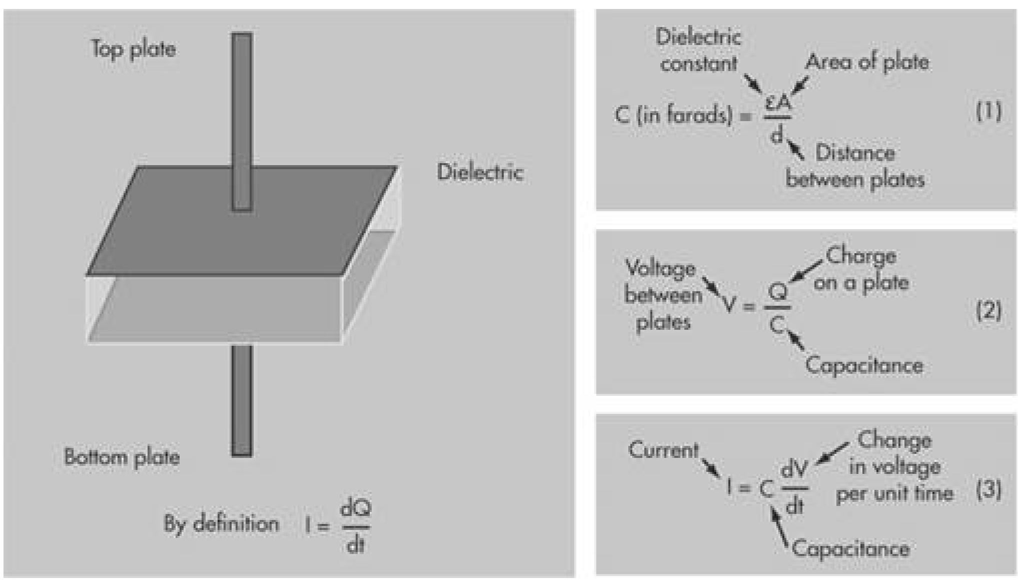


Fig.17.1 Parallel plate capacitor

The capacitance is measured with a bridge circuits. The output impedance 'Z' of a capacitive transducer is:

$$Z = 1/2\pi fC$$

Where: Z = Impedance

f = frequency, 50 Hz.

C = capacitance

In general, the output impedance of a capacitive transducer is high. This fact calls for a careful design of the output circuitry. The capacitive transducers work on the principle of change in capacitance of the capacitor. This change in capacitance could be caused by change in overlapping area 'A' of the plates, change in the distance 'd' between the plates and change in dielectric constant ' ε'.

In most of the cases the above changes are caused by the physical variables, such as, displacement, force or pressure. Variation in capacitance is also there when the dielectric medium between the plates changes, as in the case of measurement of liquid or gas levels. Therefore, the capacitive transducers are commonly used for measurement of linear displacement, by employing the following effects as shown in Fig. 17.2 and 17.3.

i) Change in capacitance due to change in overlapping area of plates.
ii) Change in capacitance due to change in distance between the two plates.
iii) Change in capacitance due to change in dielectric between the two plates

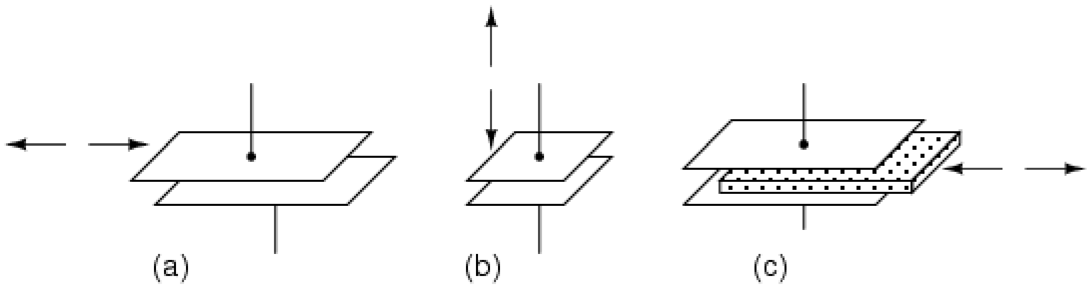


Fig. 17.2 Variable capacitive transducer varies; (a) area of overlap, (b) distance between plates, (c) amount of dielectric between plates

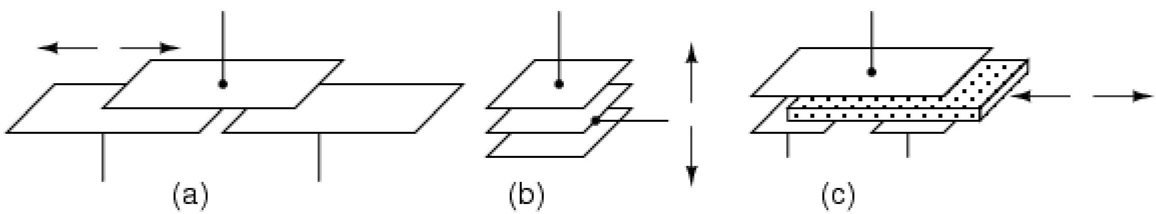


Fig. 17.3 Differential capacitive transducer varies capacitance ratio by changing: (a) area of overlap, (b) distance between plates, (c) dielectric between plates

As may be seen in Fig.17.3, all of the differential devices have three wire connections rather than two: one wire for each of the 'end' plates and one for the 'common' plate. As the capacitance between one of the 'end' plates and the 'common' plate changes, the capacitance between the other 'end' plate and the 'common' plate also changes in the opposite direction.

a) Transducers Using Change in Area of Plates

Examining the equation for capacitance, it is found that the capacitance is directly proportional to the area, A of the plates. Thus, the capacitance changes linearly with change in area of plates. Hence this type of capacitive transducer is useful for measurement of moderate to large displacements say from 1 mm to several cm. The area changes linearly with displacement and also the capacitance.

For a parallel plate capacitor, the capacitance is:

$$C = \frac{\varepsilon A}{d} = \frac{\varepsilon l w}{d} F$$

Where, l = length of overlapping part of plates; m, and
w = width of overlapping part of plates; m.

$$Sensitivity \qquad S = \frac{\partial C}{\partial l} = \varepsilon \frac{w}{d} F/m$$

The sensitivity is constant and therefore there is linear relationship between capacitance and displacement.

This type of a capacitive transducer is suitable for measurement of linear displacement ranging from 1 to 10 cm. The accuracy is as high as 0.005%.

b) Transducers Using Change in Distance between Plates

Fig. 17.2(b) shows the basic form of a capacitive transducer employing change in distance between the two plates to cause the change in capacitance. One plate is fixed and the displacement to be measured is applied to the other plate which is movable. Since, the capacitance, C, varies inversely as the distance d, between the plates the response of this transducer is not linear. Thus this transducer is useful only for measurement of extremely small displacements.

$$Sensitivity \qquad S = \frac{\partial C}{\partial l} = -\frac{\varepsilon A}{d^2}$$

Thus the sensitivity of this type of transducer is not constant but varies over the range of the transducer. The relationship between variations of capacitance with variation of distance between plates is hyperbolic and is only approximately linear over a small range of displacement. The linearity can be closely approximated by use of a piece of dielectric material like mica having a high dielectric constant, such as, a thin piece of mica.

c) Transducers Using Change in dielectric constant between Plates

If the area (A) of and the distance (d) between the plates of a capacitor remain constant, capacitance will vary only as a function of the dielectric constant (ε) of the substance filling the gap between the plates. If the space between the plates of a capacitor is filled with an insulator, the capacitance of the capacitor will change compared to the situation in which there is vacuum between the plates. The change in the capacitance is caused by a change in the electric field between the plates.

The value of dielectric constant is initially set by design in the choice of dielectric material used to make the capacitor. Many factors will cause the 'ε' to change, and this change in 'ε'will vary for different materials. The major factors that will cause a change in 'ε' are moisture, voltage, frequency, and temperature. The dielectric constant of a process material can change due to variations in temperature, moisture, humidity, material bulk density, and particle size etc. The 'ε' in the basic formula is the effective dielectric constant of the total 'space' between the electrodes. This space may consist of the dielectric material, air, and even moisture, if present. The figure 17.4 shows that how in a capacitor the position of the dielectric is varied to vary the capacitance. Physical variables, such as, displacement, force or pressure can cause the movement of dielectric material in the capacitor plates, resulting in changes in the effective dielectric constant, which in turn will change the capacitance.

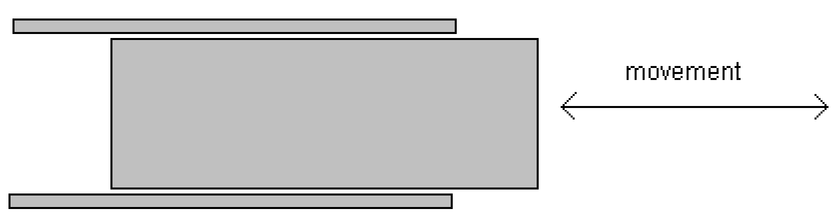


Fig.17.4 Change in capacitance due to movement of dielectric between plates

The major advantages of capacitive transducers are that they require extremely small forces to operate them and hence are very useful for use in small systems. They are extremely sensitive and require small power to operate them. Owing to their good frequency response they are very useful for dynamic studies.

The disadvantages of capacitive transducers include their non-linear behaviour on account of edge effects and the effects of stray capacitances especially when the transducers have a low value of capacitance. Therefore guard rings must be used to eliminate this effect. The metallic parts of the capacitive transducers must be insulated from each other. In order to reduce the effects of stray capacitances, the frames must be earthed.

Capacitive transducers can be used for measurement of both linear and angular displacements. The capacitive transducers are highly sensitive and can be used for measurement of extremely small displacements down to the order of molecular dimensions, i.e., 0.1×10^{-6} mm. On the other hand, they can be used for measurement of large displacements up to about 30 m as in aeroplane altimeters. The change in area method is used for measurement of displacements ranging from 10 to 100 mm. Capacitive transducers can be used for the measurement of force and pressure. The force and pressure to be measured are first converted to displacement which causes a change of capacitance. Capacitive transducers can also be used directly as pressure transducers in all those cases where the dielectric constant of a medium changes with pressure. They can be used for measurement of humidity in gases and moisture content in soil / food products etc.

Lesson 18

ELECTRICAL TRANSDUCERS: INDUCTIVE TRANSDUCRES

18.1 Inductance

Inductance is the ability of an inductor to store energy in a magnetic field. Inductors generate an opposing voltage proportional to the rate of change in current in a circuit. Inductance is caused by the magnetic field generated by electric currents. It is typified by the behavior of a coil of wire in resisting any change of electric current through the coil. Arising from Faraday's law, the inductance L may be defined in terms of the emf generated to oppose a given change in current. The quantitative definition of the self inductance L of an electrical circuit in SI units (Webbers per ampere, known as henries) is:

$$v = L\frac{di}{dt}$$

Where:

v = voltage in volts

i = current in amperes.

This property can be of two types, the self inductance and the mutual inductance. Self-inductance, or simply inductance, is the property of a circuit whereby a change in current causes a change in voltage in the same circuit. When one circuit induces current flow in a second nearby circuit, it is known as mutual-inductance. The self-inductance, *L,* of a circuit component determines the magnitude of the electromagnetic force (emf) induced in it as a result of a given rate of change of the current through the component. Similarly, the mutual inductance, *M,* of two components, one in each of two separate but closely located circuits, determines the emf that each may induce in the other for a given current change. The phenomenon of mutual induction is used as the mechanism by which transformer work.

The schematic symbol of inductance and the air-coiled solenoid producing self inductance is shown in Fig. 18.1. Solenoid is a long straight coil of wire and can be used to generate a nearly uniform magnetic field similar to that of a bar magnet. The magnetic field can be greatly strengthened by the addition of an iron core. Such cores are typical in electromagnets. Solenoids have enormous number of practical applications.

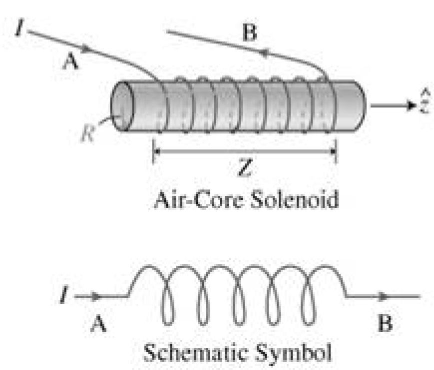


Fig. 18.1 Self-inductance

The emf induced in a coil can be given by the following expression

$$Emf \ -N\frac{\Delta\phi}{\Delta t} = -NA\frac{\Delta B}{\Delta t}$$

Where;

N= Number of turns in the coil

Φ = BA = magnetic flux

B = external magnetic field

A = area of coil

The mutual inductance, *M*, is a measure of the coupling between two inductors. The mutual inductance due the voltage induced in coil 2 due to the current in coil 1 has the following relationship:

$$M_{21} = -N_1 N_2 P_{21}$$

Where:

M_{21} = mutual inductance

N_1 = number of turns in coil 1,

N_2 = number of turns in coil 2,

P_{21} = permeance of the space occupied by the flux.

The circuit diagram representation of mutually coupled inductors is shown in Fig. 18.2. The two vertical lines between the inductors indicate a solid core that the wires of the inductor are wrapped around. "n:m" shows the ratio between the number of windings of the left inductor to windings of the right inductor.

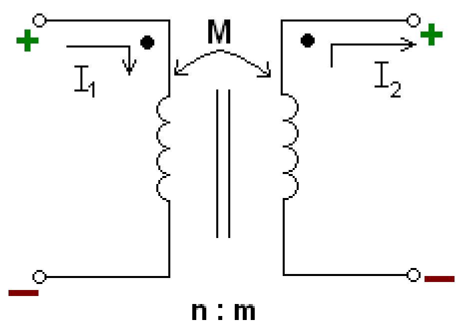


Fig. 18.2 Mutual-inductance

18.2 Inductive Transducers

The inductive transducers work on the principle of the electromagnetic induction. Just as the resistance of the electric conductor depends on number of factors, the induction of the magnetic material depends on a number of variables like the number of turns of the coil on the material, the size of the magnetic material, and the permeability of the flux path. In the inductive transducers the magnetic materials are used in the flux path and there are one or more air gaps. The change in the air gap also results in change in the inductance of the circuit and in most of the inductive transducers it is used for the working of the instrument.

There are two common type inductive transducers: simple inductance type and two-coil mutual inductance type.

18.2.1 Simple inductance type inductive transducers

In the simple inductance type of the inductive transducers simple single coil is used as the transducer. When the mechanical element whose displacement is to be measured is moved, it changes the permeance of the flux path generated by the circuit, which changes the inductance of the circuit and the corresponding output. The output from the circuit is calibrated directly against the value of the input, thus it directly gives the valve of the parameter to be measured. Fig. 18.3 shows the single coil inductive circuit. Here the magnetic material is connected to the electric circuit and it is excited by the alternating current. At the bottom there is another magnetic material that acts as the armature. As the armature is moved, the air gap between the two magnetic material changes and the permeance of the flux generated by the circuit changes that changes the inductance of the circuit and its output. The output meter directly gives the valve of the input mechanical quantity. This type of transducer can be used in a filpack machine to count the number of packets filled with milk.

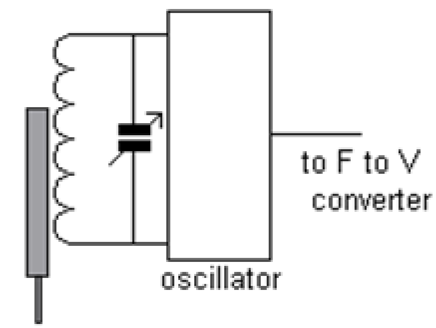


Fig. 18.3 Single coil inductive circuit

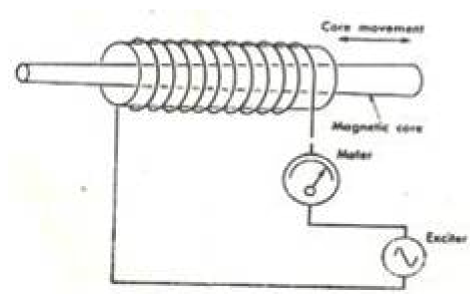


Fig. 18.4 Hollow Coil inductive circuit

In the Fig. 18.4, coil is wound around the round hollow magnetic material and there is magnetic core that moves inside hollow magnetic material. In the above circuits the change in the air gap or the change in the amount of the magnetic material in the circuit can be used to produce the output proportional to the input. In the above arrangements the supply of the current and the output is obtained from the same coil or circuit.

18.2.2 Two-coil mutual inductance type inductive transducer

In the two coil arrangement there are two different coils. In the first coil the excitation is generated by external source of the power and in the second coil the output is obtained. The output is proportional to the mechanical input. As shown in the figure 18.5 below, A is the excitation coil and B is the output coil. The inductance of the output coil changes due to change in position of the armature which is connected to the mechanical element whose motion is to be measured. As the armature position changes, the air gap between the fixed magnetic material and the armature changes.

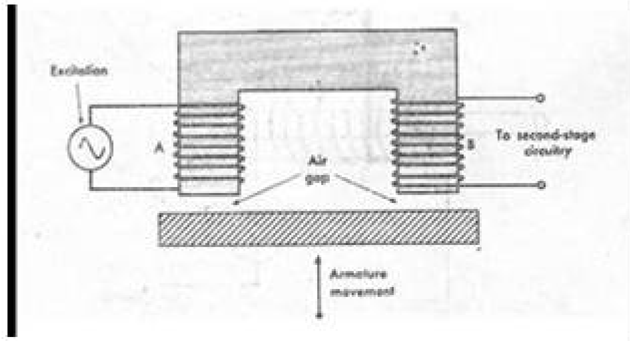


Fig. 18.5 Two-Coil mutual inductance type inductive transducer

18.3 Linear Variable Differential Transformer (LVDT)

The linear variable differential transformer (LVDT) is the most widely used inductive transducer to translate linear motion into electrical signal.

18.3.1 Construction

A differential transformer consists of a primary winding and two secondary windings. The windings are arranged concentrically and next to each other. They are wound over a hollow bobbin which is usually of a non-magnetic and insulating material. A ferro-magnetic core (armature) in the shape of a rod of cylinder is attached to the transducer's sensing shaft. The core slides freely within the hollow portion of the bobbin. In the simplex winding configuration, the linear variable displacement transformer LVDT is shown in Fig.18.6. There is one primary and two secondary windings. The secondaries are connected so their outputs are opposite. If an AC excitation is applied across the primary winding then voltages are induced in the secondaries. A movable core varies the coupling between it and the two secondary windings. When the core is in the centre position, the coupling to the secondary coils is equal. As the core moves away from the centre position, the coupling to one secondary becomes more and hence its output voltage increases, while the coupling and the output voltage of the other secondary decreases.

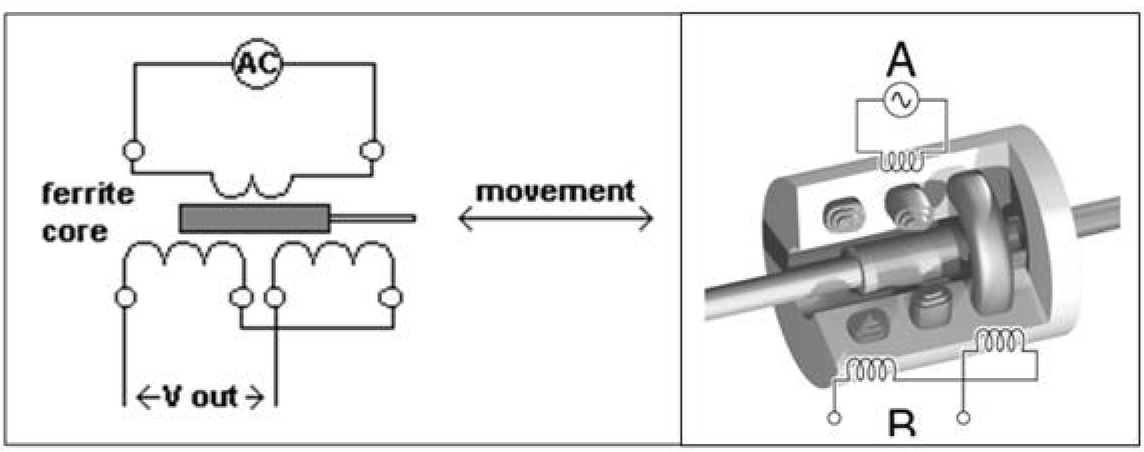


Fig. 18.6 Linear variable differential transformer

18.3.2 Working principle

Any physical displacement of the core causes the voltage of one secondary winding to increase while simultaneously, reducing the voltage in the other secondary winding. The difference of the two voltages appears across the output terminals of the transducer and gives a measure of the physical position of the core and hence the displacement.

When the core is in the neutral or zero position, voltages induced in the secondary windings are equal and opposite and cancel out. The net output is negligible. As the core is moved in one direction from the null position, then there will be more voltage in one secondary than the other. The voltages will not cancel out and there will be an AC signal at the output proportional to the distance the core has moved. The differential voltage, i.e., the difference of the secondary voltages, will increase while maintaining an in-phase relationship with the voltage from the input source. In the other direction from the null position, the differential voltage will again increase, but will be 180°C out of phase with the voltage from the input source. Using a phase detector circuit it is also possible to indicate the direction the core has moved. By comparing the magnitude and phase of the output (differential) voltage with the input source, the amount and direction of movement of the core and hence of displacement may be determined. Variation of output voltage with core position is shown in Fig.18.7.

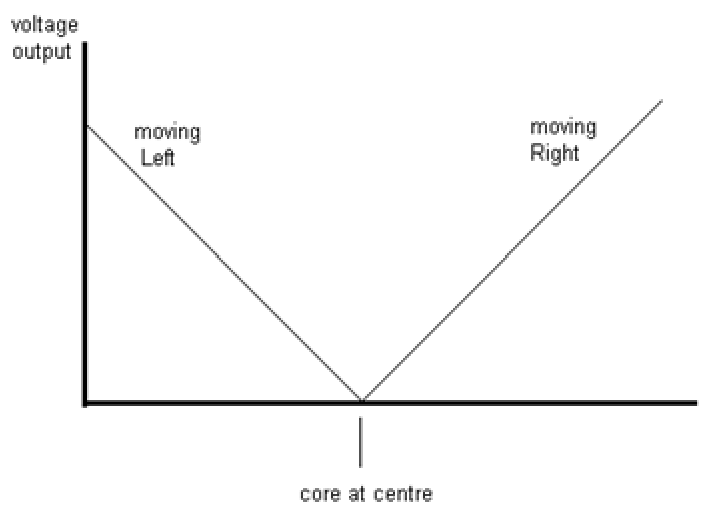


Fig. 18.7 Variation of output voltage in LVDT with core position

The output voltage of these transducers is practically linear for displacement up to 5 mm. The transducer has infinite resolution and a high sensitivity. It is simple, light in weight, and easy to align and maintain. These transducers can usually tolerate a high degree of shock and vibration without any adverse effects. In addition to this they have low hysteresis and hence repeatability is excellent under all conditions.

The disadvantages of LVDT include their relatively large displacements are requirement for appreciable differential output. They are sensitive to stray magnetic fields but this can be overcome by providing appropriate shielding. Temperature affects the performance of the transducer.

18.3.3 Numerical

1. The output of an LVDT is connected to a 10 V voltmeter through an amplifier with a gain of 250. The voltmeter scale has 100 divisions and the scale can be read up to 1/5th of a division. An output of 2 mV appears across the terminals of the LVDT, when core is displaced through a 0.5 mm. Determine the following:

i) Sensitivity of the measuring system

ii) Resolution of instrument

Solution

Given that

The output voltage of LVDT: $V_0 = 2$ mV

Displacement = 0.5 mm

$$\frac{V_0}{Displacement} = \frac{2mV}{0.5mm} = 4mV/mm$$

Sensitivity of LVDT = Sensitivity of the measuring system = Amplification factor x Sensitivity of LVDT

= 250 x 4 mV/mm = 1000 mV/mm or 1 V/mm.

Full-scale of voltmeter = 0 – 10 V

No. of divisions on voltmeter scale = 100

1 Scale division = 10 / 100 = 0.10 V or 100 mV

Minimum voltage that can be read on voltmeter = $\frac{100mV}{5} = 20mV$

$$Resoluton\ of\ instrument = \frac{20mV}{1000mV/mm} = 0.02$$

Lesson 19

MEASUREMENT OF PRESSURE – I

19.1 Introduction

Pressure measurement is one of the most common of all measurements made on systems. Pressure along with flow measurements is extensively used in industry, laboratories and many other fields for a wide variety of reasons. Pressure measurements are concerned not only with determination of force per unit area but are also involved in many liquid level, density, flow and temperature measurements.

19.2 Pressure

Pressure is the force per unit area exerted by a fluid on the surface of the container. Pressure measurements, are usually made relative to some reference. Everyday pressure measurements, such as, the pressure in a car tire, are usually made relative to ambient air pressure. In other cases measurements are made relative to a vacuum or to some other ad hoc reference. When distinguishing between these zero references, the following terms are used:

i) Atmospheric pressure

The pressure due to air surrounding the earth's surface is called as atmospheric pressure.

ii) Absolute pressure

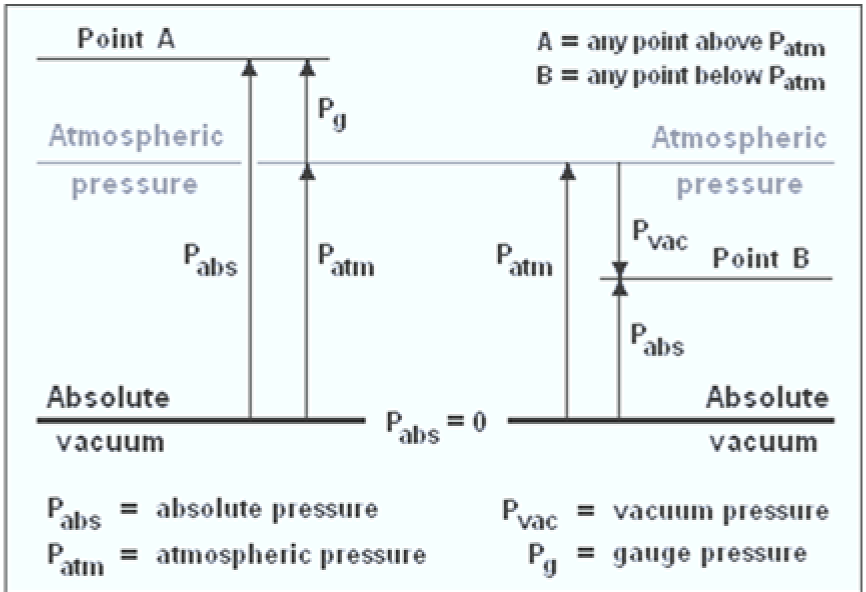
It is known that pressure is force per unit area when the interaction of fluid particles among themselves is zero, a zero pressure intensity will occur. This is possible only when the population of molecules is negligibly small which means perfect vacuum. Hence the pressure intensity measured from a state of prefect vacuum is called as absolute pressure. So it is equal to gauge pressure plus atmospheric pressure

iii) Gauge Pressure

A pressure measuring instrument generally measures the difference between the unknown pressure (P) and the atmospheric pressure (P_{ata}). When the unknown pressure (P) is greater than the atmospheric pressure (P_{atm}), the pressure measured by the instrument is called as the gauge pressure. In Gauge pressure is zero referenced against ambient air pressure, so it is equal to absolute pressure minus atmospheric pressure. Negative signs are usually omitted.

iv) Vacuum pressure

A Pressure measuring instrument generally measures the difference between the unknown pressure (P) and the atmospheric pressure (P_{atm}). When the atmospheric pressure (P_{atm}) is greater than the unknown pressure (P), the pressure measured by the instrument is called as the vacuum pressure



Source: Milton Beychok

The relationship between absolute, gauge and vacuum pressures.

Atmospheric pressure is typically about 100 kPa at sea level, but is variable with altitude and weather. If the absolute pressure of a fluid stays constant, the gauge pressure of the same fluid will vary as atmospheric pressure changes. Use of the atmosphere as reference is usually signified by a (g) after the pressure unit e.g. 30 psi g, which means that the pressure measured is the total pressure minus atmospheric pressure.

Following table presents various units of pressure measurement and their equivalents to each other:

Table 19.1

Pressure Units

	pascal (Pa)	bar (bar)	atmosphere (atm)	torr (torr)	pound-force per square inch (psi)	kilogram-force per square centimeter (kgf/cm^2)
1 Pa	≡ 1 N/m^2	10^{-5}	9.8692×10^{-6}	7.5006×10^{-3}	145.04×10^{-6}	1.01972×10^{-5}
1 bar	100,000	≡ 10^6 dyn/cm^2	0.98692	750.06	14.504	1.01972
1 atm	101,325	1.01325	≡ 1 atm	760	14.696	1.03323
1 torr	133.322	1.3332×10^{-3}	1.3158×10^{-3}	≡ 1 torr ≈ 1 mmHg	19.337×10^{-3}	1.35951×10^{-3}
1 psi	6,894.76	68.948×10^{-3}	68.046×10^{-3}	51.715	≡ 1 lbf/in^2	7.03059×10^{-2}
1 kgf/cm^2	98,066.5	0.980665	0.967838	735.5576	14.22357	≡ 1 kgf/cm^2

Example reading: 1 Pa = 1 N/m^2 = 10^{-5} bar = 9.8692×10^{-6} atm = 7.5006×10^{-3} torr, etc.
Note: mmHg is an abbreviation for millimetre of mercury

v) Static and Dynamic Pressure

Static pressure is uniform in all directions, so pressure measurements are independent of direction in an immovable (static) fluid. Flow, however, applies additional pressure on surfaces perpendicular to the flow direction, while having little impact on surfaces parallel to the flow direction. This directional component of pressure in a moving (dynamic) fluid is called *dynamic pressure*. An instrument facing the flow direction measures the sum of the static and dynamic pressures; this measurement is called the total pressure or stagnation pressure. Since dynamic pressure is referenced to static pressure, it is neither gauge nor absolute; it is a differential pressure. While static gauge pressure is of primary importance to determining net loads on pipe walls, dynamic pressure is used to measure flow rates and airspeed. Dynamic pressure can be measured by taking the differential pressure between instruments parallel and perpendicular to the flow. Pitot-static tubes, for example perform this measurement on airplanes to determine airspeed. The presence of the measuring instrument inevitably acts to divert flow and create turbulence, so its shape is critical to accuracy and the calibration curves are often non-linear.

In processing industries the measurement of pressure is required to maintain safe operating conditions, to help control a process and to provide test data. In industrial applications the pressure is usually measured by means of indicating gauges or recorders. These instruments could be mechanical, electro-mechanical or electronic in operation. The mechanical instruments include those instruments in which pressure measurement is made by balancing unknown force with a known force and those instruments which employ quantitative deformation of air elastic member for pressure measurement. The electro-mechanical instruments usually employ a mechanical means for detecting the pressure and the electrical means for indicating or recording the detected pressure. The electronic pressure measuring instruments normally depend upon some physical change that can be detected and indicated or recorded electronically. In this text, the description will be limited only to the elastic deformation elements and transducers employed in mechanical or electro-mechanical measurement of pressure.

19.3 Measurement of Pressure

Many instruments have been invented to measure pressure, with different advantages and disadvantages. Pressure range, sensitivity, dynamic response and cost all vary by several orders of magnitude from one instrument design to the next. The oldest type is the liquid column (a vertical tube filled with mercury) manometer. Following table gives the instruments which are used in various situations:

Table 19.2

Type of pressure to be measured	Pressure Measuring instrument to be used
Low pressure	Manometer
High and medium pressure	Bourdon tube pressure gauge. Diaphragm gauge. Bellows Gauges.
Low vacuum and ultra high vacuum	McLeod vacuum gauge Thermal conductivity gauges. Ionisation gauges.
Very high pressures	Bourdon tube pressure gauge. Diaphragm gauge. Bulk modulus pressure gauge.

19.4 Manometer Gauges

The difference in fluid height in a liquid column manometer is proportional to the pressure difference. Liquid column gauges consist of a vertical column of liquid in a tube whose ends are exposed to different pressures. The column will rise or fall until its weight is in equilibrium with the pressure differential between the two ends of the tube. A very simple version is a U-shaped tube manometer (Fig. 18.1) is half-full of liquid, one side of which is connected to the region of interest while the reference pressure, which could be the atmospheric pressure or a vacuum, is applied to the other. The difference in liquid level represents the applied pressure.

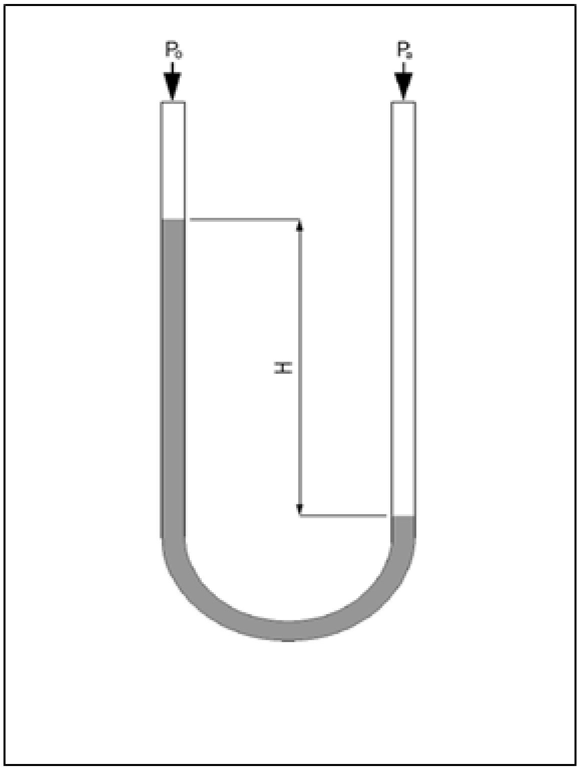


Fig. 19.1 U-Shaped tube manometer

The pressure (P) exerted by a column of fluid of height h and density ρ is given by the hydrostatic pressure equation

$$P = hg\rho.$$

Therefore the pressure difference between the applied pressure P_a and the reference pressure P_0 in a U-tube manometer can be found by solving

$$P_a - P_0 = hg\rho.$$

In other words, since the liquid is static, the pressure on either end of the liquid shown in the figure 19.1 must be balanced and so

$$P_a = P_0 + hg\rho.$$

If the fluid being measured is significantly dense, hydrostatic corrections may have to be made for the height between the moving surface of the manometer working fluid and the location where the pressure measurement is desired.

Although any fluid can be used in the manometer, mercury is preferred for its high density (13.534 g/cm^3) and low vapour pressure. For low pressure differences well above the vapour pressure of water, water is commonly used and “mm or inches of water" is a common pressure unit. Liquid-column pressure gauges are independent of the type of gas being measured and have a highly linear calibration. However, they have poor dynamic response. When measuring vacuum, the working liquid may evaporate and contaminate the vacuum if its vapor pressure is too high. When measuring liquid pressure, a loop filled with gas or a light fluid can isolate the liquids to prevent them from mixing. This may not be required when mercury is used as the manometer fluid to measure differential pressure of a fluid such as water. Simple hydrostatic gauges can measure pressures ranging from a few Torr (a few 100 Pa) to a few atmospheres. (Approximately 1,000,000 Pa)

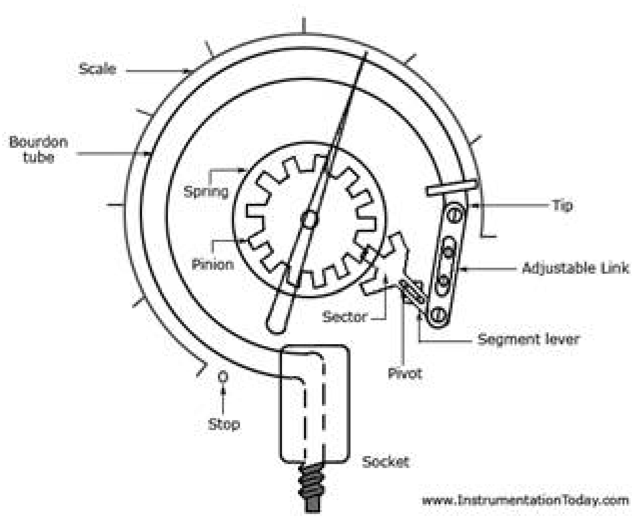
A single-limb liquid-column manometer has a larger reservoir instead of one side of the U-tube and has a scale beside the narrower column. The column may be inclined to further amplify the liquid movement.

Based on the use and structure following type of manometers are used

1. Simple Manometer
2. Micro manometer
3. Differential manometer
4. Inverted differential manometer

19.5 Bourdon Tube

It is most widely used as a pressure sensing element. It consists of a narrow bore tube of elliptical cross-section, sealed at one end. The pressure is applied at the other end which is open and fixed. The tube is formed into a curve, a flat spiral or a helix. When the pressure is applied, the effect of the forces is to straighten it so that the closed end is displaced. Fig.19.2 illustrates a C bourdon tube as used in direct indicating gauge which usually has an arc of 250°. The process pressure is connected to the fixed socket end of the tube while the tip end is sealed. Because of the difference between inside and outside radii, the bourdon tube presents different areas to pressure, which causes the tube to tend to straighten when pressure is applied. The resulting tip-motion is non-linear because less motion results from each increment of additional pressure. This non-linear motion has to be converted to linear rotational pointer response. This is done mechanically by means of a geared sector and pinion movement as shown in figure. The tip motion is transferred to the tail of the movement sector by the connector link. The angle between the connecting link and the sector tail is called the 'travelling angle'. This angle changes with tip movement in a non-linear fashion and so the movement of the pinion and, therefore, pointer is linear.



Bourdon Tube Pressure Gauge

Fig. 19.2 Bourdon pressure gauge

Frequently used bourdon tube materials include bronze, alloy and stainless steel. These elements are not ideally suited for low pressure, vacuum or compound measurements because the spring gradient of bourdon tube is too low.

The advantages of Bourdon tube pressure gauges are that they give accurate results. Bourdon tubes are simple in construction and their cost is low. They can be modified to give electrical outputs. They are safe even for high pressure measurement and the accuracy is high especially at high pressures. The Bourdon gauge coupled with a S.S, capsule type sensing bulb is used in milk homogenizer.

The Bourdon tube pressure gauges have some limitations also. They respond slowly to changes in pressure. They are subjected to hysteresis and are sensitive to shocks and vibrations. As the displacement of the free end of the bourdon tube is low, it requires amplification. More over, they cannot be used for precision measurement.

19.6 Elastic Diaphragm Gauges

As already discussed that when an elastic transducer, such as diaphragm, is subjected to a pressure, it deflects. This deflection is proportional to the applied pressure when calibrated. Elastic diaphragm gauges are built on this principle. The main part of the diaphragm gauge is a thin circular plate which is firmly fixed around its edges. The diaphragm may either be flat, dish, corrugated or corrugated as shown in Fig 19.3.

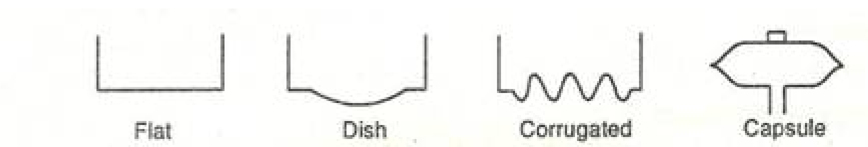


Fig. 19.3 Diaphragm elements

The top portion of the diaphragm is fixed with a bourdon tube of negligible weight. This bourdon tube is in-turn connected to a link – sector – pinion arrangement using mechanical means for displacement magnification. A pointer is connected to the pinion which makes it sweep over a pressure calibrated scale. The bottom side of the diaphragm is exposed to the pressure which is to be measured. Due to the applied pressure, the diaphragm deforms. That is the diaphragm tends to move upwards. This deformation of the diaphragm is proportional to the applied pressure. In a mechanical system, this deformation is magnified by the link – sector – pinion arrangement. That is, the linear displacement of the diaphragm is converted to a magnified rotary motion of the pinion. When the pinion rotates, it makes the pointer attached to it to assume a new position on the pressure calibrated scale which becomes a measure of the applied pressure. As the top side of the diaphragm is usually subjected to the atmospheric pressure, generally less than the applied pressure, the elastic diaphragm gauges usually read gauge pressure.

Fig. 19.4 Elastic diaphragm gauges

If the displacement is sensed by a secondary transducer such as a parallel plate capacitor, its movable plate is connected to the external circuit. In such arrangement the movable plate moves upwards, thus reducing the gap between the plates. This makes the capacitance of the capacitor becomes a measure of the applied pressure.

Elastic diaphragm gauges are they are used to measure medium pressure. But they can also be used to measure low pressures including vacuum. They are used to measure draft in chimneys of boilers and as level gauges for milk in silos, which are fitted at floor level.

Lesson 20

MEASUREMENT OF PRESSURE – II

20.1 Dead Weight Tester

The dead weight tester is basically a pressure producing and pressure measuring device. It is used to calibrate pressure gauges. The dead weight tester apparatus consists of a piston – cylinder combination fitted above the chamber as shown in Fig. 20.1.The chamber below the cylinder is filled with oil. The top portion of the piston is attached with a platform to carry weights. A plunger with a handle is provided to vary the pressure of oil in the chamber. The pressure gauge to be tested is fitted at an appropriate place as shown in the Fig. 20.1.

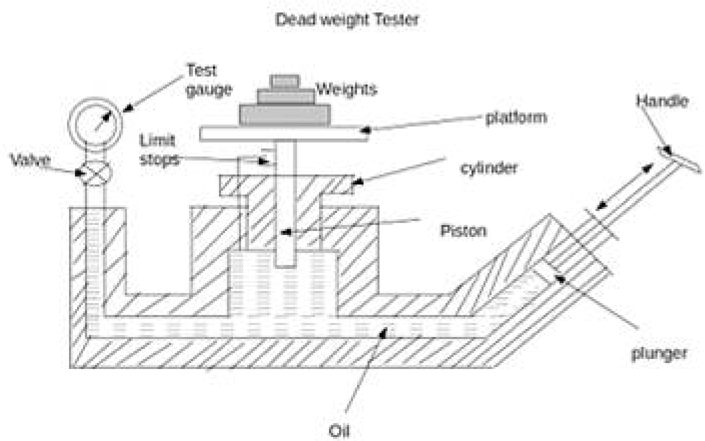


Fig. 20.1 Dead weight tester

To calibrate a pressure gauge, an accurately known sample of pressure is introduced to the gauge under test and then the response of the gauge is observed. In order to create this accurately known pressure, the valve of the apparatus is closed and a known weight is placed on the platform above the piston. By operating the plunger, fluid pressure is applied to the other side of the piston until the force developed is enough to lift the piston-weight combination. When this happens, the piston weight combination floats freely within the cylinder between limit stops. In this condition of equilibrium, the pressure force of fluid is balanced against the gravitational force of the weights plus the friction drag on the piston. The pressure which is caused due to the weights placed on the platform is calculated using the area of the piston. Now the pressure gauge to be calibrated is fitted at an appropriate place on the dead weight tester. Now the valve in the apparatus is opened so that the fluid pressure P is transmitted to the gauge, which makes the gauge indicate a pressure value. This pressure value shown by the gauge should be equal to the known input pressure P. If the gauge indicates some other value then the gauge is calibrated, adjusting the pressure on the gauge so that it reads a value equal to input pressure. Gauge tester is used to calibrate all kinds of pressure gauges and a wide range of pressure measuring devices. It is simple in construction and easy to use.

20.2 McLeod Vacuum Gauge

The McLeod Gauge is used to measure vacuum pressure. It also serves as a reference standard to calibrate other low pressure gauges. The components of McLeod gauge include a reference column with reference capillary tube. The reference capillary tube has a point called zero reference point. This reference column is connected to a bulb and measuring capillary and the place of connection of the bulb with reference column is called as cut off point. It is called so because if the mercury level is raised above this point, it will cut off the entry of the applied pressure to the bulb and measuring capillary. Below the reference column and the bulb, there is a mercury reservoir operated by a piston.

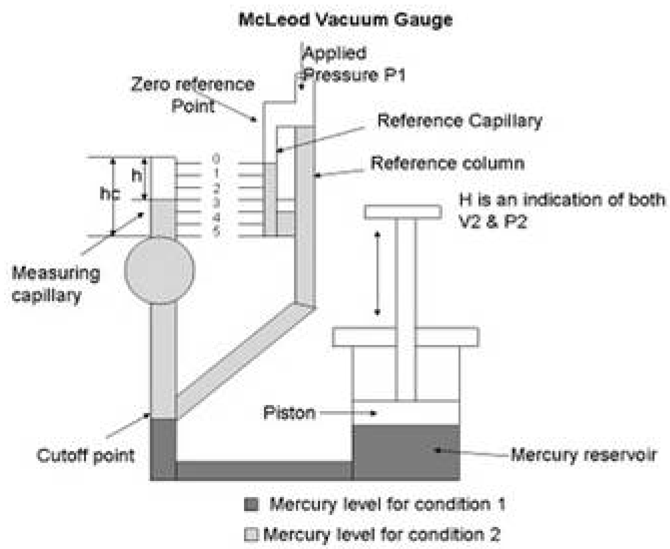


Fig. 20.2 McLeod vacuum gauge

The pressure to be measured (P_1) is applied to the top of the reference column of the McLeod Gauge as shown in Fig. 20.2. The mercury level in the gauge is raised by operating the piston to fill the volume as shown by the dark shade in the diagram. When the applied pressure fills the bulb and the capillary, again the piston is operated so that the mercury level in the gauge increases. When the mercury level reaches the cut-off point, a known volume of gas (V_1) is trapped in the bulb and measuring capillary tube. The mercury level is further raised by operating the piston so the trapped gas in the bulb and measuring capillary tube is compressed. This is done until the mercury level reaches the "Zero reference Point" marked on the reference capillary. In this condition, the volume of the gas in the measuring capillary tube is read directly by a scale besides it. That is, the difference in height 'H' of the measuring capillary and the reference capillary becomes a measure of the volume (V_2) and pressure (P_2) of the trapped gas. Now as V_1, V2, and P_2 are known, the applied pressure P_1 can be calculated using Boyle's Law given by:

$$P_1 V_1 = P_2 V_2$$

The working of McLeod Gauge is independent of the gas composition. A linear relationship exists between the applied pressure and height and there is no need to apply corrections to the readings. The limitations are that the gas whose pressure is to be measured should obey the Boyle's law and the presence of vapours in the gauge affects the performance.

20.3 Pirani Gauge

The Pirani gauge consists of a metal wire open to the pressure being measured. The wire is heated by a current flowing through it and cooled by the gas surrounding it. If the gas pressure is reduced, the cooling effect will decrease; hence the equilibrium temperature of the wire will increase. The resistance of the wire is a function of its temperature and by measuring the voltage across the wire and the current flowing through it, the resistance can be determined and so the gas pressure is evaluated.

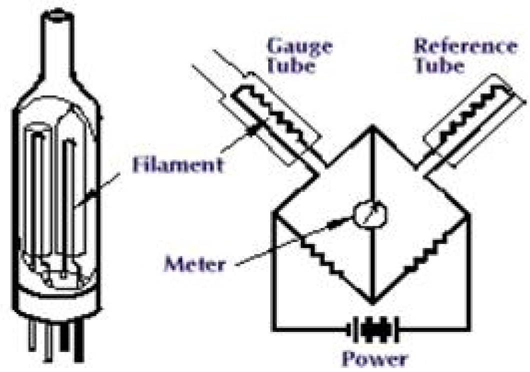


Fig. 20.3 Pirani gauge

Fig. 20.3 shows a Pirani gauge withtwo platinum alloy filaments which act as resistances in two arms of a Wheatstone bridge. One filament is the reference filament and the other is the measurement filament. The reference filament is immersed in a fixed-gas pressure, while the measurement filament is exposed to the system gas. A current through the bridge heats both filaments. Gas molecules hit the heated filaments and conduct away some of the heat. If the gas pressure around the measurement filament is not identical to that around the reference filament, the bridge is unbalanced and the degree of unbalance is a measure of the pressure. The unbalance is adjusted and the current needed to bring about balance is used as a measure of the pressure.

20.4 Ionization Gauge

These gauges are the most sensitive gauges for measuring very low pressures or high vacuum. The principle of operation of these gauges sensing pressure of gas by measuring the electrical ions produced when the gas is bombarded with electrons. Fewer ions will be produced by lower density gases. The electrons are generated by thermo ionic emission. These electrons collide with gas atoms and generate positive ions. The ions are attracted to a suitably biased electrode known as the collector. The current in the collector is proportional to the rate of ionization, which is a function of the pressure in the system. Hence, measuring the collector current gives the gas pressure.

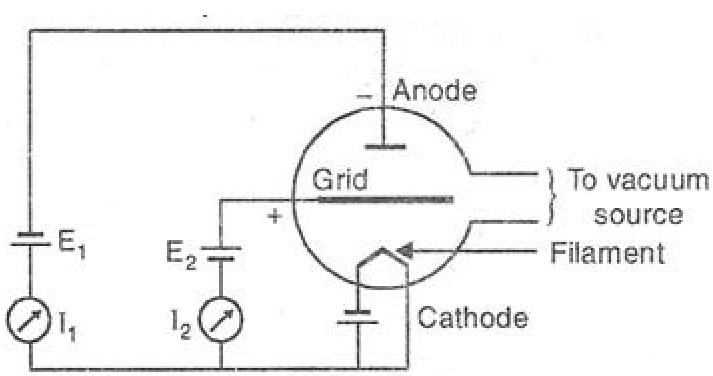


Fig. 20.4 Hot filament ionization gauge

The ionization gauges are of two types, the hot cathode ionization gauges and the cold cathode ionization gauges. In hot cathode (Fig. 20.4) version an electrically heated filament produces an electron beam. The electrons travel through the gauge and ionize gas molecules around them. The resulting ions are collected at a negative electrode. The current depends on the number of ions, which depends on the pressure in the gauge. The working of cold cathode gauge is also same with the only difference in the production of electrons which are produced in the discharge of a high voltage.

20.5 Thermal Conductivity Vacuum Gauge

The thermal conductivity vacuum gauge works on the principle that at low pressure the thermal conductivity of a gas is a function of pressure. The Fig. 20.5 shows the basic elements of a thermocouple vacuum gauge. It consists of a linear element which is heated by a known current source and is contact with a thermocouple attached to its centre. The heater element together with the thermocouple is enclosed in a glass enclosure. The vacuum system to be evaluated is connected to this enclosure. The heater element is supplied with a constant electrical energy. The temperature of the heating element is a function of heat loss to the surrounding gas, which in turn is a function of thermal conductivity of gas that is dependent on the pressure of the gas. The temperature is measured by the thermocouple and is calibrated to read the pressure of the gas.

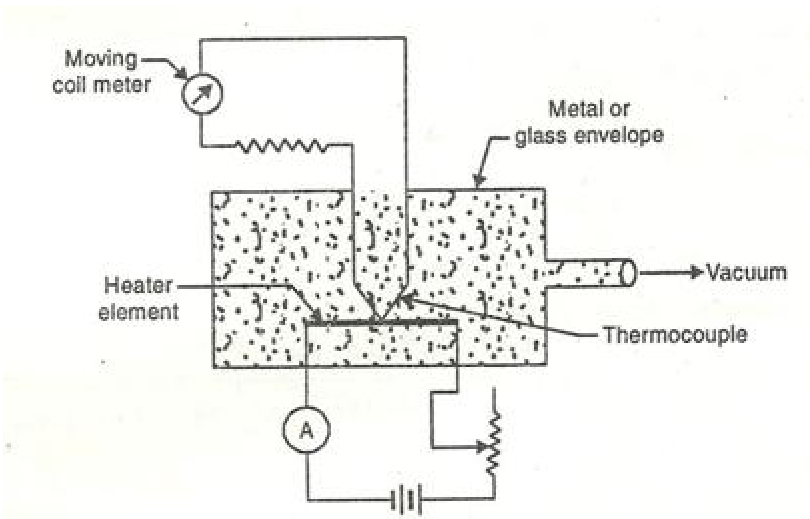


Fig. 20.5 Thermal conductivity vacuum gauge

This gauge is inexpensive and rugged in construction. It provides a convenient and continuous reading with a possibility of remote display. It however needs an individual and frequent calibration for different gases.

Lesson 21

MEASUREMENT OF PRESSURE – III

21.1 Strain Gauge Pressure Transducer

The strain gauge, as explained in Lesson 16, is a fine wire which changes its resistance when mechanically strained. A strain gauge may be attached to the diaphragm so that when the diaphragm flexes due to process pressure applied on it, the strain gauge stretches or compresses. This deformation of the strain gauge causes the variation in its length and cross sectional area due to which its resistance changes.

The small change in resistance that occurs in stain gauge is measured using a Wheatstone bridge. Fig. 21.1 shows the null type bridge circuit.

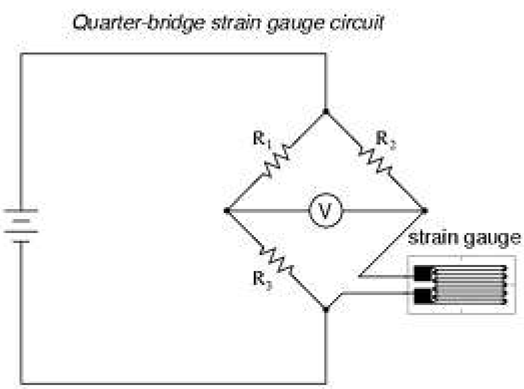


Fig. 21.1 Strain gauge resistance measurement using wheatstone bridge

The strain gauge represents the resistance R_4 whose value depends upon the physical variable being measured. Under balanced conditions;

$$R_4 = R_2 (R_3 / R_1)$$

The ratio of resistors R_3 and R_1 is fixed for a particular measurement. The bridge is balanced by varying the value of resistor R_2. Thus if three resistances are known the fourth may be determined.

21.2 Capacitive Pressure Transducer

The capacitance between two metal plates changes if the distance between these two plates changes. A variable capacitance pressure transducer is as shown in Fig. 21.2. The movable plate in the capacitor is the diaphragm. When the pressure is applied on the diaphragm it deflects and changes its position, due to which the distance between the plates is changed. The change in capacitance between a metal diaphragm and a fixed metal plate is measured and calibrated to the change in pressure. These pressure transducers are generally very stable and linear. They can withstand vibrations. But they are sensitive to high temperatures and are more complicated to setup than most pressure sensors. Their performance is also affected by the dirt and dust as they change the dielectric constant

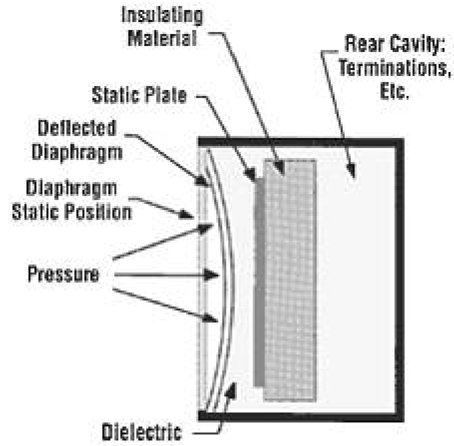


Fig. 21.2 Variable capacitance pressure transducer

21.3 Potentiometric Pressure Sensors

The potentiometric pressure sensor provides a simple method for obtaining an electrical output from a mechanical pressure gauge. The device consists of a precision potentiometer, whose wiper arm is mechanically linked to a Bourdon or bellows element (Fig. 21.3). The movement of the wiper arm across the potentiometer converts the mechanically detected sensor deflection into a resistance measurement, using a Wheatstone bridge circuit.

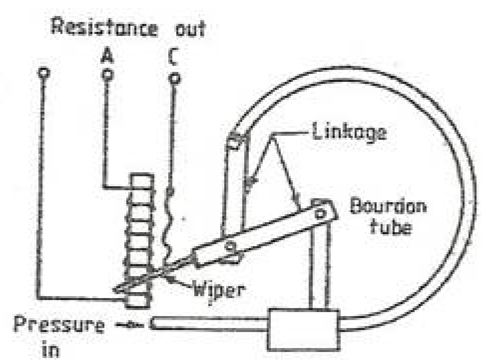


Fig.21.3 Potentiometric pressure sensors

Potentiometric pressure sensors drive a wiper arm on a resistive element. It consists of a potentiometer (a variable resistance) which is made by winding resistance wire around an insulated cylinder. A movable electrical contact, called a wiper slides along the cylinder, touching the wire at on point on each turn. The position of wiper determines the resistance between the end of the wire and the wiper. A potentiometric pressure sensor has a Bourdon tube as the detecting element that moves the wiper. As the wiper moves the change in resistance between the terminals is equivalent to the pressure sensed by the Bourdon tube.

These devices are simple and inexpensive. Resistance can easily be converted into a standard voltage or current signal. They also provide a strong output that can be read without additional amplification. This permits them to be used in low power applications. They are however used in low-performance applications, such as, dashboard oil pressure gauges.

For reliable operation the wiper must bear on the element with some force, which leads to repeatability and hysteresis errors. They have finite resolution, as the wiper moves from one turn to the next the resistance jumps from one value to the other. Errors also will develop due to mechanical wear of the components and of the contacts. Each time the wiper makes and breaks contact with a turn of wire, it causes an extra electrical signal, which is called noise. The addition of noise to the standard electrical signal makes the signal some what confusing. The amount of noise becomes greater as the potentiometer wears out. To reduce the noise some potentiometer are made by depositing a resistance material on a non-conducting ceramic surface. The wiper moves over this surface just as in a wire wound potentiometer, but the resistance can change continuously rather than in increments and is less electrical noise.

21.4 Inductive Pressure Transducer

Reluctance in a magnetic circuit is equivalent to resistance in the electric circuit. Whenever the spacing or coupling between two magnetic devices or coils changes, the reluctance between them also changes. Thus a pressure sensor can be used to change the spacing or coupling between two coils by moving one part of the magnetic circuit. This changes the reluctance between the coils, which in turn changes the voltage induced by one coil in the other. This phenomenon has been explained in the construction and working of LVDT in Lesson 17.

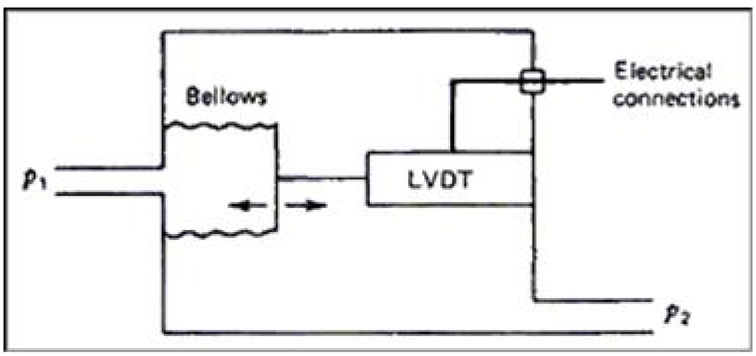


Fig. 21.4 Inductive pressure transducer

LVDTs and other inductive devices are used to convert the displacement motion of bellows or Bourdon tube into proportional electrical signals. Fig. 21.4 shows how an LVDT can be connected to the bellows so that the pressure measurement is converted directly from displacement to voltage. In addition, the displacement and pressure are nearly linearly related, and because the LVDT voltage is linear with displacement, the voltage and pressure are also linearly related.

Lesson 22

MEASUREMENT OF TEMPERATURE – I

22.1 Introduction

Temperature is a physical property of matter that quantitatively expresses the hotness or coldness of an object or a process. The objects of low temperature are cold, while various degrees of higher temperatures are referred to as warm or hot. For most temperature measurements the Celsius scale (°C) is used. The freezing point of water in the Celsius scale is 0°C and boiling point is 100°C. The Celsius scale has the same incremental scaling as the Kelvin scale, however, the 0°C on Celsius scale is equal to 273.15K. A few countries, most notably The United States, use the Fahrenheit scale for common purposes. On this scale the freezing point of water is 32 °F and the boiling point is 212°F.

Several methods have been developed for measuring temperature. Most of these methods depend upon measuring some physical property of a working material that varies with temperature. One of the most common devices for measuring temperature is the glass thermometer. Other important temperatures measuring transducers are the bimetallic strips, resistance temperature detector, thermocouples, thermistor, pyrometers etc.

22.2 Thermometers

22.2.1 Liquid-in-glass thermometer

This type of thermometer consists of a liquid-filled glass bulb and connecting micro-fine size of capillary tube. The bulb is filled with mercury or some other liquid, which acts as the working fluid. The increase in temperature causes the fluid in the bulb to expand and to contract as the temperature falls. Thus, the temperature can be determined by measuring the volume of the fluid. The differential expansion between the glass and the liquid causes the liquid to rise in the capillary. Such thermometers are usually calibrated so that one can read the temperature simply by observing the level of the fluid in the thermometer.

A variety of liquids, such as mercury, alcohol, toluene and pentene are used in thermometer construction to cover diverse ranges of temperature. These thermometers are available in many configurations, such as, the read out thermometers, the digital readout thermometers and the recording thermometers which uses a pen on a rotating drum to continuously record temperature readings.

22.2.2 Gas filled thermometer

This type of thermometer has a Bourdon tube connected to a hollow bulb by a capillary tube. The system is filled with a gas which is usually nitrogen or helium. The pressure in the system follows the gas law and the indication of temperature is obtained from the Bourdon tube. The temperature-pressure-motion relationship is nearly linear. The effect of atmospheric pressure is minimized by filling the system to a high pressure. These systems are also available with liquid filled designs. In such a system, the volume change of the liquid actuates the Bourdon tube for temperature indication.

22.2.3 Vapor-pressure thermometer

The construction of such thermometer is same as that of the gas filled thermometer. Only difference is instead of gas pressure they utilize the vapor pressure of certain stable liquids to measure temperature. Since a nonlinear relationship exists between the temperature and the vapor pressure, the motion of the bourdon tube is greater at the upper end of the vapor-pressure curve.

22.3 Bimetallic Thermometers

The bimetallic thermometer is based on the principle that all metals change in their dimension, that is, expand or contract whenever there is a change in temperature. The rate at which this expansion or contraction takes place, depends on the 'temperature co-efficient of expansion' of the metal. This temperature coefficient of expansion is different for different metals. This difference in thermal expansion rates is used to produce deflections which are proportional to temperature changes.

A bimetallic strip is thus used to convert a temperature change into mechanical displacement. The device consists of two strips of different metals which expand at different rates as they are heated. Invar is commonly used as the low expansion metal. It is an iron-nickel alloy containing 36% nickel and its co-efficient of thermal expansion is around 1/20th of the other metals. Brass is used as high expansion material. These strips are joined together throughout their length by riveting, brazing or welding so that there is no relative motion between them. The different expansions of both the metals force the flat strip to bend one way if heated, and in the opposite direction if cooled below its initial temperature. The metal with the higher coefficient of thermal expansion is on the outer side of the curve when the strip is heated and on the inner side when cooled. Thus an increase in temperature will result in the deflection of the free end of the strip as shown in the Fig. 22.1. This deflection is linear and can be related to temperature changes.

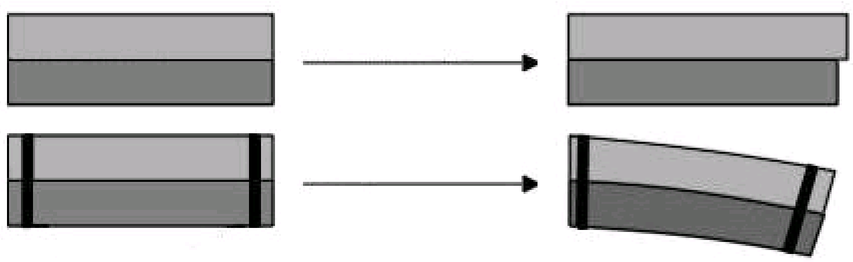


Fig. 22.1 Bimetallic strip

Different common forms of bimetallic sensors include Flat, Spiral or Cantilever, type. Metals used in bimetallic strips are Brass and Nickel-iron alloyed with chromium & manganese as high expansion metal and Invar (alloy of nickel & iron) as low expansion metal. The bimetallic thermometers are simple, robust and inexpensive. Their accuracy is between +or- 2% to 5% of the scale. The only limitation is that when regularly used, the bimetallic may permanently deform, which will introduce errors. They are not recommended for temperature above 400'C. The bimetallic strip is also used in control devices. The spiral strip is used in air conditioning thermostats. A helical strip put inside a SS tube as sensor is used for horizontal milk tanks.

22.4 Resistance Thermometer or Resistance Temperature Detector (RTD)

The electrical resistance of some metals change with change in temperature. Resistance thermometer utilizes this characteristic. With the increase of temperature, the electrical resistance of some metals increases in direct proportion to the rise of temperature, so if the electrical resistance of a wire of known and calibrated material is measured, the temperature of the wire can be determined.

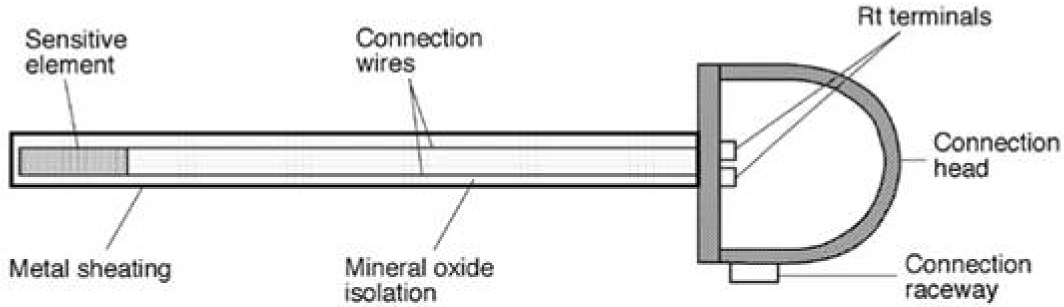


Fig. 22.2 Resistance thermometer

In this type of thermometer, a temperature sensitive resistance element is fabricated in a suitable probe form to insert in a medium whose temperature is to be measured. Resistance elements are generally long, spring like wires enclosed in a metal sheath as shown in Fig. 22.2. The conductors used for resistance thermometer are platinum, nickel of various purities. Platinum is the most commonly used metal for RTD elements due to its chemical inertness, nearly linear and large enough temperature versus resistance relationship and stability. The resistance element is surrounded by a porcelain insulator which prevents short circuit between wire and the metal sheath. Two leads are attached to each side of the platinum wire. When this instrument is placed in a liquid or a gas medium whose temperature is to be measured, the sheath quickly reaches the temperature of the medium. This change in temperature causes the platinum wire inside the sheath to heat or cool, resulting in a proportional change in the wires resistance. This change in resistance can be directly calibrated to indicate the temperature.

Resistance of metal at temperature ‘t’ is given by:

$$R_t = R_0 (1 + \alpha_0 t)$$

Where:

R_t = Resistance at t°C

R_0 = Resistance at 0°C

α_0 = Temperature coefficient of resistance at 0°C

The common configuration of RTD has the platinum resistance element range in length from 1/8" to 3". There are many options. The standard resistance is 100 Ω at 0° C. The most common outside diameter is 1.5 to 12.5 mm. The 316 Stainless steel is commonly used tubing material. RTDs are available in 2, 3 and 4 wire configuration and 3 wire configurations are the most common for industrial applications. Teflon and fiberglass are the standard wire insulation materials. Three wire RTDs normally use a Wheatstone bridge measurement circuit to measure the resistance. Now when sensing element resistance changes, the wheat-stone bridge becomes unbalanced and thus galvanometer will give deflection which can be calibrated to give suitable temperature scale.

Resistance thermometers possess high accuracy of measurement. They have a wide temperature range from –200 to 650°C. They are fast in response and have good reproducibility. The limitations include their high cost, requirement of a bridge circuit and power supply.

They are widely used in HTST pasteurizer and spray dryers.

22.5 Thermocouples

The working principle of a thermocouple depends on the thermo-electric effect. When two dissimilar metals are joined so as to form a closed circuit, there are two junctions where they meet each other. If one of those junctions is heated, then, a current flows in the circuit which can be detected by a galvanometer. The amount of the current produced depends on the difference in temperature between the two junctions and on the characteristics of the two metals. This was first observed by Seebeck in 1821 and is known as Seebeck effect.

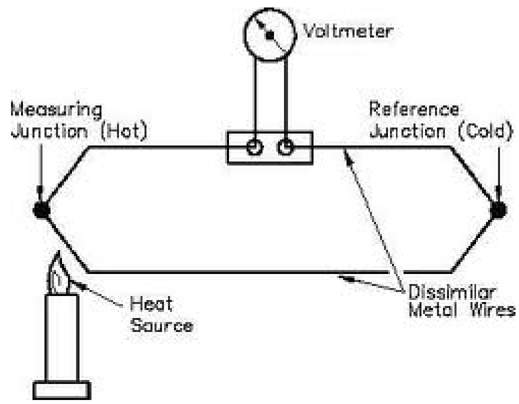


Fig. 22.3 Thermocouple

Instrument based on the above principle is known as thermocouple. Fig. 22.3 shows a thermocouple made from two different kinds of metals. The wires are joined at the ends which form two junctions – a measuring junction and a reference junction. Heating the measuring junction produces a voltage greater than the voltages across the reference junction the difference between two voltages is measured and voltmeter reading is converted to its corresponding temperatures. The conversion table is generally supplied by the thermocouple manufacturers. There are various types of thermocouples which are used in industries, viz. Copper constantan, iron constantan, chromel alumel, platinum rhodium and chromels-constantan.

Thermocouples can be classified in two categories

i) Base metal thermocouples

ii) Rare metal thermocouples

Base-metal thermocouples use the combination of pure metals and alloy of iron, copper and nickel and are used up to 1450 K. These types of thermocouples are more sensitive, cheaper and have nearly linear characteristics. But operating range is low and vulnerable to oxidation. Rare-metal thermocouples use a combination of pure metal and alloys of platinum, tungsten, rhodium, molybdenum etc. which are used for higher temperature measurement up to 2500^{o}C. The characteristics of thermocouples are given in the Table 22.1.

Table 22.1 Characteristics of thermocouples

Sr. No.	Type	Thermocouple	Useful temperature range (^{o}C)	Sensitivity ($\mu V/^{o}C$)

1.	T	Copper-Constantan	-180 to 400	20-60
2.	J	Iron-Constantan	-180 to 850	50-55
3.	K	Chromel-Alumel	-200 to 1300	40-55
4.	E	Chromel-Constantan	-180 to 850	50-80
5.	R	Platinum-Platinum/13%Rhodium	0 to 1600	5-12
6.	S	Platinum-Platinum/10%Rhodium	0 to 1400	5-12

When high sensitivity is required, thermocouples are attached in series. This is known as thermopile.

The thermocouples used in industries consist of a protective well and head across the measuring junction to protect thermocouples from harmful atmospheres, corrosive fluids, mechanical damage and to support the thermocouples to avoid damages in pressurized systems. Thermocouples can be connected in parallel to provide the average temperature in a system. They can also be used to measure the difference between two temperatures. A single thermocouple can be utilized by two separate measuring instruments, with proper precautions. The e.m.f. charts and tables for various thermocouples are available. The thermocouple tables are based upon the reference junction temperature of 0°C, therefore, a direct conversion from the tables can be made only when an ice bath is used at the reference junction. If it is not possible to maintain the reference junction temperature at 0°C a correction factor must be applied to the milli volt values shown in the thermocouple tables.

Thermocouples are cheaper than RTD. They are rugged in construction and can be used for wide temperature range. No external power is required. They are simpler to use than resistance thermometers. There is no need of a bridge circuit. They have extremely wide temperature range from – 270°C to 2800°C. Their electrical output is adaptable to a variety of readout and / or control devices. They can process long transmission distances.

However they have some disadvantages, such as, their instability, low and non-linear output signal. They need to hold reference junction temperatures constant or compensation for any deviations. They require signal amplification for many applications and need expensive accessories for control applications

Example: A T type thermocouple has linear calibration between 0 and 500 ^oC with emf at maximum temperature (reference temperature ^oC) equal to 21.5 mV. Determine the correction to be made to the indicated emf, if the cold junction temperature is 25 ^oC. If the indicated emf is 9.0 mV, determine the temperature of the hot junction.

Solution:

Sensitivity = 2.15 / 500 = 0.043 mV/ ^oC

E correction = 0.043 x 25 = 1.075 mV

Difference of temperature between hot and cold junction = 9.0/0.043 = 209.30 ^oC

The reference junction temperature = 25 ^oC

∴ The hot junction temperature = 209.30+25 = 234.3 ^oC

Lesson 23

MEASUREMENT OF TEMPERATURE – II

23.1 Thermistor

Thermistor or thermal resistor is thermal sensitive resistor. Its resistance changes with temperature. Depending upon the way it responds to temperature, the change in resistance character divides the thermistor into two types. The positive temperature coefficient (PTC) thermistor is that in which resistance of the thermistor increases with the increase in temperature. These thermistors are usually made from Barium, Titanate. The negative temperature coefficient thermistor (NTC) in which, resistance of thermistor decreases with increase in temperature. In broad term a thermistor is semiconductor component that behave as a resistor with usually, negative temperature coefficient of resistance. In some cases, resistance of a thermistor at room temperature may decrease to 5 percent for each one degree Celsius rise in temperature.

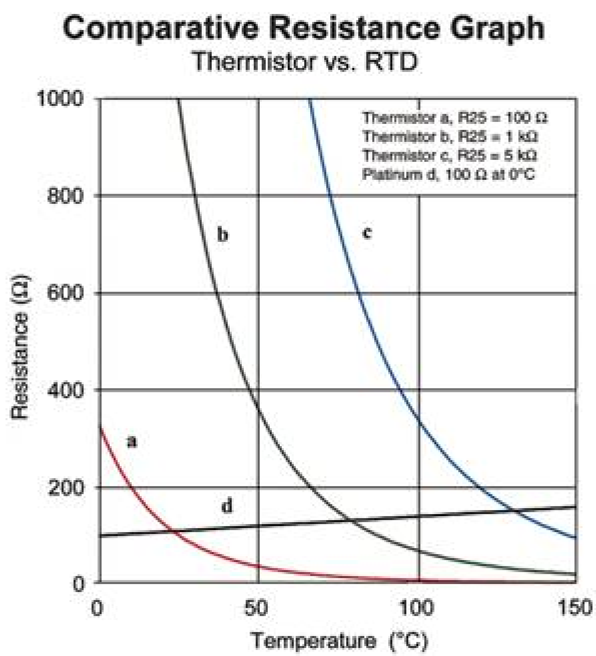


Fig. 23.1 resistance-temperature characteristics of RTD and thermistors

Fig. 23.1 gives the comparison between the changes in resistance due to change in temperature for both the thermistors and the RTD. Positive resistance-temperature correlation in RTD and high negative correlation for thermistors is clearly illustrated. Thermistors are composed of sintered mixture of metallic oxides such as manganese, nickel, cobalt, copper, iron and uranium. They are available in a number of configurations, as shown in Fig. 23.2. Most familiar is the bead type, usually glass coated. They can also be made into washers, discs or rods. Different types of thermistors configurations are shown in the figure below. Thermistors can also be encapsulated in plastic, cemented, and soldered in bolts, encased in glass tubes, needles or a variety of other forms. These assemblies serve to support the sensors, protect against damage to the wires, direct flow across the unit uniformly, permit sealing of conduits or flow lines, and provide for easier handling.

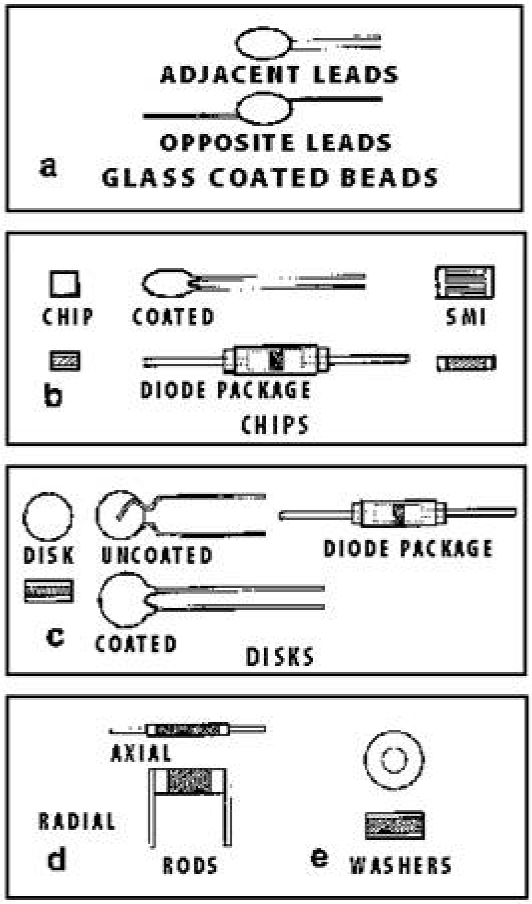


Fig. 23.2 Different types of thermistor configurations

Bead thermistors are the smallest thermistors which are in the form of heads with a diameter of 0.15mm to 1.25mm. This is the most familiar type of thermistor and is usually glass coated. Beads may be sealed in the tips of solid glass rods to form probes. Glass probe have a diameter of about 2.5mm. The probes are used for measuring temperature of liquids.

Thermistors are also made into discs by pressing material under high pressure into cylindrical flat shapes with a diameters ranging from 2.5mm to 25mm. they are mainly used for temperature control. The washer type thermistors are usually long cylindrical units. Leads are attached to the ends of the rods. The advantage of this type is, it produce high resistance under moderate power.

To measure temperature with a thermistor, it is placed in the environment whose temperature is to be measured. As the temperature of the substance or environment increases, the resistance of the thermistor decreases, and vice-versa. This change in thermistor resistance can be detected which will be the measure of the temperature of the substance. Generally, the thermistor is placed as one leg of a wheat-stone bridge circuit. At balanced condition, when there is no change in temperature the galvanometer indicates zero. As the temperature increases or decreases, the resistance of the thermistor also decreases or increases due to which the wheat-stone bridge circuit becomes unbalanced. Thus an electric current flows through the galvanometer which indicates on the calibrated scale. The deflection of the galvanometer can be calibrated as a temperature scale.

All types of thermistors are of small sizes and have fast response. These are most sensitive and are suitable for narrow spans. The thermistor is at least 10 times more sensitive than the platinum resistance element. Since the resistance is a function of absolute temperature, cold junction compensation is not necessary. Due to the large resistance, the contact or lead-wire resistance is considered as negligible as compared to the resistance of thermistors. The cost of thermistors is very low. The major limitations of using thermistors are that they have a highly non-linear resistance-temperature characteristic and the problems of self-heating effects necessitate the use of much lower current levels than those with metallic sensors. The temperature-resistance characteristic of a thermistor is of exponential type and is given by:

$$R = R_0\, exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

Where, R_0 is the resistance at the reference temperature T_0 (Kelvin)

R is the resistance at the measured temperature T (Kelvin)

β is the experimentally determined constant for the given thermistor material.

The values of β usually lie between 3000 and 4000 K depending on the formulation or grade.

Example: A thermistor used for temperature measurement has β=3140 K and the resistance at 27°C is 1050 Ω. If the resistance of the thermistor is measured as 2330 Ω, find the temperature.

Solution. The resistance-temperature characteristic of the thermistor is given by:

$$R = R_0\, exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

As per the data given in the statement:

$R_0 = 1050\ \Omega$

$T_0 = 273 + 27 = 300$ K

$\beta = 3140$ K

$R = 2330\ \Omega$

Taking the logarithm of both sides of equation and rearranging we get,

$$\frac{1}{T} = \frac{In\ R - LnR_0}{\beta} + \frac{1}{T_0}$$

$$= \frac{7.754 - 6.957}{3140} + \frac{1}{300}$$

$= 3.587 \times 10^{-3}$

= 278.78 K

23.2 Pyrometers

When temperature to be measured is high and physical contact with the hot body or medium is not possible, pyrometers are used to measure the temperature. Pyrometers are used under conditions where corrosive vapours or liquid could damage the thermocouples, resistance thermometer and Thermistor. The pyrometers also find applications where the temperatures are above the range of thermocouple. There are two types of pyrometers which are commonly used, viz. radiation pyrometers and optical pyrometers.

23.2.1 Radiation pyrometer

The radiation pyrometer measures the heat emitted by a hot object. The radiation pyrometers operate on the principle that the energy radiated from a hot body is a function of its temperature. Basically, thermal radiations are electromagnetic radiation lies in the wavelength region from about 0.1 to 100 micrometer. The energy radiated by the hot body whose temperature is measured is focused by the lens to the detector. The detector is usually a thermocouple and the detector output is given to a PMMC instrument, digital display or recorder.

There are two principles used for the construction of radiation temperature measuring devices. The *Total radiation pyrometer* is one in which the total radiant energy from a heated body is measured, and the *Selective radiation pyrometer* in which the radiated energy from the heated body is measured at a given wavelength.

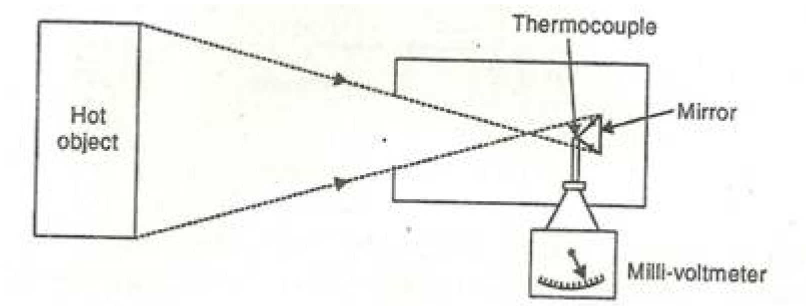


Fig. 23.3 Radiation pyrometer

A total radiation pyrometer is shown in Fig. 23.3. Radiations from hot object is collected and focussed on a thermocouple with the help of a mirror. This increases the thermocouple temperature and generates an emf. The rise in temperature is the function of amount of radiation emitted by the hot object. This instrument has a high speed of response and is primarily used to measure the temperature in the range of 700 to 2000°C. Direct contact is not necessary with the object whose temperature is to be measured.

23.2.2 Optical pyrometer

The principle of temperature measurement by brightness comparison is used in optical pyrometer. A colour variation with the growth in temperature is taken as an index of temperature. The optical pyrometer compares the brightness of image produced by temperature source with that of reference temperature lamp. The current in the lamp is adjusted until the brightness of the lamp is equal to the brightness of the image produced by the temperature source. Since the intensity of light of any wave length depends on the temperature of the radiating object, the current passing through the lamp becomes a measure of the temperature of the temperature source when calibrated. The current in the lamp is adjusted until the brightness of the lamp is equal to the brightness of the image produced by the temperature source. The main parts of an optical pyrometer are shown in the Fig. 23.4.

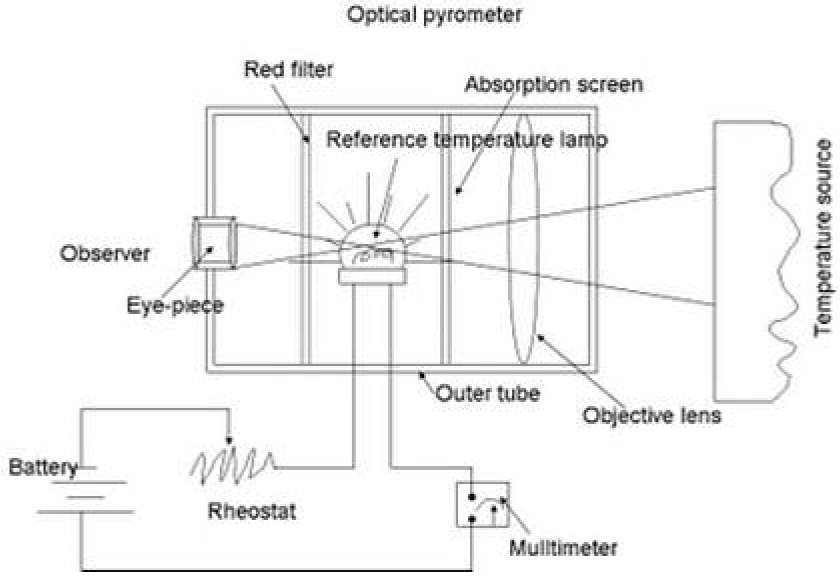


Fig. 23.4 Optical pyrometer

The instrument has an eye piece at one end and an objective lens at the other end. A power source (battery), rheostat and multimeter to measure current are connected to a reference temperature bulb. An absorption screen is placed in between the objective lens and reference temperature lamp. The absorption screen is used to increase the range of the temperature which can be measured by the instrument. The red filter between the eye piece and the lamp allows only a narrow band of wavelength of around 0.65µm.

When a temperature of the source is to be measured, the radiations from the source are focused onto the filament of the reference temperature lamp using the objective lens. The eye piece is adjusted in such a way that the filament of the reference temperature lamp is in sharp focus and the filament is seen super imposed on the image of the temperature source. The lamp current is then controlled. The filament will appear dark as in first image (A) of the Fig. 23.5, if the filament is cooler than the temperature source. The filament will appear bright as in second image (B) of the figure if the filament is hotter than the temperature source. If the filament and temperature source are in the same temperature the filament will disappear (C).

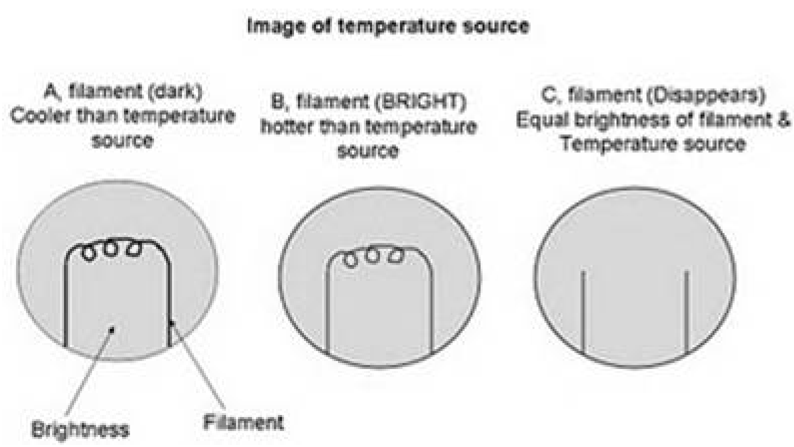


Fig. 23.5 Images of temperature source in Optical pyrometer

Hence the lamp current is controlled until the filament and the temperature source have the same brightness which will be noticed when the filament disappears on the superimposed image of the temperature source. At this instance, the current flowing through the lamp which is indicated by the multimeter connected to the lamp becomes a measure of the temperature of the temperature source when calibrated.

Optical pyrometers are used to measure temperature of furnace and hot bodies. Physical contact of the instrument is not required to measure temperature of the temperature source.
Accuracy is high (± 5°C) and is easy to operate.

Lesson 24

MEASUREMENT OF LIQUID LEVEL

24.1 Introduction

The measurement of liquid level in tanks and vessels is essential requirement of processing industries. This can be achieved through mechanical means by employing float and measuring the displacement. In another method provides the direct conversion to liquid level position to electrical signal. In this case the liquid level is determined indirectly. The measurement is generally done by two conversions; the first conversion usually is liquid level to a displacement through a float in a liquid or a spring loaded plate in contact with the surface in the case of granular solids. This displacement is then converted into an electrical signal by a secondary transducer connected to float or plate. There are, however, many applications other methods like optical or economic means or gamma rays are used.

24.2 Sight Glass or Gauge Glass

Sight glass is used for continuous indication of liquid level in a tank. As shown in Fig. 24.1, it consists of a graduated tube made up of toughened glass which is connected to the interior of the tank in which level is to be measured at the bottom. The level of liquid in the sight glass is at the same level of that of liquid in the tank. As the liquid in the tank rises or falls, the level in the sight glass also rise or falls accordingly. Thus the level of liquid in the sight glass gives the level of the liquid in the tank. It is not necessary that the liquid in the sight glass be same as the liquid in the tank. Any other liquid in the sight glass can also be used. The standard practice is not to use the glass tube of length more than 90 cm. The use of sight glass is common in boilers to indicate the liquid level. The only drawback is that the reading of the level is only available at the tank, which is sometimes not convenient. The viscous liquid may sometime clog the sight glass tube. Since sight glasses are located outside the tanks, the liquid in the sight glass may freeze in clod weather even though the liquid inside the tank does not, and thus, it may cause error in the reading. Accuracy and readability depends on cleanliness of glass and fluid.

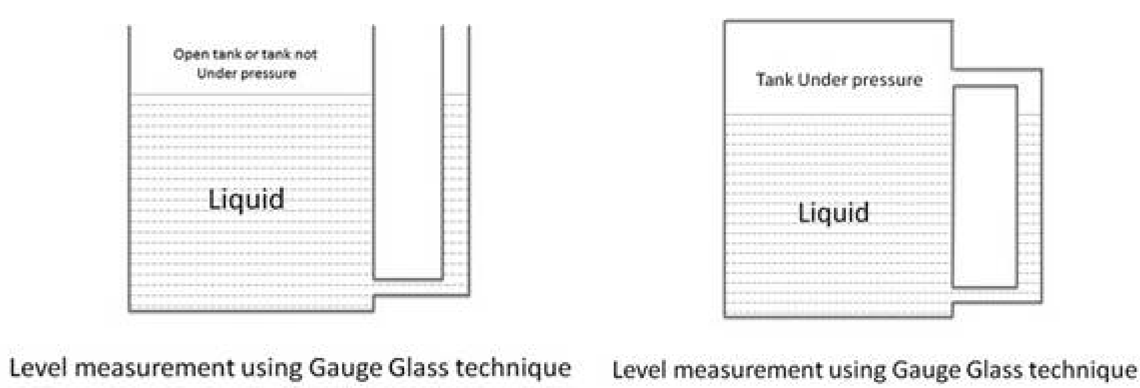


Fig. 24.1 Sight Glass or gauge Glass

24.3 Float Type Level Indicator

It consists of a float which rests on the surface of the liquid. The movement of the float is transmitted to a pointer through suitable mechanism. The pointer indicates the liquid level on a calibrated scale. Various types of floats are used which include hollow metal spheres, cylindrical or disc shaped floats. The float type level indicators are low in cost, reliable and operate over a large temperature range. A float type level indicator for indicating level in a tank is shown in Fig. 24.2a.

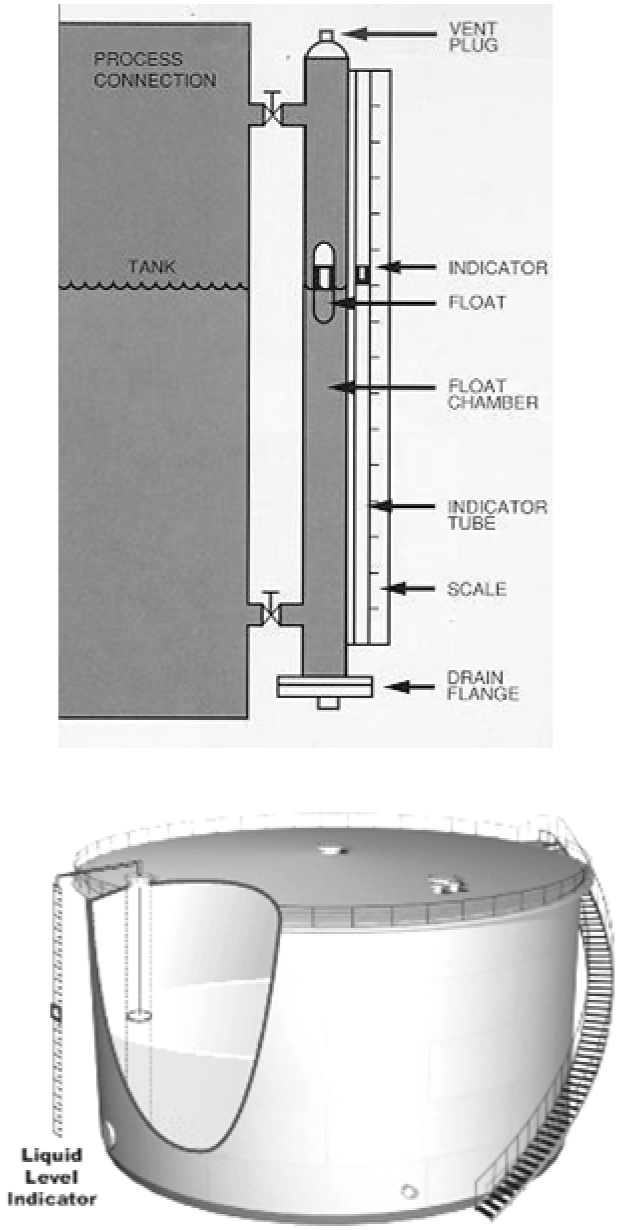


Fig. 24.2 (a) Float type level indicator

The indication of liquid level can be transmitted to a distant place by using hydraulic transmission system also. A float can be used to operate a voltage potential divider (Fig. 24.2 b).

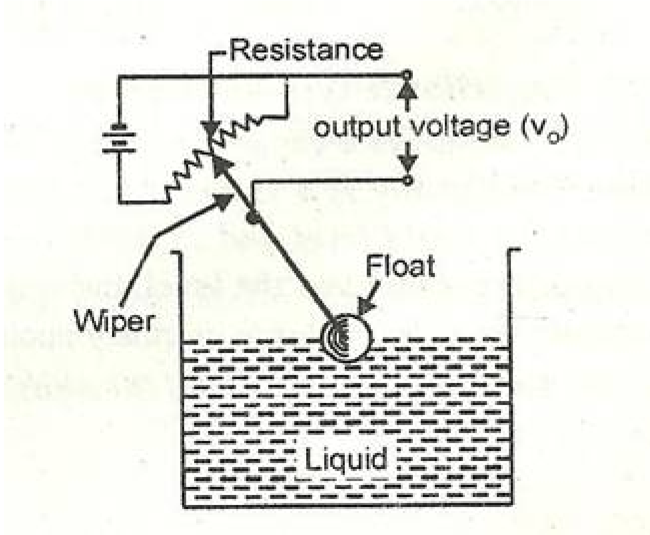


Fig. 24.2(b) Float type level indicator

As the liquid level rises in the tank, the float is raised. Its arm causes the wiper to move over the potential divider whose output terminals are connected to a voltmeter. As a float rises, a greater part of the potential divider is included in the output circuit giving an increased output voltage. Therefore, the output voltage is proportional to the liquid level. The output terminals from the potential divider may also be taken to a remote for display and control.

24.4 Electric Methods

The electric transducers used for level measurements include the resistive, inductive, and capacitive transducers.

24.4.1 Resistive method

This method uses mercury as a conductor and a number of contact rods are placed in such a way that their tips are at various liquid levels in the vessel. As liquid level increases, the rising level of mercury above the datum, shorts successive resistors and increases the value of conductance, thereby indicating the value of liquid height directly. Where there is a need for a fairly continuous record of the level, more and more contact rods can be added, with separate signal outputs for each contact rod. Such a system uses low voltage to eliminate danger to the operators and to prevent arcing at the contact points and the signal thus obtained can be transmitted to have indication at the desired place. These transducers can be used in pressurized containers also. The unit is simple to calibrate. However in order to have a step-less indication of the liquid level, an extremely large number of contact rods are needed. This system also encounters difficulties if there is saturated vapour above the liquid phase. Also any change in the conductivity of the liquid may result in errors.

24.4.2 Inductive method

The inductive level transducers are mainly used for measurement of level of liquids which are conductive. The method employed is based on variable permeability. The arrangement, as shown in Fig. 24.3, uses two coils L_1 and L_2 wound around a steel tube containing the liquid. The coils are connected in series through a resistance and the circuit is energized by an alternating current source. The inductance of each coil is initially equal. One of the coils acts as the search coil and is set at a predetermined level. The inductance of the search coil changes rapidly as the conducting liquid moves into the plane of the coil. The method works well because the tape material is weakly magnetic and the liquid metal is a conductor which allows eddy currents to flow in it. The relationship between the output voltage and the liquid level is essentially non-linear.

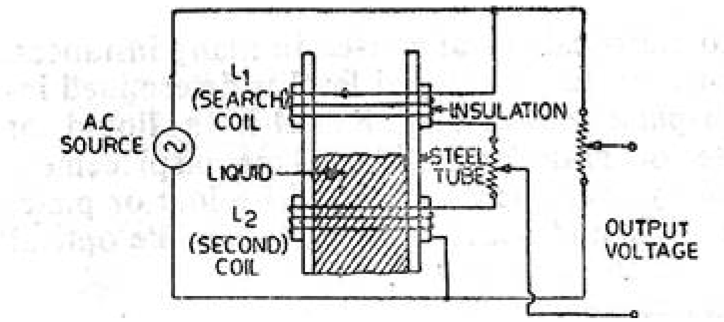


Fig. 24.3 Inductive level indicator

24.4.3 Capacitive methods

Change in capacitance with change in area of plates, distance between plates and the dielectric constant has already been explained in Lesson 16. All these principles are employed in detecting the level of liquids and solids in a container.

i) Variable area method

The variable area capacitive transducer is used for measurement of levels of both solids and liquids. The electrical conducting container containing the materials is used as one connection point of the transducer. The other point is a metal rod completely covered by insulating material inside the container. The insulating material acts as the dielectric medium and the capacitance varies linearly with the height of the material. The relationship is given by:

$$C = \frac{2\pi\varepsilon h}{\log_e(d_2/d_1)} F$$

Where, ε = Permittivity; F/m,

h = Height of material; m,

d_1 = Diameter of the metal rod; m, and

d_2 = External diameter of the insulator; m.

The container should be earthed to avoid any danger of electric shock to the personnel and to prevent any errors due to external metallic objects.

ii) Capacitive voltage divider method

In case, the conductivity of a liquid is high, its surface can be used as one electrode of the capacitor. The other electrode is a fixed reference plate parallel to the surface of the liquid. A system incorporating these features is shown in Fig. 24.4. This uses an auxiliary electrode P_1 placed at a fixed distance above the reference electrode P_2. The two electrodes P_1 and P_2 are electrically insulated from each other. An AC voltage is applied between the liquid and the electrode P_1.

Potential of electrode P_2 with respect to earth $E_0 = E_A \frac{C_1}{C_1 + C_2} V$

Capacitance C_2 is inversely proportional to the distance between the liquid surface and P_2. Thus the output voltage decreases with rise of liquid level and therefore the relationship between them is non-linear.

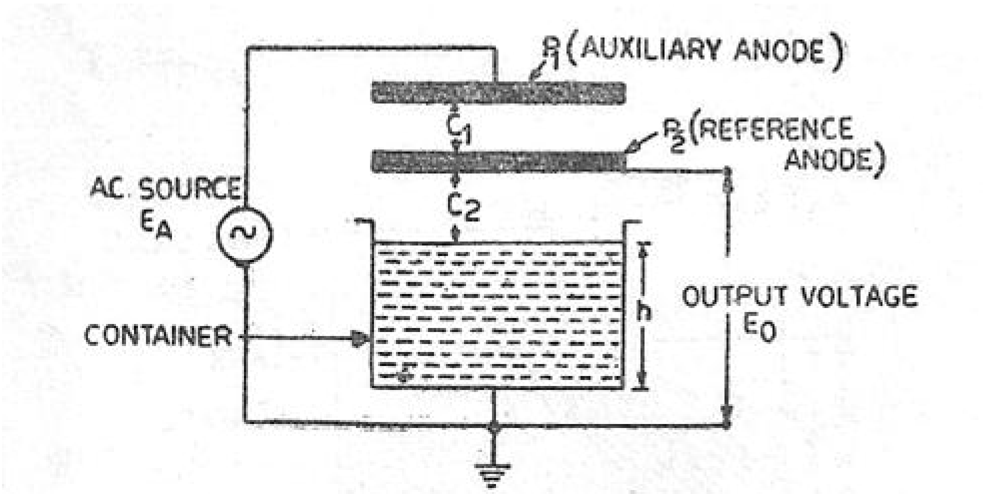


Fig. 24.4 Capacitive voltage divider liquid level gauge

iii) Variable dielectric constant method

If the liquid is non-conducting it can be used as a dielectric in a capacitor. The arrangement for measurement of liquid level for non-conducting liquids is illustrated in the Fig. 24.5. An insulated metal electrode firmly fixed near and parallel to the metal wall of the tank. If the liquid is non-conductive, the electrode and the tank wall form the plates of a parallel plate capacitor with the liquid in between them acting as the dielectric. If the liquid is conductive the rod and the liquid form the plates of the capacitor, and the insulation between them is the dielectric. Where the tank is not of metal, two parallel insulated rods or electrodes, kept at a fixed distance apart are used. The two rods act as two plates of a parallel plate capacitor.

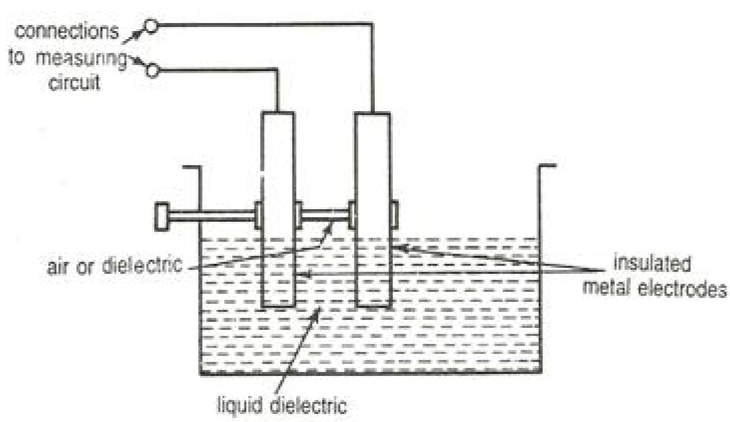


Fig. 24.5 Dielectric liquid level gauge

The capacitance of this capacitor depends, among other factors, upon the height of the dielectric between the plates. The higher the liquid level, the greater is the capacitance. The lesser the height, the smaller is the capacitance. Thus, the capacitance is proportional to the height of the liquid in the tank. The capacitance in the above cases may be measured and this measured capacitance is an indication of liquid levels.

24.5 Measurement of Liquid Level with Gamma Rays

Gamma rays are being increasingly used for detection of liquid levels. A source of gamma rays is placed at the bottom of the tank. At the top of the tank there is a sensor of gamma rays like a Geiger Müller tube. If the tank is empty the intensity of gamma radiation reaching the sensor will be more. But if there is some liquid in it, some of the rays will be absorbed by the liquid and the radiations reaching the tube will be small, and hence its output is small. The higher the level of the liquid, the greater is the absorption and hence lesser will be the output of the Geiger Müller tube. Thus the output of Geiger Müller tube is inversely proportional to the liquid level. The output of the Geiger Müller tube is in the form of pulses which may be counted by a counter. Thus the counter may be directly calibrated in terms of the liquid level.

24.6 Ultrasonic Method

An ultrasonic transmitter receiver can be mounted on the top of tank for measurement of level of either solids or liquids. The beam is projected downwards by the transmitter and is reflected back by the surface of the solid or liquid contained in the tank. The beam is received by the receiver. The time taken by the beam is a measure of the distance travelled by the beam. Therefore, the time ‘t’ between transmitting and receiving a pressure pulse is proportional to the distance ‘h’ between the ultrasonic set and surface of the contents of the tank. As the level in the tank is more, the distance ‘h’ will be less and accordingly the time ‘t’ will be less. The time is then the measure id level of liquid in the tank.

24.7 Level Transmitter for Milk Silos

A pressure gauge is mounted at the bottom of the milk silo. The gauge measures the pressure at the bottom which is proportional to the level. A differential bellow type elastic element and pneumatic amplifier is used for measurement and indication, since the pressure difference with different column heights can be low.

Lesson 25

MEASUREMENT OF FLOW

25.1 Introduction

Flow measurement is the quantification of bulk fluid movement. Flow rate and the quantity is one of the important process variable requiring frequent measurements. Flow rate measurement plays an important role in plant material balancing, quality control and the operation of any continuous process. In engineering contexts, the volumetric flow rate is usually given the symbol 'Q', and the mass flow rate, the symbol '$\dot{m}$'. Flow measurements find applications in transportation of fluids and slurries, gas and water supply systems, irrigation system and industrial process control. Many accurate and reliable methods are available for the flow measurements.

25.2 Orifice and Venturi Flow Meters

Differential pressure flow meters, including the orifice meter, venturi meter, and flow nozzle meter, are widely used to measure pipe flow rate. In each case, a constriction in the flow path causes a pressure drop across the meter. The relationship is derived from Bernoulli's theorem which states that in a flowing stream, the sum of the pressure head, the velocity head and the elevation head at one point is equal to their sum at another point. The pressure head is the vertical distance through which the liquid would rise in an open end tube as a result of static pressure. The pressure drop across the meter is thus measured and correlated with flow rate. These devices are also called the variable head flow meters. They measure the volume rather than the mass flow rates, the latter however can be computed.

There are several designs of such flow meters, based on the mode of restriction in the flow line, such as, orifice plate or venturi tube. The orifice plates are the simplest and cheapest form of element which is inserted in the line and the pressure drop across it is measured. The Venturi effect is the reduction in fluid pressure that results when a fluid flows through a constricted section of pipe as shown in Fig. 25.1. It consists of a tube with a short, narrow center section and widened, tapered ends, so that a fluid flowing through the center section at a higher velocity than through an end section creates a pressure differential that is a measure of the flow of the fluid.

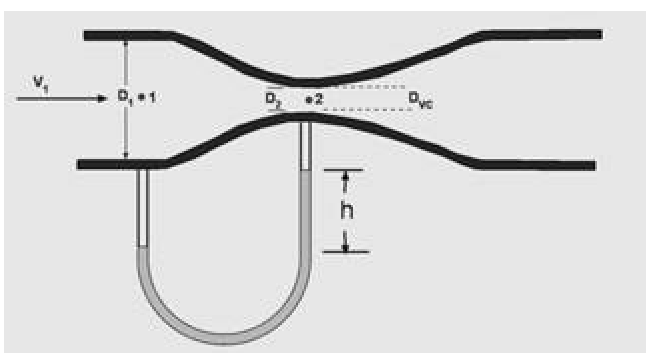


Fig. 25.1 Venturi flow meter

The venturi tube are made up of cast iron or steel and are built in several forms, such as long form, short form and eccentric form etc. they are available in sizes from 100 mm to 800 mm.

25.3 Rotameter

The term *rotameter* derives from early versions of the floats, which had slots to help stabilize and center them and which caused them to rotate. The operating principle of rotameter is based on a float of given density's establishing an equilibrium position where, with a given flow rate, the upward force of the flowing fluid equals the downward force of gravity. It is achieved by rising in the tapered tube with an increase in flow until the increased annular area around it creates a new equilibrium position. By design, the rotameter operates in accordance with formula for all variable-area meters, directly relating flow rate to area for flow. Rotameters are the most widely used type of variable-area flow meter. When the flow is constant, the float stays in one position that can be related to the volumetric flow rate. That position is indicated on a graduated scale. Note that to keep the full force of gravity in effect, this dynamic balancing act requires a vertical measuring tube.

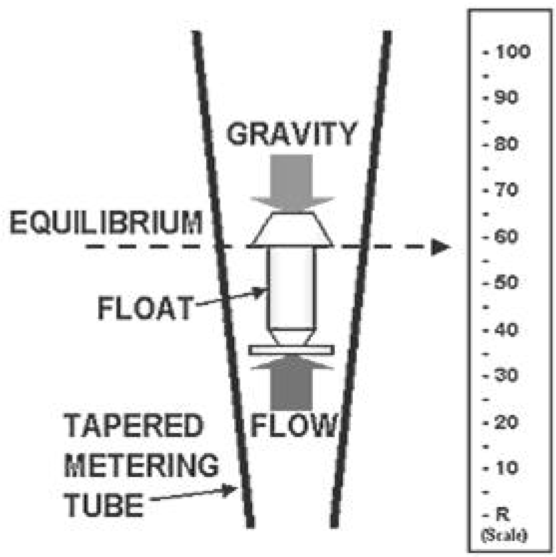


Fig. 25.2 Rotameter

The gradually increasing diameter of the tapered tube provides an increase in the annular area around the float. The volumetric flow rate is given by the following equation:

$$Q = kA\ (gh)^{1/2}$$

where:

Q = volumetric flow rate, litres per hr.

K = constant

A = annular area between the float and the tube wall

g = acceleration due to gravity

h = pressure drop (head) across the float

With ‘h’ being constant in a variable area meter, we have area ‘A’ as a direct function of flow rate ‘Q’. Thus, the taper of the rotameter tube can be designed so that the height of the float in the tube is a measure of flow rate.

The two basic components of every rotameter as shown in Fig. 25.2 are the *tapered metering tube* and the *float.* Tube sizes vary from $^1/_{16}$ to 4 inch. Arbitrary linear scale graduations can be put for display of 0%–100%. The scale calibration can be made in terms of direct reading of a specific gas or liquid for flow rates of the fluid being measured. The metal body of the rotameter is rigidly constructed to maintain tube alignment. The end fittings provide process pipe connections, either threaded female or flanged with O-rings or packing glands for sealing at both ends of the tube. Provisions are also made for easy removal of the glass tube for cleaning.

In Glass Tube rotameters, the tapered metering tube made of borosilicate glass. The Metal Tube rotameters are designed for applications where the temperature or pressure exceeds the limits of glass tubes. Flow rate is indicated by a pointer on an indicating scale by means of a magnet inside the float, magnetically linked to the pointer. Metal tube meters are generally made of corrosion-resistant type 316 stainless steel. They are well suited to measuring steam flow where conditions or regulations prevent the use of glass, and useful as well where the nature of the fluid would preclude reading a float position. Plastic tube rotameters are the cost-effective alternative to glass or metal meters for a wide variety of fluid measurements. In this tube is made up of a single piece of clear acrylic that is practically unbreakable in most industrial process applications. Floats are available in a variety of shapes and materials, with varying densities that can be used to change the meter's range and to resist corrosion from the measured fluid. The float materials include Type 316 stainless steel, tantalum, Monel, Teflon, and PVC.

To select the correct rotameter for a given application, it is important to have the data with regard to the nature of the fluid, the fluid density and viscosity at the specified operating temperature, operating and maximum temperature and pressure and the minimum and maximum flow rates.

25.4 Ultrasonic Flow Meters

The ultrasonic flow meters use transducers to transmit and/or receive ultrasonic waves in the process of pipe flow measurement. The ultrasonic waves have the frequency > 20 kHz. Two types of ultrasonic flow meter are in common use to measure pipe flow rate. They are the doppler ultrasonic flow meter and the transit time ultrasonic flow meter.

i) Doppler ultrasonic flow meter

In a doppler ultrasonic flow meter, as shown in Fig. 25.3 (a), one transducer transmits ultrasonic waves and the other transducer receives ultrasonic waves. The fluid for which pipe flow rate is being measured must have material like particles or entrained air that will reflect ultrasonic waves. The frequency of the transmitted beam of ultrasonic waves will be altered, or shifted, due to being reflected by the air bubbles or particles. The frequency shift, which is proportional to the fluid flow rate through the meter, is measured by the receiving transducer. The receiving transducer can thus generate a signal that is proportional to flow rate.

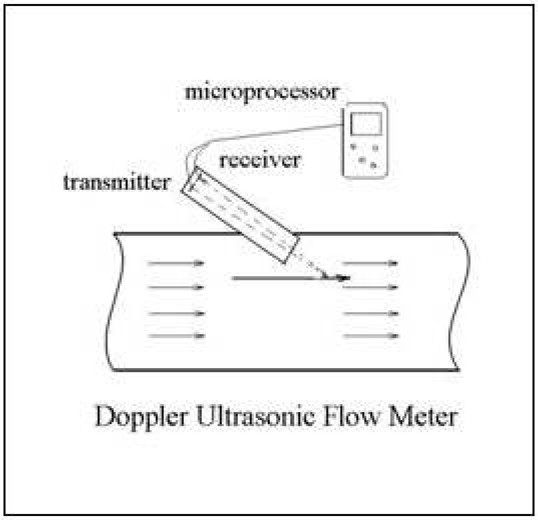


Fig. 25.3 (a) Doppler ultrasonic flow meter

ii) Transit time ultrasonic flow meter

This type of meter measures the difference in travel time for pulses transmitted against the flow and pulses transmitted in the direction of the flow rate. In the transit time ultrasonic flow meter shown in Fig. 25.3 (b), both transducers serve as transmitter and receiver of ultrasonic waves alternately.

The two transducers are mounted on the outside of the pipe so that one is a known distance upstream of the other. A pulse will be transmitted by the downstream transducer, for example, and it will be detected by the upstream transducer, giving the 'transit time' for upstream flow. Then the process will be reversed and the upstream transducer will transmit a pulse to be detected by the downstream transducer, to give a 'transit time' in the direction of flow. A microprocessor is typically used to calculate the pipe flow rate based on the difference between the downstream transit time and the upstream transit time.

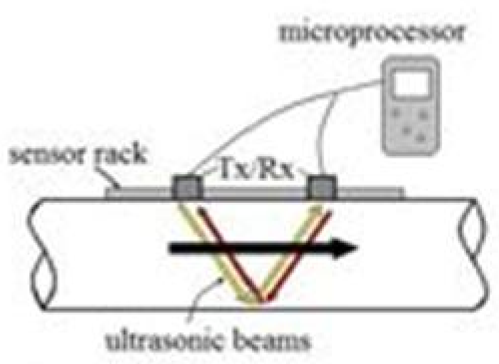


Fig. 25.3 (b) Transit time ultrasonic flow meter

The doppler and transit time ultrasonic flow meter both cause negligible pressure drop when in use for pipe flow measurement. The effect of fluid viscosity on pipe flow rate measurement is negligible for both types. The doppler ultrasonic flow meter can be used to measure the pipe flow rate of dirty liquids and slurries. A transit time ultrasonic flow meter can be used for pipe flow measurement of both liquids and gases. Both the doppler and transit time ultrasonic flow meter have a cost that is relatively high in comparison with other types of pipe flow meter.

25.5 Turbine Flow Meter

The turbine flow meter (Fig. 25.4) translates the mechanical action of the turbine rotating in the liquid flow around an axis into a user-readable rate of flow in litres per min. The turbine tends to have all the flow traveling around it. The turbine wheel is set in the path of a fluid stream. The flowing fluid impinges on the turbine blades, imparting a force to the blade surface and setting the rotor in motion. When a steady rotation speed has been reached, the speed is proportional to fluid velocity.

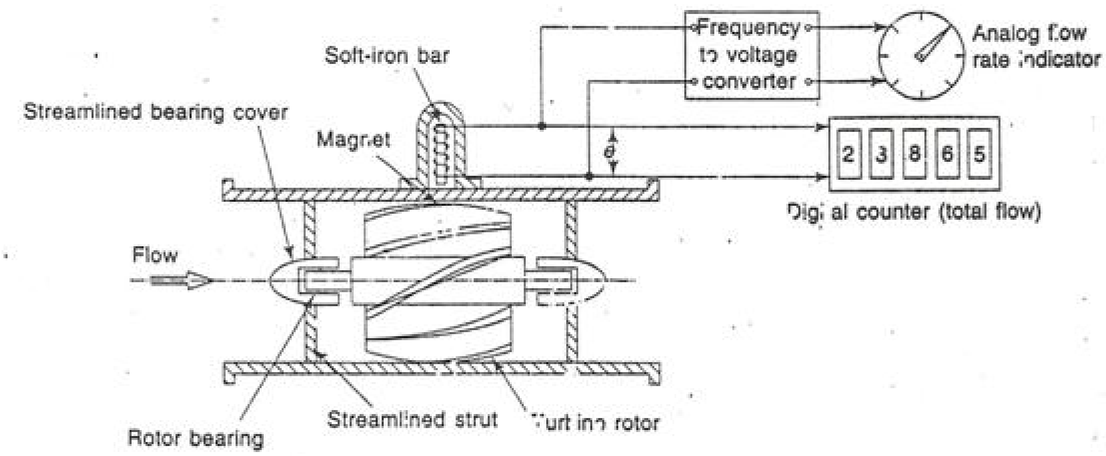


Fig. 25.4 Turbine flow meter

Turbine flow meters are used to measure total quantity of flow. They can also be used for the measurement of natural gas and liquid flow. The flow direction is generally straight through the meter, allowing for higher flow rates and less pressure loss than displacement-type meters. Strainers are generally required to be installed in front of the meter to protect the measuring element from gravel or other debris that could enter the water distribution system. Turbine meter bodies are commonly made of bronze, cast Iron, or ductile iron. Internal turbine elements can be plastic or non-corrosive metal alloys.

25.6 Target Flow Meter

The drag force on a body (target plate) becomes the measure of the flow rate. The drag force on the target plate can be measured by attaching a suitable force measuring transducer. Cantilever beam arrangement with bonded strain gauges is commonly used to measure the drag force developed on the target plate.

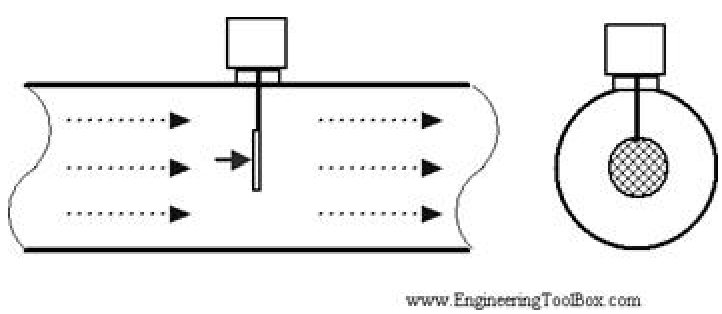


Fig. 25.5 Target flow meter

Target Flow Meter can be used for any type of liquid, gas, steam or cryogenics. There are no moving parts such as bearings etc. to wear out causing failures. It can be used for any size of line from 12mm and up, with any type of mounting. It can accept bi-directional flow, where signal polarity indicates direction of flow. The calibration of target flow meter, however, must be verified in the field.

25.7 Rotary Vane Flow Meter

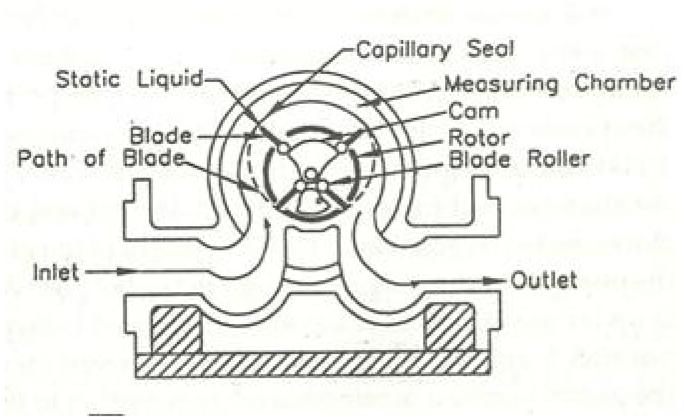


Fig. 25.6 Rotary vane flow meter

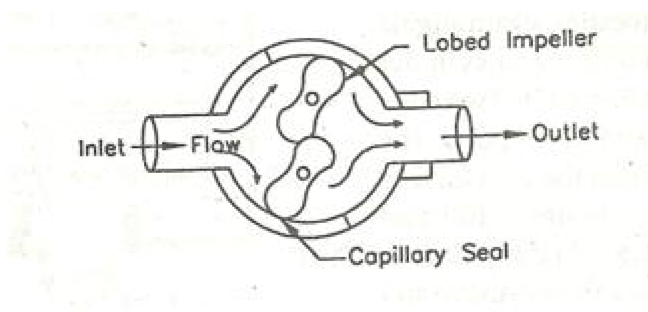


Fig. 25.7 lobe type flow meter

25.8 Electro Magnetic Flow Meter

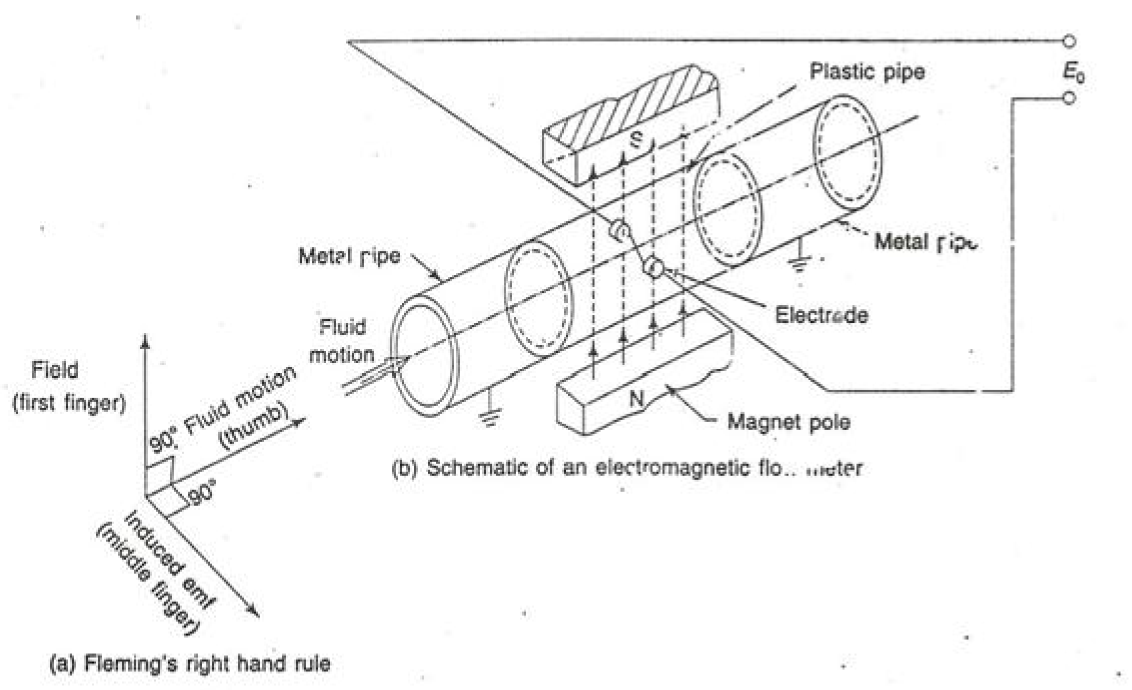


Fig. 25.8 Electromagnetic flow meter

Lesson 26

MEASUREMENT OF SPEED AND HUMIDITY

26.1 Introduction

Speed is a rate variable defined as a time-rate of motion. Common form and units of speed measurement include: linear speed expressed as m/s or km/h and angular speed of a rotating component usually expressed as revolution per minute or rad/s. Measurement of rotational speed has acquired prominence over the linear speed. Continuous measurement of linear speed is usually made in terms of angular speed and then converted in to linear speed of a reciprocating part. RPM measurement is important when controlling or monitoring the speed of motors, conveyors, turbines, etc.

Several methods for the measurement of rotational speed are available. Angular measurements are made with a device called tachometer. The word "tachometer" is derived from the Greek words *tachos*, meaning "speed," and *metron*, meaning "to measure." Tachometer may be broadly classified in to two categories: mechanical tachometer and electrical tachometer.

26.2 Mechanical Tachometer

Mechanical tachometer employs only mechanical parts and mechanical movements for the measurement of speed. Most common type of mechanical tachometers are hand tachometer and the revolution counter.

26.2.1 Hand-held tachometer

The hand-held tachometer is shown in Fig. 26.1. It consists of a worm gear attached to spindle. The worm gear meshes with a spur gear that in turn moves a pointer on calibrated dial to indicate revolutions. Generally two dials are placed in position. In one dial each division represents one revolution of the spindle while on the other on division represents the one revolution of the former. A stop watch is attached to the revolution. For measuring the speed the tachometer is manually pressed at the contact point at the rotating shaft whose speed is to be measured. The spindle starts rotating and provides motion to the pointer through the worm gear indicating the total revolution of the shaft in a given period of time noted with the help of a stop watch. The average speed is then calculated.

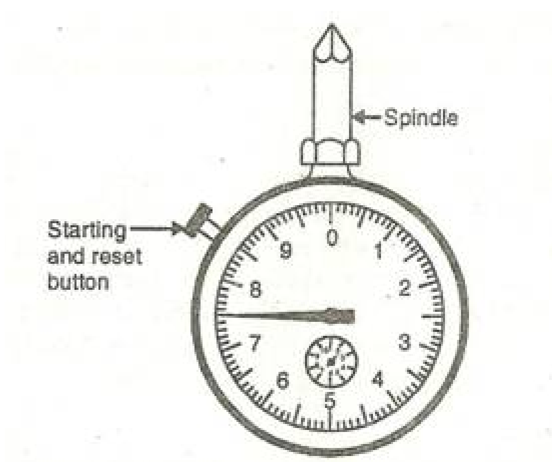


Fig.26.1 Hand-held tachometer

In another arrangement an automatic timer is used to indicate the speed directly in rpm on the calibrated dial. The spindle operates when brought in contact with the shaft. The counter however does not function until the start button pressed to start the watch and engage the automatic clutch. Depressing the starting knob also serves to wind the timer watch. The revolution counter automatically gets disengaged after a short period of time. These tachometers can measure up to a speed of 30000 rpm with an accuracy of 1%. The revolution counter is used with a timing device to determine the number of revolutions in a measured length of time. Thus it measures an average rotational speed over a short interval of time rather than instantaneous rotational speed.

Digital tachometers have become more common as they give numerical readings instead of using dials and needles.

26.2.2 Centrifugal tachometer

The principle of operation of centrifugal tachometer is that the centrifugal force is proportional to the speed of rotation. The schematic diagram of a centrifugal tachometer is shown in Fig. 26.2. Two small weights in the form of balls are attached to the spindle and rotate along with the spindle. As the spindle rotates the centrifugal force is developed by these balls. This centrifugal force compresses the spring and a grooved collar or sleeve attached to its free end slides on the spindle and its position can be calibrated with the spindle speed. Through a series of linkages, motion of the sleeve is amplified and communicated to the pointer of the instrument to indicate speed. Certain attachments are provided with the spindle to indicate the linear speed. These types of instrument can be used up to 40000 rpm. They are also used in the speed governors to break circuit for speed control. These tachometers have a distinct advantage over revolution counter in that they indicate whether or not the speed remains substantially constant.

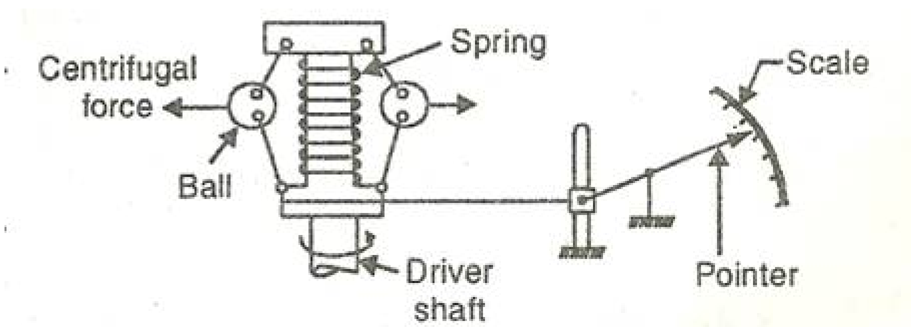


Fig. 26.2 Centrifugal tachometer

26.2 Electrical Tachometer

Electrical tachometers provide the advantages of electrical transducers and in view of this they are preferred over mechanical tachometer. They depend for its indication upon an electrical signal generated in proportion to the rotational speed of the shaft. Depending upon the type of transducer, electrical tachometers have been constructed in the variety of designs. For example *commutated capacitor tachometer* based on alternately charging and discharging capacitor controlled by speed of rotating member. In *eddy current type tachometer* the rotating shaft rotates a permanent magnet and this induces eddy currents in a disc. The eddy current produces a torque that rotates the disc against the torque of a spring. The disc turns in the direction of rotating magnetic field until the torque developed equals that of spring. A pointer attached to the disc indicated the rotational speed on a calibrated scale. The *tachometer generator* has been developed on the principle that the e.m.f. generated depends upon the magnetic field and the speed. If for the field the permanent magnetic pole pieces are used then the generated voltage only depends upon the speed. The tachogenerator may be AC or DC type of tachometer depending upon the taking out means of e.m.f. generated. Hence the speed can be calculated by measuring the e.m.f. generated.

26.3 Photoelectric Tachometer

The photoelectric tachometer utilizes a rotating shaft to intercept a beam of light falling on a photo conductive cell. The shaft has an intermittent reflecting (white) and non reflecting (black) surfaces. When a beam of light hits the reflecting surface on the rotating shaft, light pulses are obtained and the reflected light is focused on to the photoelectric cell. The frequency of light pulses is proportional to the shaft speed and so will be the frequency of electric output pulses from the photo electric cell.

Another similar method consists of an opaque disc mounted on the rotating shaft as shown in Fig. 26.3. The disc has a number of evenly spaced peripheral holes. A light source is placed on one side of the disc and a light sensor on the other side of the disc inline with it.

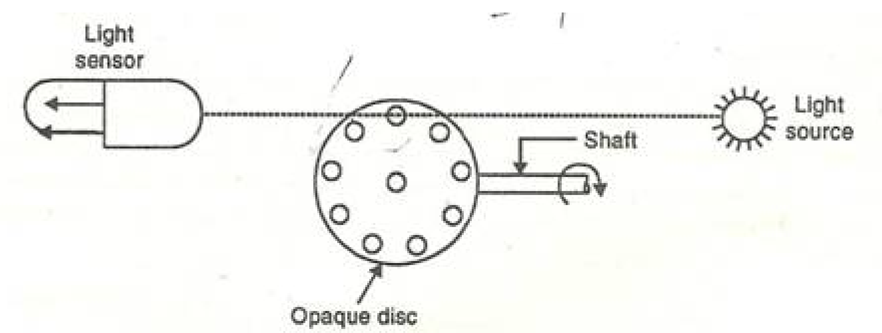


Fig. 26.3 Photoelectric tachometer

When the opaque portion is between the light source and the light sensor, no light falls on the light sensor and there is no output. At the time when a hole appears between the two, the light illuminates the sensor and a pulse of voltage is produced. The frequency of pulse generation is determined by the number of holes in the disc and its speed of rotation. Since the number of holes is fixed in the disc the frequency of the output is calibrated to measure the rotational speed of the rotating shaft. Photoelectric tachometer is a digital instrument. It however requires replacing the light source periodically.

26.4 Measurement of Humidity

Humidity is due to the presence of water vapours in a gas or air. It is generally measured in terms of absolute humidity, relative humidity or the dew point temperature. The *absolute humidity* is the mass of water vapour present in the unit mass of the moist air or gas. The *relative humidity* is the ratio of the water vapour pressure of the in a mixture of gas to the water vapour pressure in a saturated mixture the same temperature. The *dew point temperature* is the saturation temperature of the gas water mixture. At dew point the relative humidity is 100%.

The instrument which measures the humidity directly is known as hygrometer. It can be calibrated to indicate the absolute or relative humidity. The most common humidity measuring instrument is the *sling psychrometer* which has two thermometers. The dry bulb thermometer measures the ambient temperature where as the wet bulb thermometer measures the temperature of saturated air i.e. the reduction in temperature due to evaporative cooling. The relative humidity is determined from the two temperatures readings with the help of psychrometric chart.

The other most frequently used hygrometers are the resistive hygrometer, impedance type hygrometer and the dew point recorder.

26.5 Resistive Hygrometer

A typical resistive type hygrometer is shown in Fig. 26.4. It consists of two metal wire grids which are bonded to a plastic sheet. Over this whole there is a coating of moisture sensitive chemical lithium chloride, which exhibits a change in resistivity with the humidity.

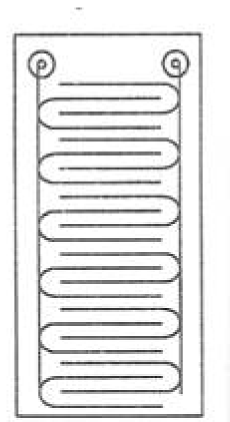


Fig. 26.4 Resistive hygrometer

If the sensing unit is exposed to variation in humidity, then there is a change in resistance. At higher relative humidity the lithium chloride absorbs more moisture and the resistance decreases. The resistance of the sensing unit is measure by applying AC to the Wheatstone bridge. The DC voltage is not applied as it tends to break down the lithium chloride.

26.6 Impedance Type Hygrometer

It measures the moisture content of the sample by means of a probe whose impedance is a function of the vapours present in the air or gas. A typical impedance type probe is shown in Fig. 26.5. The probe consists of an aluminum strip, which is anodized to form porous layer of aluminum oxide. A thin coat of gold is applied over the aluminum oxide. Leads from the gold and aluminum electrodes connect the sensing element to the external circuitry. Water vapours penetrate the gold layer and equilibrate over the aluminum oxide. The number of water molecules absorbed over the aluminum oxide is a function of water vapour present in the sample. This contributes towards an increase in the conductivity of the aluminum oxide. The total probe impedance is the reciprocal of the probe conductivity.

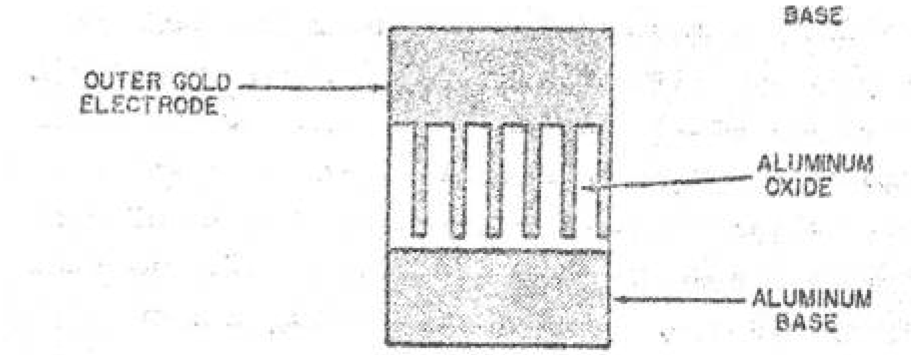


Fig. 26.5 Impedance type hygrometer

26.7 Dew Point Recorder

This method uses a resistive hygrometer. As shown in Fig. 26.6, it consists of a thin metal tube covered with a glass cloth saturated with lithium chloride. A double winding of silver is made over the glass cloth. The winding is connected to AC supply. The salt picks up moisture from the surrounding and electric conductivity between the wire changes. At low humidities the current flow through winding is small and the temperature rise of the winding is low. Conversely at high moisture the current flow though the winding is large and the temperature of the coil is high. The inside temperature of the cell is measured with the help of thermometer and the absolute humidity or the dew point temperature is determined. The instrument has a fast response and can be used to measure the dew point with an accuracy of ±2%.

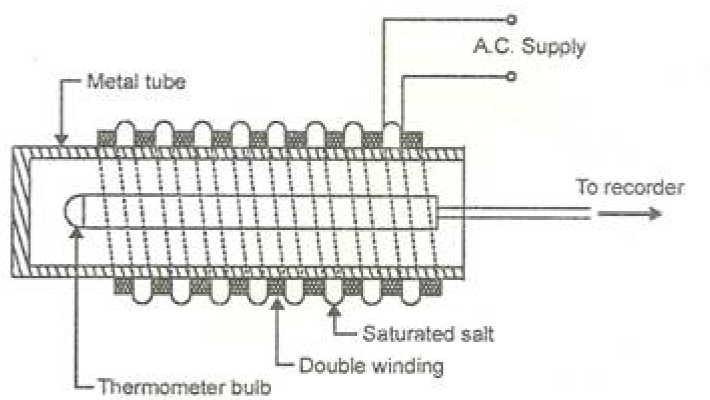


Fig. 26.6 Dew point recorder

26.8 Hair Hygrometer

Hair and other organic materials absorb moisture from the ambient atmosphere. The amount depends upon the temperature and the partial pressure of atmosphere. As the water content of the hair increases, the hair lengthens, closely approximating the relative humidity. Hairs are joined in parallel to form a hygrometer probe. They are sufficiently apart to give the free access to moisture. Hairs are in firm tension to maintain them straight. Animal or human hairs and synthetic fibers are used to form such probes. The lower and the upper limits for the use of hair hygrometer are 15 to 95% relative humidity.

Lesson 27

ELEMENTS OF GENERALIZED PROCESS CONTROL

27.1 Introduction

Most industrial processes require that certain variables such as temperature, flow, level or pressure and concentration, remain at or near some reference value (set-point). The *set-point* is a value for a process variable that is desired to be maintained. A *closed control loop* exists where a process variable is measured, compared with a set-point and action is taken to correct any deviation from the set-point. The system that serves to maintain a process variable at the set point is called controller which is the part of a control system. In automatic control system, controller performs the basic operation used by many systems provides regulation or command to the process variable to be controlled. Our goal using this type of feedback control is to determine the value or state of some physical quantity and often to maintain it at that value, despite variations in the system or the environment.

Automatic control system provides the means of attaining optimal performance of dynamic systems and improving productivity. This defines as a series of operations during which some materials are placed in more useful state by continually measuring ***process variables (***A *process variable* is a condition of the process fluid that can change the manufacturing process in some way) and taking actions such as opening valves, slowing down pumps and turning up heaters so that the measured process variables are maintained at operator specified set point values. Mainly there are four basic objectives of automatic process control which are as under.

1. Suppressing the influence of external disturbances
2. Optimizing the performance
3. Increasing the productivity
4. Cost effective

27.2 Fundamental Structure of Control Systems

A control system is that means by which any quantity of interest in a machine or mechanism can be changed, maintained or unaltered in accordance with desired manner. This system uses an interconnection of components forming a system configuration that will provide a desired system response. Input Signals flow through the system and produce an output as shown in Fig.27.1(a).

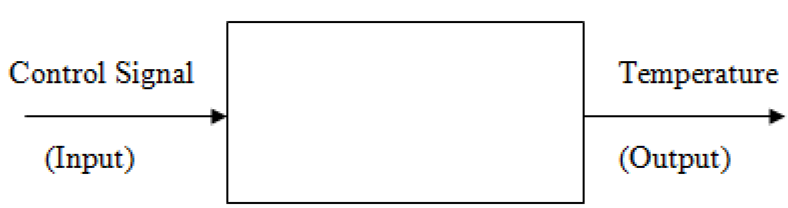


Fig. 27.1 (a) Representation of input and output of a process

The input will usually be an ideal form of the output. In other words the input is really what we want the output to be. It's the desired output. The output of the system has to be measured. In the Fig. 27.1 (b), we have shown the system in which we are trying to control - the "plant" and a sensor that measures what the controlled system is doing.

The input to the plant is usually called the control effort, and the output of the sensor is usually called the measured output, as shown Fig. 27.1 (b).

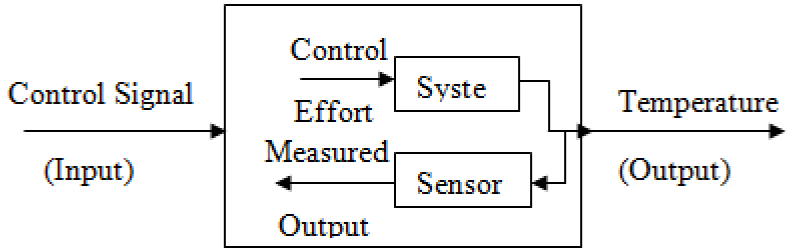


Fig. 27.1 (b) Representation of input and output of a process

For example, if we want the output to be 100°C, then that's the input.

To control the process output, it is necessary to first measure the process output which is to be controlled at a desired set point. The sensor measures the actual process output. In the block diagram representation (Fig. 27.2), the sensor senses the process-output temperature and generates a proportionate output signal. A sensor might be an LM35, which produces a voltage proportional to temperature - if the output signal is a temperature. Sensor is needed in the system to measure what the system is doing. The sensor measures the output e.g. temperature of the system to be controlled, and converts it into proportionate electrical signal. The LM35 temperature sensors, for example, produce 0.01 volts for every 1.0°C change. To control the system we need to use the information provided by the sensor. Usually, the output, as measured by the sensor is subtracted from the input (which is the desired output) as shown in Fig. 27.2. That forms an error signal that the controller can use to control the plant.

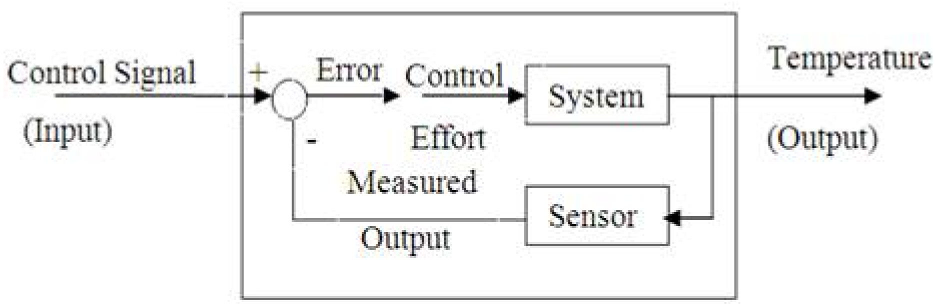


Fig. 27.2 Representation of input and output of a process with error comparator

The device which performs the subtraction to compute the error E is a comparator. Finally, the last part of this system is the controller which is as shown in Fig.27.3.

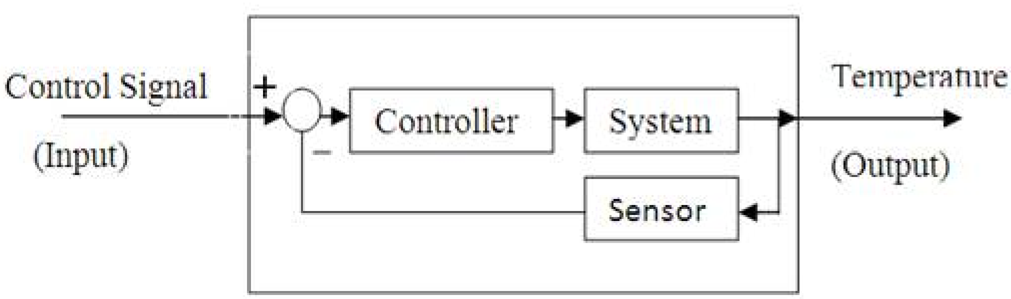


Fig. 27.3 Block diagram of negative feedback control loop

The controller receives the error signal from the comparator and generates an actuating signal which can be used to control the process-output through the actuating element. Thus, the controller has two functions:

1. To compute what the control effort should be.
2. To apply the computed control effort.

27.3 Types of Control System

Mainly there are two types of control system:

1) Open-loop systems and

2) Closed-loop systems

27.3.1 Open loop systems

The open-loop system (Fig. 27.4) is also called the non-feedback system. It utilizes an actuating device to control the process directly without using feedback. Gas geyser, electric geyser etc. used for heating of water are few examples of open-loop control system. This is the simpler of the two systems. However, since it is not possible to achieve desired accuracy of control of the parameter and its use is limited in the industry. In open-loop control system there is only a forward action from the input to the output.

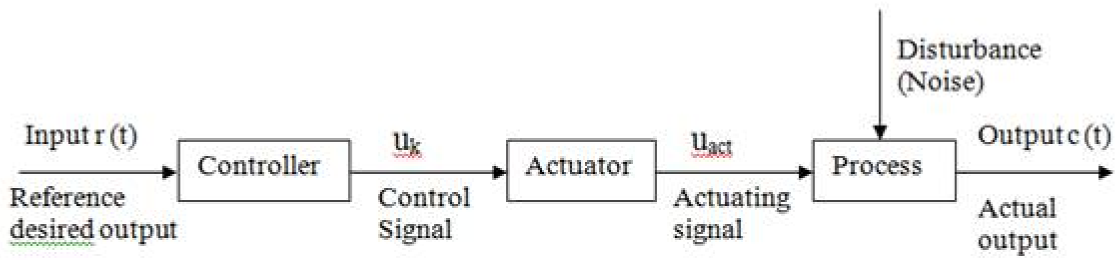


Fig. 27.4 Block diagram of open-loop control system

27.3.2 Closed loop systems

The closed-loop system is also called the feedback system. Feedback control system is to control the process by using the difference between the output and reference input. A closed-loop control system uses a measurement of the output and feedback of this signal to compare it with the desired output (reference or command) as explained above in Section 27.2.

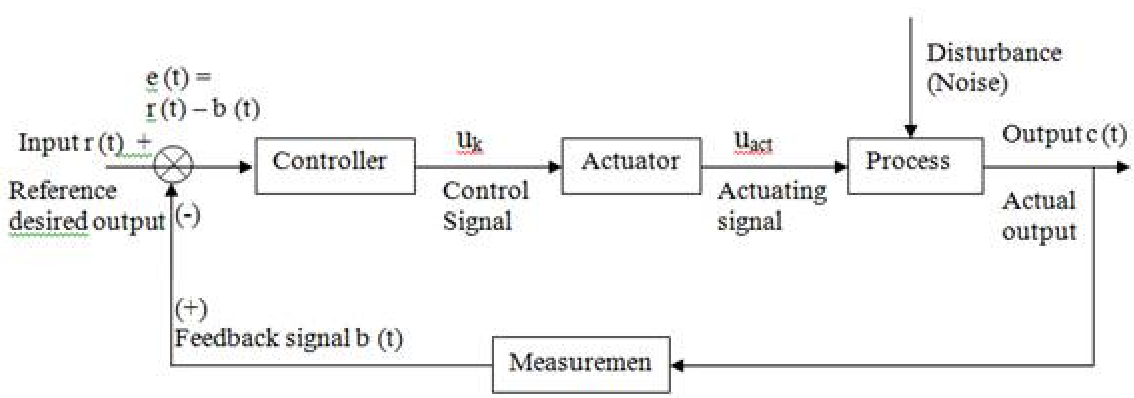


Fig. 27.5 Block diagram of closed-loop system

The basic functions of an automatic controller in a closed-loop system are:

1) To receive the actual measured value of the variable being measured.
2) To compare that value with a reference or desired value.
3) To determine the deviation with the help of comparator.
4) To provide an output control signal to reduce the deviation to zero or a small value.

27.4 Basic Elements of Generalized Process Control

In the process control, four basic elements are normally involved:

1. Process
2. Measurement
3. Evaluation (with a controller)
4. Control element

Fig. 27.6 shows the block diagram of generalized process control and the function of each block are given as follows:

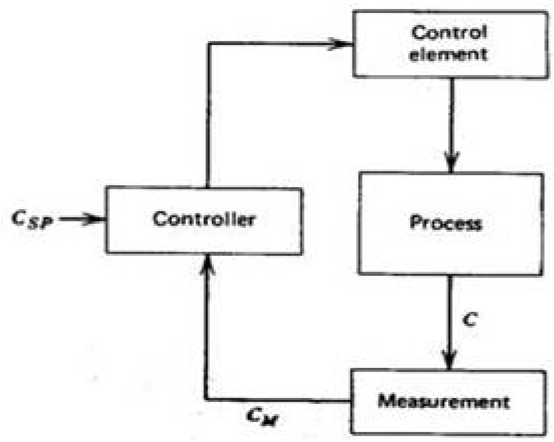


Fig. 27.6 Block diagram of generalized process control

1. Process

The term *Process* as used in relation to *process control* refers to the methods of converting raw materials into the end product(s). The raw materials which either pass through or remain in a liquid, gaseous, or slurry (a mix of solids and liquids) state during the process, are transferred, measured, mixed, heated or cooled, filtered, stored, or handled in some other way to produce the end product. Many dynamic variables may be involved in a process, and it may be desirable to control all these variables at the same time. There are *single-variable* processes, in which only one variable is to be controlled. However, most industrial processes are multivariable processes, in which many variables, perhaps interrelated, may require regulation.

2. Measurement

To perform control, it is necessary to measure the process parameter, so that we can have information on the variable itself. In general, a measurement refers to the transduction of the variable into some corresponding *analog* of the variable, such as a pneumatic pressure, an electrical voltage, or current. A *transducer is* a device that performs the initial measurement and energy conversion of a dynamic variable into analogous electrical or pneumatic information. Further transformation or *signal conditioning* may be required to complete the measurement function. The result of the measurement is a transformation of the dynamic variable into some proportional information in a useful form required by the other elements in the process-control loop.

3. Evaluation

The next step in the process-control sequence is to examine the measurement and determine what action, if any, should be taken. The evaluation may be performed by an operator, or by electronic/pneumatic signal processing, or by a computer. A *controller* is a device that receives data from a measurement instrument, compares that data to a programmed set-point, and, if necessary, signals a control element to take corrective action. Computer use is growing rapidly in the field of process control because it is easily adapted to the decision making operations and because of its inherent capacity to handle control of multivariable systems. The controller requires an input of both a *measured representation* of the dynamic variable and a representation of the *desired value* of the variable, expressed in the same terms as the measured value. The desired value of the dynamic variable is referred to as the *set point*. Thus, the evaluation consists of a *comparison* of the controlled variable measurement and the set point and a determination of action required to bring the controlled variable to the set point value.

4. Control element

The *correcting* or *final control element* is the part of the control system that acts to physically change the manipulated variable. This element accepts an input from the controller, which is then transformed into some proportional operation performed on the process. In any process control loop, final control elements are typically used to correct a variable that is out of set-point.

In most cases, the final control element is a valve/servo motor used to restrict or cut off fluid flow, but motors, louvers (typically used to regulate air flow), solenoids, and other devices can also be final control elements. For example, a final control element may regulate the flow of fuel/air to a burner to control temperature, the flow of a catalyst into a reactor to control a chemical reaction.

A block diagram can be used simply to represent the composition and interconnection of a system. Also, it can be used together with transfer function to represent the cause and effect relationship throughout the system. Transfer Function defines the relationship between an input signal and an output signal for a system.

Each element in a process-control loop is represented in a block diagram as a separate step. The controlled dynamic variable in the process is denoted by C and the measured dynamic variable is labeled as C_M. The controlled variable set point, labeled C_{SP}, must be expressed in the same proportion as that provided by the measurement function. The evaluation operation generates an *error signal* ($E = C_M - C_{SP}$) to the controller for comparison and corrective action.

To further illustrate, the block diagram concept in Fig. 27.7 shows a typical flow control system. In this example, the dynamic variable is the flow rate that is converted to electric signal as an analog. The process is the flow, and the measurement is to determine the difference of pressure. With the set point in the controller, the flow of the process is controlled through the control element i.e. the valve.

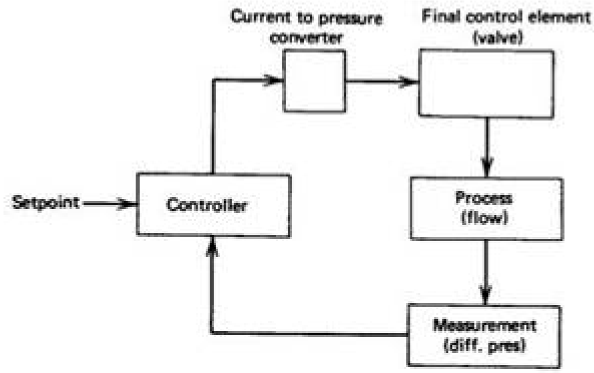


Fig. 27.7 Process Control System to regulate flow and the corresponding block diagram

27.5 Process Equations

The purpose of a process control loop is to regulate some dynamic variable in a process. The dynamic variable or a process parameter may depend on many other parameters (in the process) and thus suffer changes from many different inputs. One of these parameters is selected as a controlling parameter. This means that if a measurement of variable shows the deviation from the set point, then the controlling parameter is changed. For an example, consider the control of liquid temperature in tank shown in Fig. 27.8.

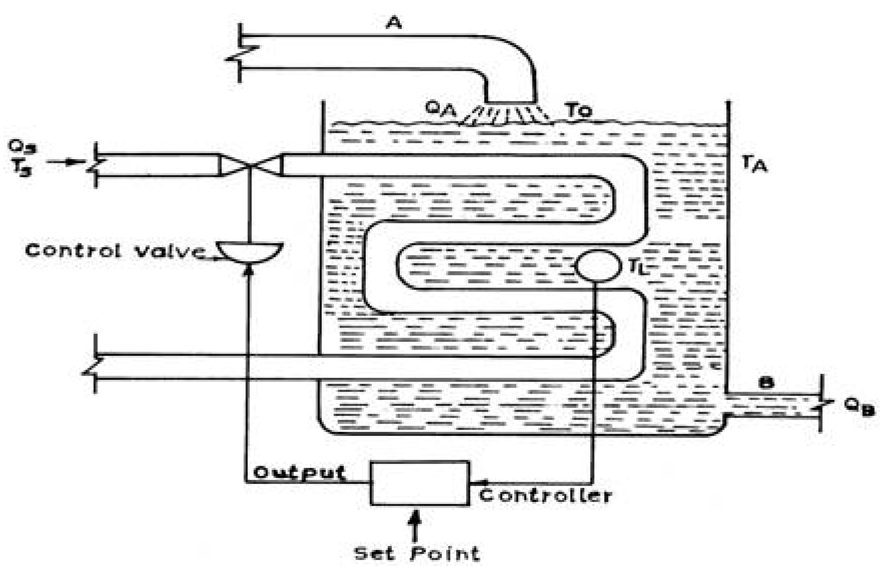


Fig. 27.8 Hot water temperature control system

Here the dynamic variable is the liquid temperature T_L. This temperature depends on many parameters in process like input flow rates in pipe A, output flow rates via pipe B, ambient Temperature T_A, the steam temperature Ts, inlet temperature To, and the steam flow rates Q_S. In this case, steam flow rate is the controlling parameter. If one of other parameters changes, accordingly there is change in temperature results. In order to bring the temperature back to the original value the steam flow rate is adjusted accordingly. This can be described by a process equation where liquid temperature is a function as:

$T_L = F\ (Q_A, Q_B, Q_S, T_A, T_S, T_B, T_O)$

Where:

Q_A, Q_B = flow rates in pipes A and B

Q_S = Steam Flow rate

T_A = ambient temperature

T_O = Inlet fluid temperature

T_S = steam temperature

27.5.1 Process load

Process load refers to set of all parameters excluding the dynamic variable. At some point in time, a process load change causes a change in dynamic variable e.g. when all parameters in a process have their nominal values, it is known as the nominal load on the system. The required control parameters value under these conditions is the nominal value of that parameter. If the set point is changed, then the control parameter is altered to cause the variable to adopt new operating point. The load is still nominal, however, because of other parameters are assumed unchanged. Now if one of the parameters changes from nominal value, causing a corresponding shift in the controlled variable then a process load change is said to have occurred.

27.5.2 Process lag

It represents a delay in reaction of controlled variable to a change of load variable e.g. the process control loop in a process responds to assure, some finite time later that the variable returns to set point value. Part of this time is consumed by the process itself and referred to as process lag. Process time lags are affected by capacitance which is the ability of a process to store energy; resistance, the part of the process that opposes the transfer of energy between capacities and transportation time, the time required to carry a change in a process variable from one point to another in the process. This time lag is not just a slowing down of a change, but rather the actual time delay during which no change occurs.

27.5.3 Self-regulation

Self regulation is characteristic that a dynamic variable adopts some nominal value commensurate with the load with no control action. The output will move from one steady state to another for the sustained change in input. This means that for change in some input variable the output variable will rise until it reaches a steady state (inflow = outflow). It is the tendency of the process to adopt a specific value of controlled variable for nominal load with no control operations. A significant process characteristic is its tendency to find a specific value of dynamic variable for nominal load with no control operations. The control operations may be significantly affected by such self-regulation. The process of Fig. 27.8 has self regulation as shown by the following arguments:

(a) Suppose we fix the steam valve at 50 % and open the control loop so that no changes in valve position are possible.

(b) The liquid heats up until the energy carried away by the liquid equals that input energy from the steam flow.

(c) If load changes, a new temperature is adopted (because the system temperature is not controlled).

(d) The process is self regulating because the temperature will not run away but stabilizes.

Lesson 28

CONTROL SYSTEM PARAMETERS

28.1 Introduction

A control system monitors and determines a difference between a desired and measured parameter values, applies a weighting factor to the difference and selects a control strategy based on the weighted difference. The weighting factor generally reflects the confidence in the accuracy of the parameter value determined by the parameter monitor. The weighting factor may be determined based on one or more ambient operating conditions or parameters, or on statistical analyses of monitor values and/or control system parameter values.

28.2 Control System Parameters

28.2.1 Error

Error is the difference between the measured variable and the setpoint. Error can be either positive or negative. The objective of any control scheme is to minimize or eliminate error. The deviation or error of dynamic variable from set point is given by:

$$E = C_m - C_{sp}$$

Where E = error

C_m = measured value of variable

C_{sp} = set point of variable

The above equation expresses error in an absolute sense, usually in units of measured analog of control signal. Note that a positive error indicates a measurement above the set points whereas a negative error indicates a measurement below the set point.

28.2.2 Variable range

The dynamic variable under control or controlled variable has a range of values within which control is required to be maintained at set point. This range can be expressed as the minimum and maximum values of the dynamic variable or the nominal value plus and minus the spread about this nominal value e.g. if a standard signal 4-20 mA transmission is employed, then 4 mA represents the minimum value of the variable and 20 mA the maximum value.

28.2.3 Control parameter (output) range

It is the possible range of values of final control element. The controller output is expressed as a percentage where minimum controller output is 0% and maximum controller is 100%. But 0% controller output does not mean zero output. For example, it is necessary requirement of the system that a steam flow corresponds to 1/4th opening of valve. The controller parameter output has a percentage of full scale when the output changes within the specified limits in expressed as:

$P = [Sp – Smin]/ [Smax – Smin] \times 100$

Where:

P = Controller output as percentage of full scale

Sp = Value of the output

Smax = Maximum value of the controlling parameter

Smin = Minimum value of the controlling parameter

28.2.4 Control lag

Processes have the characteristic of delaying and retarding changes in the values of the process variables. This characteristic greatly increases the difficulty of control. The control system can have a lag associated with it. The control lag is the time required by the process and controller loop to make the necessary changes to obtain the output at its set point. The control lag must be compared with process lag while designing the controllers. *A process time lag is* the general term that describes the process delays and retardations. It refers to the time for the process control loop to make necessary adjustments to the final control element e.g. if a sudden change in liquid temperature occurs, it requires some finite time for the control system to physically actuate the steam control valve.

28.2.5 Dead time

Sometimes a dead zone is associated with the process control loop. The time corresponding to dead zone is called dead time. This is the elapsed time between the instant a deviation (error) occurs and when the corrective action first occurs.

28.3 Controller Modes

The method used by the controller to correct the error is the control mode. Controller modes are an expression of relation between controller output and dynamic variable deviation from the set point. The actions of controllers can be divided into groups based upon the functions of their control mechanism. Each type of controller has advantages and disadvantages and meets the needs of different applications. Grouped by control mechanism function, the two types of controllers are:

1. Discontinuous controllers
2. Continuous controllers

28.3.1 Continuous controller mode

In this mode there is a possibility of smooth variation in control parameter and the controllers automatically compare the value of the process variable to the set-point to determine if an error exists. If there is an error, the controller adjusts its output according to the parameters that have been set in the controller. When there is an error, the controller makes a change in its output. It determines:

- **How much?** Proportional Mode
- **How long?** Integral Mode
- **How fast?** Derivative Mode

28.3.2 Discontinuous controller mode

In this mode controller command initiates a discontinuous change in control parameter. The manipulated variable of a discontinuous controller mode can only be changed in set steps. The best-known discontinuous-action controller is the two-step control that can only assume the conditions ‘on’ or ‘off’. An example is the thermostat of a hot air oven. It switches the electric current for the heating element ‘on’ or ‘off’ depending on the set temperature.

28.3.3 Types of discontinuous controller modes

The choice of operating modes for any given process control system is a complicated decision. It involves not only process characteristics but cost analysis, product rate, and other industrial factors. The different types of discontinuous controller operating modes are defined as follows:

(A) Two Position Controller Mode: A two position controller mode uses a device that has two operating conditions: completely on or completely off. These also called ON-OFF control or Discrete controllers. On /off control activates an output until the measured value reaches the reference value. Fig. 28.1 shows the input to output characteristic for a two position controller for a refrigerator that switches from its ‘OFF’ to its ‘ON’ state when the measured variable increases above the set point.

Conversely, it switches from its ‘ON’ state to its ‘OFF’ state when the measured variable decreases below the set point. This device provides an output determined by whether the error signal is above or below the set point. The magnitude of the error signal is above or below the set point. The magnitude of the error signal past that point is of no concern to the controller.

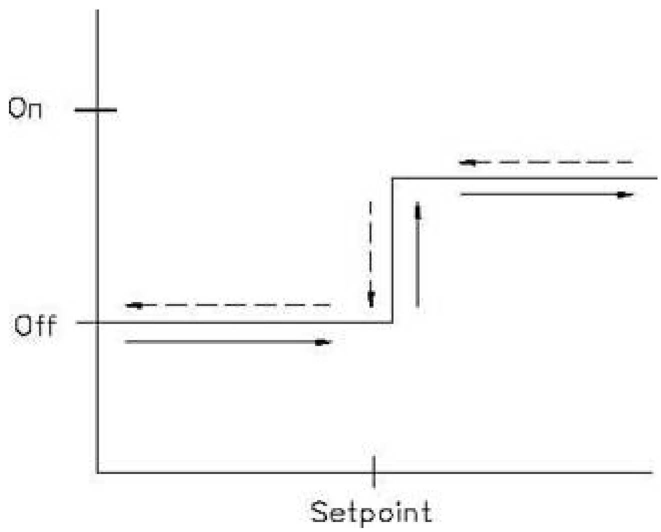


Fig. 28.1 Two position controller input/output relationship

While simple and low cost, this mode of control has a tendency to overshoot the desired value. Flow Diversion Valve (FDV) used in HTST plant and solenoid valves are two position ON-OFF controller.

(B) Multi-position Mode or Multistep Mode Controllers

Multistep controllers are controllers that have at least one other possible position in addition to on and off. Multistep controllers operate similarly to discrete controllers, but as set-point is approached, the multistep controller takes intermediate steps. Therefore, the oscillation around set-point can be less dramatic when multistep controllers are employed than when discrete controllers are used. This mode is used to provide several intermediate values rather than only two settings of controller output. This discontinuous control mode is used to reduce the cycling behaviour and also overshoot and undershoot inherent in two position control. This mode is represented by:

$P = P_i \qquad E_p > E_i \qquad I = 1, 2, 3, \ldots\ldots\ldots\ldots\ldots\ldots\ldots n$

The meaning here is that as error exceeds certain set limits + Ei, the controller output is adjusted to preset values Pi.

(C) Floating Control Modes

In this control mode, specific output of the controller is not uniquely determined by error. If error is zero, the output will not change but remains (floats) at whatever settings it was when the error went to zero. When the error moves off zero, the controller output begins to change e.g. a floating control will operate a control valve which, as level rises and falls will throttle down or gradually open a level control valve in the inlet (or outlet) line, thereby controlling the level at a pre-set height in the tank.

Lesson 29

TYPES OF CONTROLLER MODES

29.1 Proportional Control Mode

In the *proportional (throttling) mode*, there is a continuous linear relation between value of the controlled variable and position of the final control element. In this control mode, the output of the controller is proportional to error e(t). The relation between the error e(t) and the controller output p is determined by a constant called proportional gain constant denoted as K_p. The output of the controller is a linear function of e(t).

$p(t) = K_p e(t) + p(0)$ ………………………………………………………… (1)

Where:

K_p = Proportional gain constant

P(0) = Controller output with zero error or bias

The direct and reverse action is possible in the proportional controller mode. The error may be positive or negative because error (r-b) depending upon whether b is less or greater than the reference setpoint r(t).

If the controlled variable i.e. input to the controller increases, causing increase in the controller output, the action is called direct action. For example the output valve is to be controlled to maintain the liquid level in a tank. If the level increases, the valve should be opened more to maintain the level. On the other hand if the variable decreases, causing increase in the controller output, the action is called reverse action. Conversely, increase in the controlled variable, causing decrease in controller output is also a reverse action.

29.1.1 Characteristics of proportional mode

The various characteristics of the proportional mode are:

1. When the error is zero, the controller output is constant equal to p_0.
2. If the error occurs, then for every 1 % of error the correction of K_p % is achieved. If error is positive, K_p % correction gets added to p_0 and if error is negative, K_p % correction gets subtracted from p_0.
3. The band of error exists for which the output of the controller is between 0 to 100%.
4. The gain K_p and error band PB are inversely proportional to each other.

29.1.2 Proportional gain

Proportional gain is the percentage change of the controller output relative to the percentage change in controller input. Gain, also called sensitivity, compares the ratio of amount of change in the final control element to amount of change in the controlled variable. Mathematically, gain and sensitivity are reciprocal to proportional band. The gain k_P can be expressed as:

$K_P = 100 / P$

Where

P = proportional band

The gain determines how fast the system responds. If the value is too large the system will be in danger to oscillate and/or become unstable. If the value is too small the system error or deviation from set point will be very large.

29.1.3 Proportional band

Proportional band, (also called throttling range), is the change in value of the controlled variable that causes full travel of the final control element. The proportional band of a particular instrument is expressed as a percent of full range. For example, if full range of an instrument is 200^{o}F and it takes a 50^{o}F change in temperature to cause full valve travel, the percent proportional band is 50^{o}F in 200^{o}F, or 25%.

The proportional band *P,* express the value necessary for *100%* controller output. If $P = 0$, the gain or action factor k_p would be infinity - the control action would be *ON/OFF*.

29.1.4 Offset

Offset, also called droop, is deviation that remains after a process has stabilized. Offset is an inherent characteristic of the proportional mode of control.

29.2 Integral Control Mode

With **integral** action, the controller output is proportional to the amount of time the error is present. Integral action eliminates offset that remains when proportional control is used. In such a controller, the value of the controller output p(t) is changed at a rate which is proportional to the actuating error signal e(t). Mathematically it is expressed as:

$$\frac{de(t)}{dt} = K_i\, e(t)$$

Where K_i = constant relating error and rate

The constant K_i is also called integral constant. Integrating the above equation, the actual output at any time t can be obtained as

$$p = K_i \int e(t)dt + p(0)$$

Where p(0) = controller output when integral action starts i.e. at t = 0.

29.2.1 Advantages

1. Integral controllers tend to respond slowly at first, but over a period of time they tend to eliminate errors.
2. The integral controller eliminates the steady-state error, but has the poor transient response and leads to instability.

29.2.2 Characteristics of integral mode

1. If error is zero, the output remains at a fixed value equal to what it was, when the error become zero.
2. If the error is not zero, then the output begins to increase or decrease, at a rate Ki % per second for every ± 1 % of error.
3. The inverse of Ki is called integral time and denoted as Ti.

$$Ti = \frac{1}{Ki} = \text{Integral Time}$$

29.2.3 Application of P and I control modes

The comparison of proportional and integral mode behavior at the time of occurrence of an error signal is given in Table 29.1.

Table 29.1 Comparison of P and I controllers

Controller	Initial behaviour	Steady state behaviour
p	Acts immediately. Action according to Kp.	Offset error always present. Larger the Kp, smaller the error.
I	Acts slowly. It is the time integral of the error signal.	Error signal always become zero.

It can be seen that proportional mode is more favorable at the start while the integral is better for steady state response. In pure integral mode, error can oscillate about zero and can be cyclic. Hence in practice, integral mode is never used alone but combined with the proportional mode, to harness the merits of both modes.

29.4 Derivative Control Mode

In this mode, the output of the controller depends on the rate of change of error. Hence, it is also called rate action mode or anticipatory action mode. The mathematical equation for the mode is:

$$p(t) = K_d \frac{\mathrm{de(t)}}{dt}$$

Where Kd = Derivative gain constant

The derivative gain constant indicates by how much % the controller output must change for every % per second rate of change of the error. Generally Kd is expressed in minutes. The important feature of this type of control mode is that for a given rate of change or error signal, there is a unique value of the controller output.

The advantage of the derivative control action is that it responds to the rate of change of error and can produce the significant correction before the magnitude of the actuating error becomes too large. Derivative control thus anticipates the actuating error, initiates an early corrective action and tends to increase stability of the system, improving the transient response. The derivative or differential controller is never used alone because when error is zero or constant, the controller has either no output or the nominal output for zero error.

29.4.1 Characteristics of derivative control mode

For a given rate of change of error signal, there is a unique value of the controller output. When the error is zero, the controller output is zero. When the error is constant i.e. rate of change of error is zero, the controller output is zero. When the error is changing, the controller output changes by K_d % for even 1 % per second rate of change of error.

When the error is zero or a constant, the derivative controller output is zero. Hence, it is never used alone. Its gain should be small because faster rate of change of error can cause very large sudden change of controller output. This may lead to instability of the system.

29.4.2 Advantages

1. With sudden changes in the system the derivative controller will compensate the output fast.
2. The long term effects the controller allows huge steady state errors.
3. A derivative controller will in general have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response.

29.4.3 Drawbacks of derivative action

1. The output of controller is zero at constant error condition.
2. It will amplify the noise present in the error signal.

29.5 Composite Control Modes

Due to offset error, proportional mode is not used alone. Similarly, integral and derivative modes are not used individually in practice. Thus, to take the advantages of various modes together, the composite control modes are used. Composite modes of controller operation combine advantages of each 'pure' mode. The various composite control modes are:

1. Proportional + Integral mode (PI)
2. Proportional + Derivative Mode (PD)
3. Proportional + Integral + Derivative Mode (PID)

29.6 Proportional-Integral Control

This is a control mode that results from a combination of proportional mode and integral mode. The analytical expression for this is:

$p(t) = Kp\ e(t) + Kp\ Ki \int e(t)\,dt + p(0)$

The main advantage of this composite control mode is that the one-to-one correspondence of proportional mode is available and integral mode eliminates the inherent offset.

29.7 Proportional-Derivative Control Mode

This involves the series or cascade combination of proportional and derivative modes. The controller output could be expressed as:

$$P(t) = Kp\ e(t) + Kp\ Kd \frac{de(t)}{dt} + P(0)$$

This system cannot eliminate the offset of proportional controllers. However, it can handle fast process load changes as long as the offset error is acceptable.

29.8 Proportional Integral Derivative Controller (Three Mode Controllers)

The three mode controller uses proportional, integral and derivative (PID) action and is the most versatile of all controller actions. The proportional part of this controller multiplies the error by a constant. The integral part integrates the error. Finally, the derivative part differentiates the error. The functions of the individual proportional, integral and derivative controllers complement each other. If they are combined it is possible to make a system that responds quickly to changes (derivative), tracks required positions (proportional), and reduces steady state errors (integral). The output of the controller is the sum of the previous three signals as given in the following equation:

$p(t) = K_p\, e(t) + K_p\, K_i \int e(t)\, dt + K_p\, K_d \frac{de(t)}{dt} + p(0)$

Where K_p, K_i and K_d are the proportional, integral and derivative gains respectively.

The proportional, integral and derivative terms must be individually adjusted or ‘tuned’ to a particular system.

29.8.1 Advantages

1. This mode eliminates the offset of proportional mode.
2. It provides the most accurate and stable control of the three controller types.
3. It is recommended in systems where compensation is required for frequent changes in load, set point, and available energy.
4. It can help achieve the fastest response time and smallest overshoot.

Lesson 30

FINAL CONTROL ELEMENTS AND ACTUATORS

30.1 Introduction

Final control elements are devices that complete the control loop. They link the output of the controlling elements with their processes. Some final control elements are designed for specific applications. The final control element is the last element of the closed control loop that implements the control action. It receives the output signal (control or actuating signal) from a process controller and adjusts accordingly the value of the manipulated variable by changing the amount of matter or energy entering the process in a way to bring the controlled variable (process variable) to its set point. The final control element is probably the most important because it exerts a direct influence on the process.

For example, neutron-absorbing control rods of a reactor are specifically designed to regulate neutron-power level. However, the majority of final control elements are general application devices such as valves, dampers, pumps, and electric heaters. Valves and dampers have similar functions. Valves regulate flow rate of a liquid while dampers regulate flow of air and gases. Pumps, like valves, can be used to control flow of a fluid. Heaters are used to control temperature.

These devices can be arranged to provide a type of "on-off" control to maintain a variable between maximum and minimum values. This is accomplished by opening and shutting valves or dampers or energizing and de-energizing pumps or heaters. On the other hand, these devices can be modulated over a given operating band to provide a proportional control. This is accomplished by positioning valves or dampers, varying the speed of a pump, or regulating the current through electric heater. There are many options to a process control. Out of the final control elements discussed, the most widely used in power plants are valves. Valves can be easily adapted to control liquid level in a tank, temperature of a heat exchanger, or flow rate. Control valves are the single most common type of final control element in process.

30.2 Control Valves

A control valve is a valve with a pneumatic, hydraulic, electric or other externally powered actuator that automatically, fully or partially opens or closes the valve to a position dictated by signals transmitted from controlling instruments.

Control valves are used primarily to throttle energy in a fluid system and not only for shut-off purposes. Their internals must withstand high fluid velocity and turbulence for long periods without maintenance. A control valve is simply a variable orifice that is used to regulate the flow of a process fluid according to the requirements of the process.

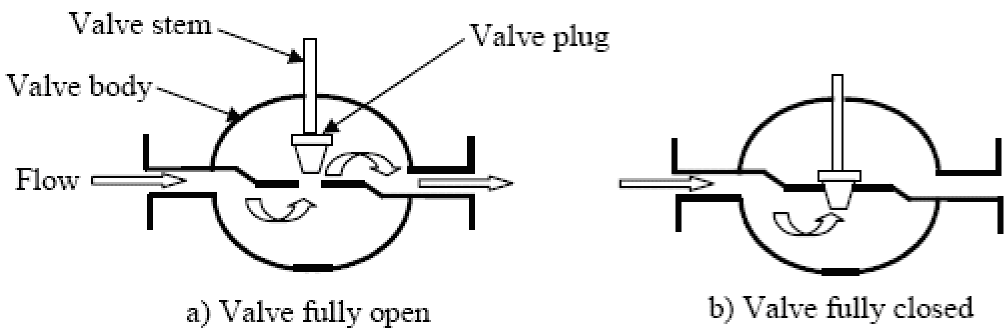


Fig. 30.1 Typical globe type control valve

Fig. 30.1 illustrates a typical globe-type control valve body in both the fully open and fully closed positions. In a control valve, an actuator that is connected to the valve's plug stem moves the valve between the open and closed positions to regulate flow in the process. The valve body is mounted in the process fluid line and is used to control the flow of fluid in the process. The *body* of a control valve is generally defined as the part of the valve that comprises the main boundary, including the connecting ends. Valves are classified into two general types based on the movement of the valve's closure part: *linear* and *rotary*.

30.3 Types of Actuator

An *actuator* is the part of a final control device that causes a physical change in the final control device when signaled to do so. The most common example of an actuator is a valve actuator, which opens or closes a valve in response to control signals from a controller. By themselves, valves cannot control a process. Manual valves require an operator to position them to control a process variable. Valves that must be operated remotely and automatically require special devices to move them. These devices are called actuators. Actuators are often powered pneumatically, hydraulically, or electrically. Diaphragms, bellows, springs, gears, hydraulic pilot valves, pistons, or electric motors are often parts of an actuator system. There are four principal types of actuator:

- Pneumatic
- Hydraulic
- Solenoid
- Electric Motor

30.3.1 Pneumatic actuator with valve

The pneumatic valve is an air-operated device which controls the flow through an orifice by positioning appropriately a plug (Fig. 30.2 and 30.3).

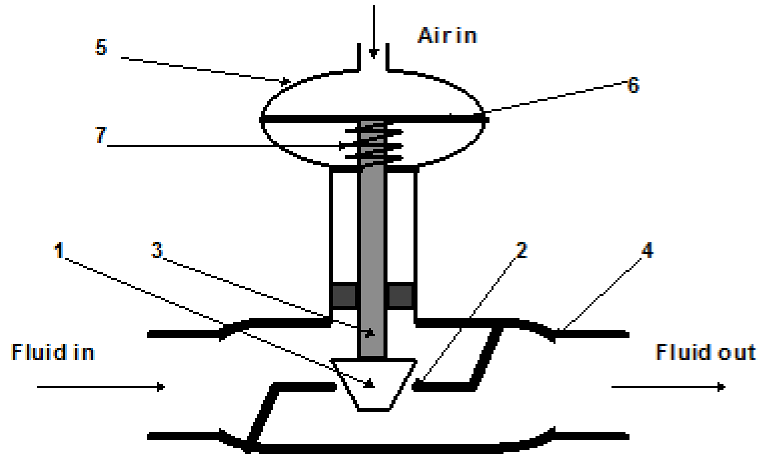


Fig. 30.2 Air-to-close pneumatic actuator with valve

The plug (1) is placed in the orifice (2) of the valve and attached to the end of the stem (3). The orifice is placed inside the body of the valve (4) made of cast iron, alloy steels, alloy steels plus corrosion-resistant alloys, or bronze. The upper part of the final control element is an actuator (5). A diaphragm (6) divides this actuator in two chambers. The upper end of the stem is supported on the diaphragm. When the airs pressure (the output signal from a pneumatic controller) above the diaphragm increases, the diaphragm deflects and the stem moves downwards thus restricting by the plug flow of the fluid through the orifice. This type of a pneumatic valve is called 'air-to-close' valve.

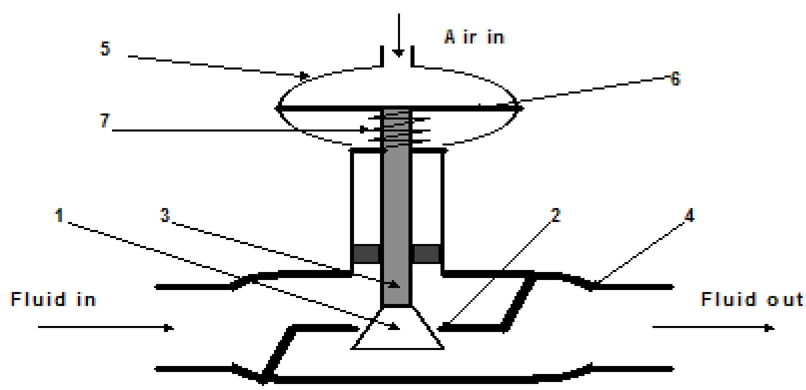


Fig. 30.3 Air-to-open pneumatic actuator with valve

When the air pressure goes down the stem under the action of a spring (7) will move upwards, thus opening the orifice. There is another type of valves, which operate in opposite action, i.e., when the air pressure increases the plug opens the orifice. Such valves are called 'air-to-open' valves. If the air pressure varies from 20 to 100 kPa the plug is moved from a fully open to fully closed position.

30.3.2 Hydraulic actuators

Pneumatic actuators are normally used to control processes requiring quick and accurate response, as they do not require a large amount of motive force. However, when a large amount of force is required to operate a valve (for example, the main steam-stop valves), hydraulic actuators are normally used. Hydraulic actuators use fluid displacement to move a piston in a cylinder positioning the valve as needed for 0-100% fluid flow. Although hydraulic actuators come in many designs, piston types are most common.

A typical piston-type Hydraulic Actuator is shown in Fig. 30.4.

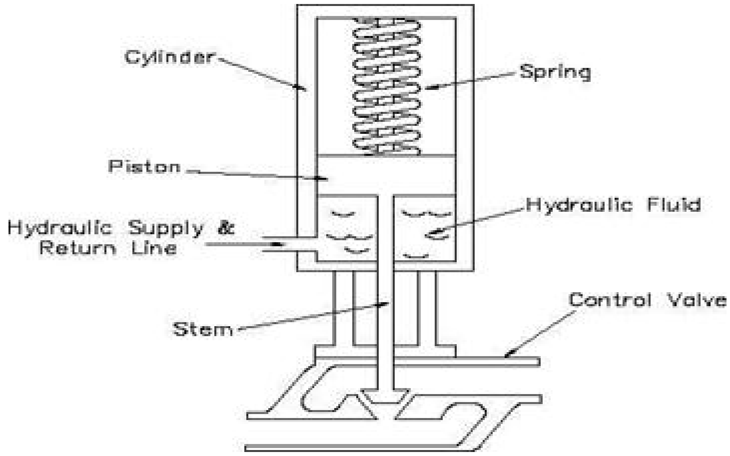


Fig. 30.4 Piston-type hydraulic actuator

It consists of a cylinder, piston, spring, hydraulic supply and returns line, and stem. The piston slides vertically inside the cylinder and separates the cylinder into two chambers. The upper chamber contains the spring and the lower chamber contains hydraulic oil. The hydraulic supply and return line are connected to the lower chamber and allows hydraulic fluid to flow to and from the lower chamber of the actuator. The stem transmits the motion of the piston to a valve.

When the hydraulic force is greater than the spring force, the piston begins to move upward, the spring compresses, and the valve begins to open. As the hydraulic pressure increases, the valve continues to open. Conversely, as hydraulic oil is drained from the cylinder, the hydraulic force becomes less than the spring force, the piston moves downward, and the valve closes. By regulating amount of oil supplied or drained from the actuator, the valve can be positioned between fully open and fully closed.

30.3.3 Electric solenoid actuators

Solenoid actuators are used on small valves and employ an electromagnet to move the stem which allows the valve to either be fully open or fully closed. A typical electric solenoid actuator is shown in Fig. 30.5. It consists of a coil, armature, spring, and stem.

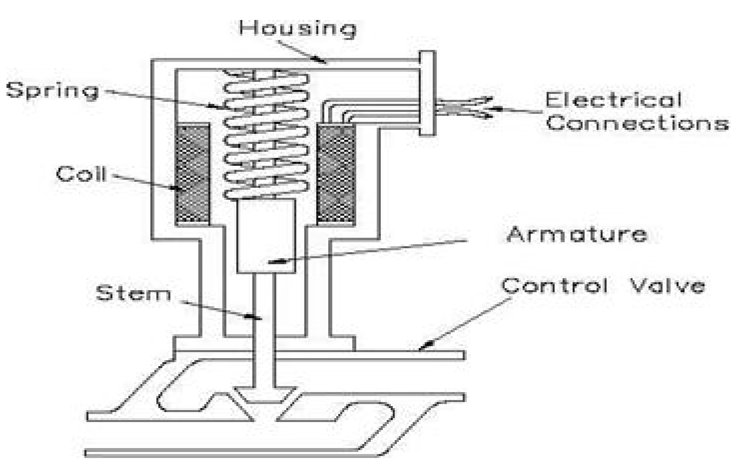


Fig. 30.5 Electric solenoid actuator

The coil is connected to an external current supply. The spring rests on the armature to force it downward. The armature moves vertically inside the coil and transmits its motion through the stem to the valve.

When current flows through the coil, a magnetic field forms around the coil. The magnetic field attracts the armature toward the center of the coil. As the armature moves upward, the spring collapses and the valve opens. When the circuit is opened and current stops flowing to the coil, the magnetic field collapses. This allows the spring to expand and shut the valve.

A major advantage of solenoid actuators is their quick operation. Also, they are much easier to install than pneumatic or hydraulic actuators. However, solenoid actuators have two disadvantages. First, they have only two positions: fully open and fully closed. Second, they don't produce much force, so they usually only operate relatively small valves.

30.3.4 Electric motor actuators

An electric motor is composed of a rotating center, called the rotor and a stationary outside, and called the stator. These motors use the attraction and repulsion of magnetic fields to induce forces, and hence motion. Equipped with limit switches and/or torque limiters, the electric motor actuator has the capability of 0-100% control and has not only a motor but also a manual hand wheel, and a clutch and gearbox assembly.

Typical electric motors use at least one electromagnetic coil, and sometimes permanent magnets to set up opposing fields. When a voltage is applied to these coils the result is a torque and rotation of an output shaft. There is a variety of motor configuration the yields motors suitable for different applications. Most notably, as the voltages supplied to the motors will vary the speeds and torques that they will provide.

Electric motor actuators vary widely in their design and applications. Some electric motor actuators are designed to operate in only two positions (fully open or fully closed). Other electric motors can be positioned between the two positions. A typical electric motor actuator is shown in Fig. 30.6. Its major parts include an electric motor, clutch and gear box assembly, manual hand wheel, and stem connected to a valve.

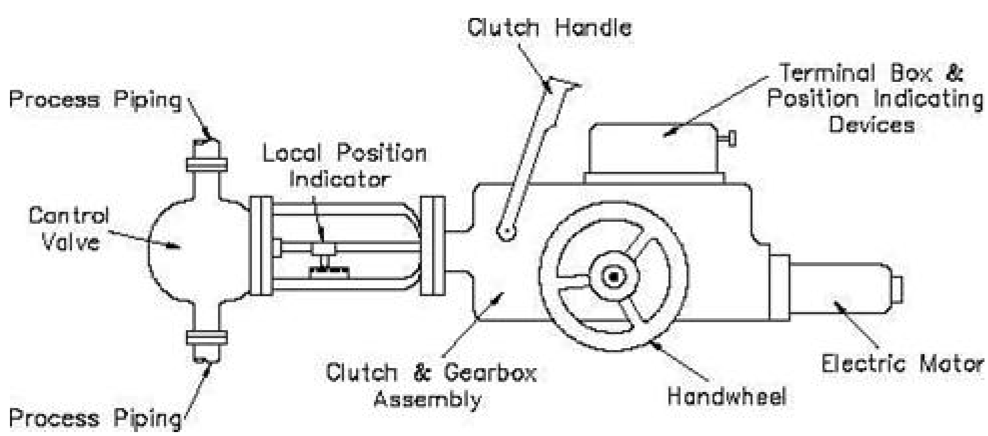


Fig. 30.6 Electric motor actuator

The motor moves the stem through the gear assembly. The motor reverses its rotation to either open or close the valve. The clutch and clutch lever disconnects the electric motor from the gear assembly and allows the valve to be operated manually with the hand wheel.

Most electric motor actuators are equipped with limit switches, torque limiters, or both. Limit switches de-energize the electric motor when the valve has reached a specific position. Torque limiters de-energize the electric motor when the amount of turning force has reached a specified value. The turning force normally is greatest when the valve reaches the fully open or fully closed position. This feature can also prevent damage to the actuator or valve if the valve binds in an intermediate position.

Lesson 31

INSTRUMENTATION AND CONTROLS IN DAIRY PLANT

31.1 Electromagnetic Switching Relay

Electromagnetic switching relay is based on the principle of electromagnetic induction and is used to switch on the power supply to electric equipments. It is employed to supply 24 V D.C. supply to Solenoid Valves, 220 to 440 V for motor starters or any other electrical equipment. The working switching relay is shown in the Figure 31.1.

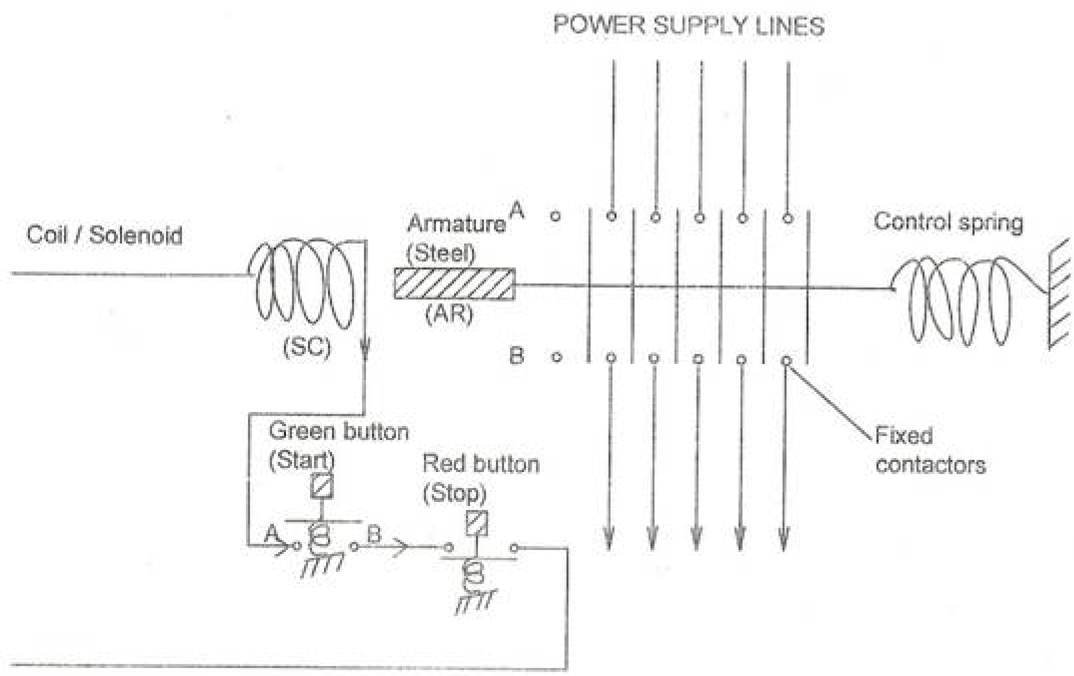


Fig. 31.1 Electromagnetic switching relay

When the green button (marked Start) is pressed the electric circuit provides the supply to the Solenoid Coil (SC). The coil becomes an electromagnet and attracts the steel Armature to the left. This movement of armature makes the contact of movable contactors to the fixed contactors and completes the circuit through the ends A and B, thus giving the power supply to any equipment connected to the terminals at the end B. The start button opens up when our finger is removed from the button. But the current to coil is maintained through auxiliary contacts A&B, which is connected in parallel to the Green button switch as shown in the figure. By closing the Red button the circuit to the coil breaks and the control spring pulls the movable contactors to the right, thus cutting the power supply and the equipment stops.

31.2 Air Operated Milk Valve

A solenoid valve is an electro-mechanically operated valve. The valve is controlled by an electric current through a solenoid. It has two main parts: the solenoid and the valve. The solenoid converts electrical energy into mechanical energy which, in turn, opens or closes the valve mechanically. One such air operated milk valve used in dairy plants is shown in figure 3.2.

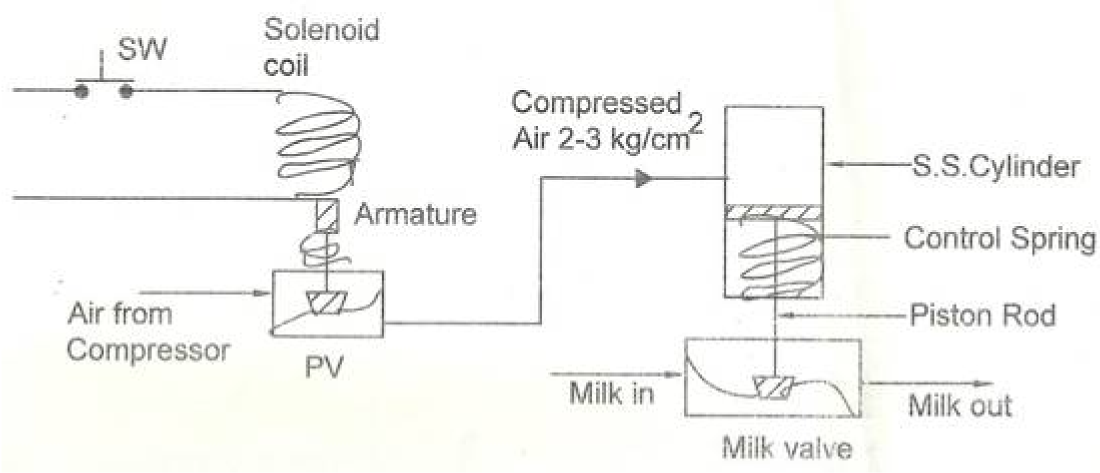


Fig. 31.2 Air operated milk valve

In the above figure the SW is the switch, it could be a manual start switch or a switch operated by any of the equipment used for the controlling parameters like, pressure, temperature, flow etc. By closing the switch SW power is supplied to the solenoid through SW. A pilot valve PV is attached to the armature of the solenoid. When the SW is closed the movement of the armature opens the pilot valve and the compressed air enters the SS Cylinder. The compressed air at the pressure of 2-3 kg/cm^2 moves the piston down and closes the milk valve. The reverse happens when the SW is disconnected. The air supply to the cylinder is closed and the air is exhausted from the cylinder (not shown in the figure). Now the movement of the valve is carried out by the control spring and the milk valve is opened.

31.3 Self Acting Steam Thermostat

Figure 3.3 shows a self acting steam thermostat with glycerin liquid, commonly used in dairy plants. A SS sensing bulb filled with glycerin under pressure is immersed in the tank, the contents of which are heated by steam. As the temperature increases the glycerin liquid expands in proportion to the temperature at the sensing bulb. This pushes the piston in the valve and the steam supply is regulated by the steam valve. The glycerin is used because its volumetric expansion is quite high and enough to generate power to operate the steam valve.

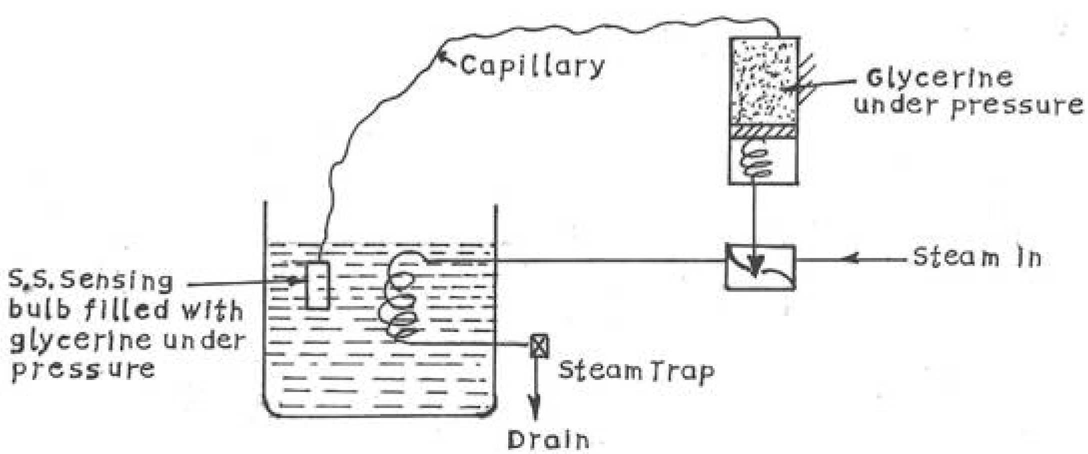


Fig. 31.3. Self acting steam thermostat with glycerin liquid

31.4 Online Denity Transducer

The online density transducer, as shown in figure 3.4, is used in the computerized dairy plants for sensing density, total solids, fat, temperature etc. The density measurement is based on measuring the period of oscillation of a mechanical oscillator operated at its normal frequency.

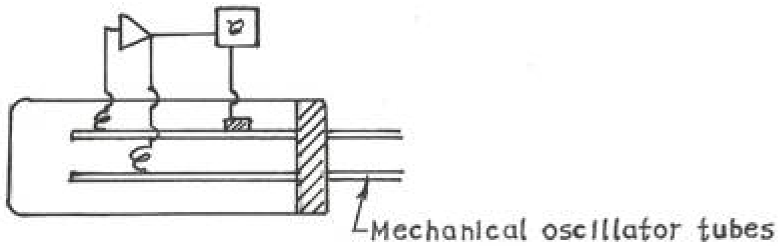


Fig. 31.4. Online density transducer

The oscillator consists of two straight parallel tubes, which are flown through by the sample. The period of oscillation depends upon the density of the sample within the mechanical oscillator and the mechanical properties of the, like inner diameter, wall thickness, elasticity etc. of the applied tube. Both density and mechanical properties of the tube depend on the temperature of the sample. Thus temperature is also measured and transmitted. The signal processor computes the density, temperature etc. and extrapolates information of total solids, dry weight, fat percent etc. in the sample.

31.5 Temperature Controller Recorders In Htst Pasteuizer

31.5.1 Flow diversion valve controller in HTST pasteurizer

In HTST pasteurizer the raw milk / product is pumped from a constant level tank to the heating section where the temperature is raised to exceed the pasteurization lower limit. The hot product temperature is measured and recorded at the end of the holding tube. If the temperature is less than the pasteurization temperature, the product is sent back to the constant level tank by the flow diversion valve and is recycled. Once the temperature exceeds the pasteurization temperature the flow diversion valve routs the product to the forward flow to the regenerator and cooling sections of the heat exchanger. The operation of a flow diversion controller of an HTST pasteurizer is shown in figure 31.5.

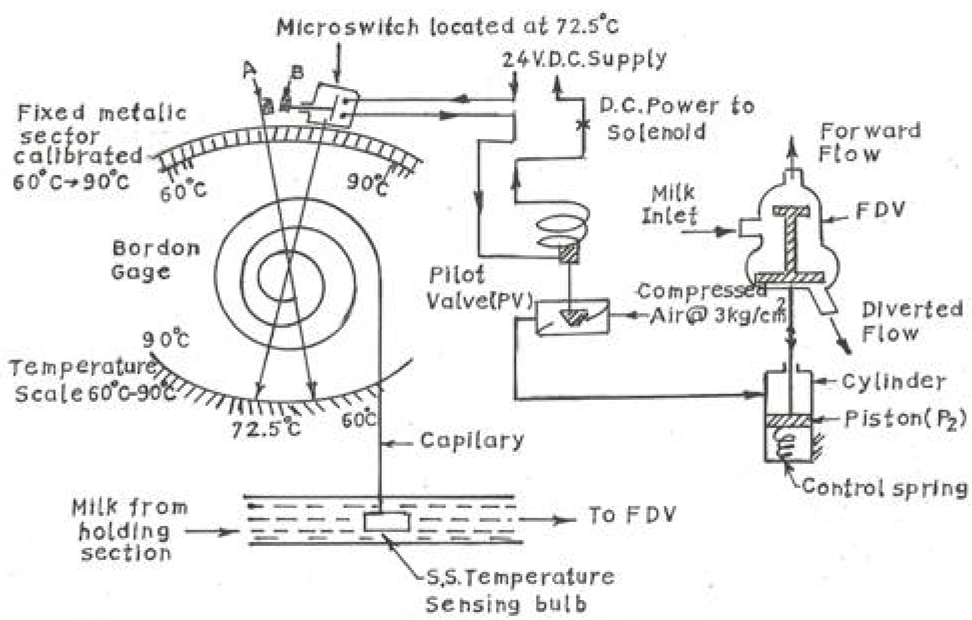


Fig. 31.5 Flow diversion valve controller in HTST pasteurizer

A SS temperature sensing bulb is inserted in the milk line that senses the temperature and provides proportionate signal to the Bourdon element by expansion of liquid through a capillary. The position of the contact ‘A’ attached to the Bourdon element is guided by the movement of the free end of the Bourdon element. As soon as the temperature of milk exceeds 72.5^{o}C the contacts A-B closes. This switches on the micro-switch (MS) that provides the 24 V DC supply to the solenoid operated pilot valve (PV). When the pilot valve opens compressed air enters the cylinder pushes the piston P_2 downwards. The stem of the flow diversion valve then moves to the downward position and closes the diverted flow port. Milk thus enters the forward flow line. The reverse happens when the temperature of milk is less than 72.5^{o}C, resulting in the diverted flow.

31.5.2 Control system in HTST pasteurizer

Complete control system of a HTST pasteurization plant is given in figure 31.6 showing the flow recorder controller and the temperature recorder controller. The temperature recorder controller gets the input with regards to the temperatures of hot water, temperature of milk at the end of the holding tube and the temperature of pasteurized chilled milk. Hot water is normally used to heat the milk in a plate heat exchanger. Steam is introduced to the water tank, and the temperature of hot water is normally kept 2 to 3^{o}C above the pasteurization temperature. The temperature of hot water is sensed and sent to temperature controller. Heating will continue until the preset temperature vale is reached.

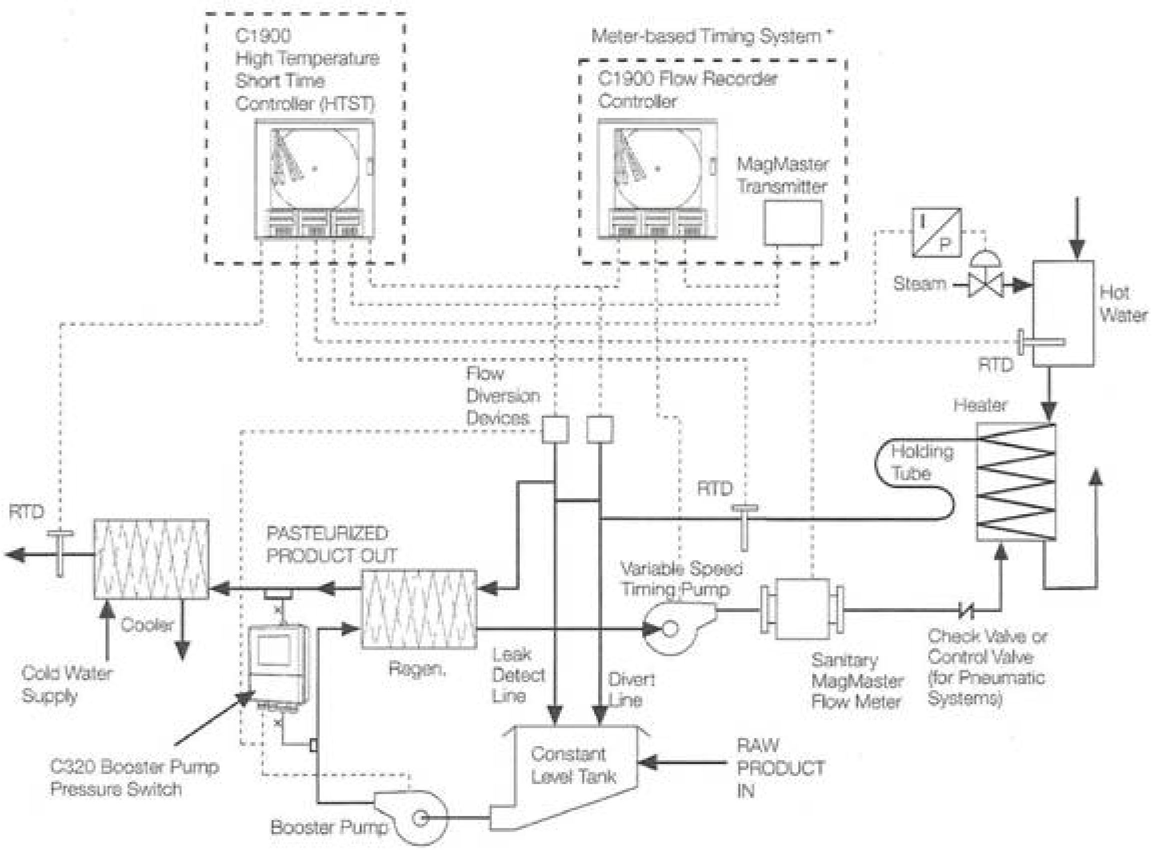


Fig. 31.6 Control system in HTST pasteurizer

31.6 Outlet Air Temperature Controller in Spray Dryer

The outlet air temperature in a spray drying chamber is controlled by keeping the inlet air temperature at a constant level and varying the milk input. The schematic diagram of outlet air temperature control in the spray dryer is given in Fig. 31.7

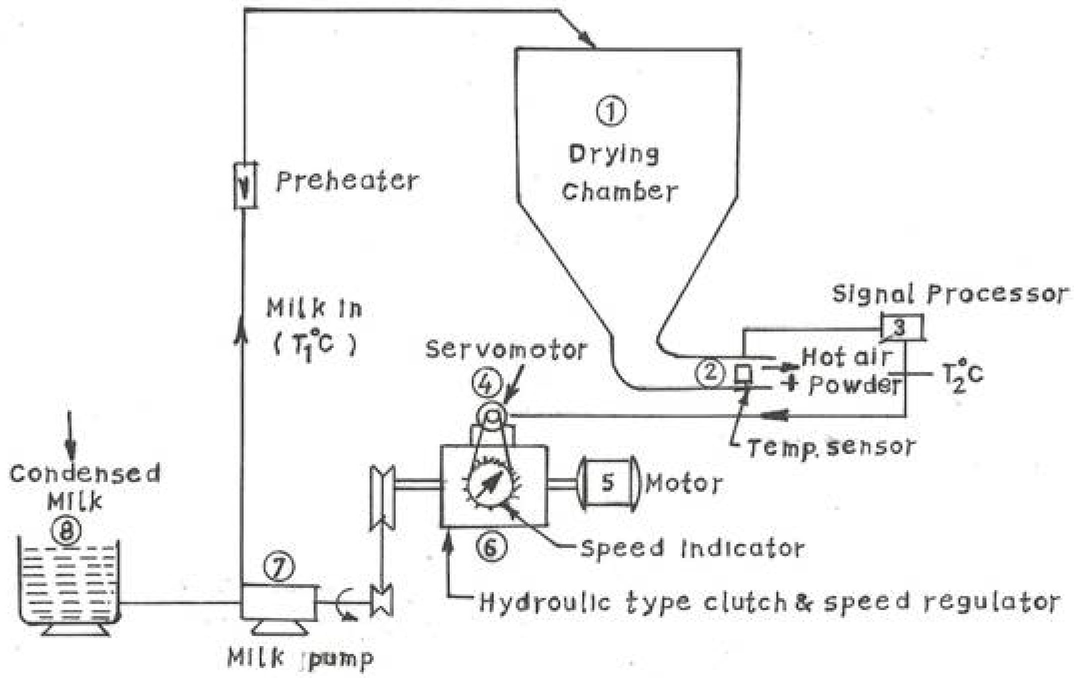


Fig. 31.7 Outlet air temperature controller in spray dryer

A thermistor sensing device senses the air temperature at the outlet of drying chamber at point (2). A Wheatstone bridge circuit is used to compare the measured temperature with the desired temperature. The output of the signal processor at (3) operates the servomotor (4), which rotates in either direction depending upon the outlet air temperature, whether it is more or less than the desired value. The servomotor controls the pressure of oil between the set of clutch plates through a pressure reducing valve. This controls the speed of milk pump and hence the milk input to the dryer to maintain a constant temperature at the outlet.

Lesson 32

INSTRUMENTATION AND CONTROLS IN CIP CLEANING AND SANITIZING

32.1 Introduction

Cleanliness is an essential component of process hygiene and a satisfactory hygiene is the statutary requirement of dairy processing industry. Dairy plants need frequent and effective cleaning of equipments. This has led to the equipment designs which are cleaned-in place and the large modern dairy plants employ automated CIP methods. In this system various cleaning, flushing and sanitizing fluids are circulated through the equipment, without dismantling it. Cleaning is achieved by the physical action of high velocity flow jets, agitation and chemical action of cleaning agents. The cleaning action may be enhanced by heating the fluids. Most of the cleaning action is provided by surfactants, acids, alkalis and sanitizers. A CIP system consists of tanks and pipe lines for distribution and return of cleaning agents. It reduces the labour requirement and improves the productive utilization of plant and machinery.

32.2 CIP Cleaning-In-Place

Cleaning-In-Place (CIP) and Sterilization-In-Place (SIP) are systems designed for automatic cleaning and disinfecting of the dairy equipments without major disassembly and assembly work. The CIP system allows cleaning one part of the plant while other areas continue to produce product. Furthermore, a modern CIP system will not only save money in terms of higher plant utilization but also due to significant savings in cleaning solutions, water and labour requirement. The system also ensures the operator safety and minimized product change over time.

CIP (cleaning-in-place) covers a variety of areas but its main purpose is to remove solids and bacteria from tanks, vessels, and pipe work in the dairy processing equipments. The type of cleaning medium or detergents includes caustic, acid, disinfectant, return water and the fresh water. The detergents are usually recycled. The number of CIP circuits depends upon the plant areas to be cleaned and the required availability for the same. The number of tanks in the CIP circuit depends on the required detergent and disinfectant volumes; however the number rarely exceeds 8 tanks per system. The volume of the tanks is as per the effective volume needed for the cleaning. The flow rates of detergents in the system are kept normally up to 150 m^3/h.

32.3 CIP System Configuration and Layout

A CIP system consists of piping for distribution and return of cleaning agents, tanks and reservoirs for cleaning solutions, heat exchangers spray heads, flow management devices and programmable control unit. Two main types of CIP systems are available: single-use units, in which all cleaning solutions are used once and discarded and the reuse units which use the cleaning media and rinse liquid more than once. The latter type of system recovers the recirculated alkali which is stored for the next cleaning event. Single use systems are preferred when there is a concern of cross contamination. For acid and alkali recirculation, concentrated solutions are metered into deionized water-filled acid / alkali tanks. The contents of the tank are mixed by recirculation through CIP supply pump. A heat exchanger heats the solution to the desire temperature. Temperature of the return flow is monitored and recorded. The steam supply to the heat exchanger is controlled by the return flow temperature signal during recirculation of the alkaline detergent. Dry running of supply pump is prevented by no-flow sensors. During the final water wash, the conductivity sensor is used to monitor the return flow which is sent to drain when a preset low conductivity value is reached indicating complete removal of acid or alkali from the system. Sensors are provided to monitor the strength of cleaning solutions. Sometimes, the cleaning solutions are dosed in line.

32.4 Automation for CIP

In simple and smaller facilities manual operation of CIP cleaning is followed. CIP cleaning of large or complex processing plant requires automation and micro-processor based controls, with PLCs. The PLCs are programmed with several different cleaning progarmmes, one for each cleaning facility. The programme specifies the cleaning route, sequence of cleaning, the flow rates and the temperatures and strength of cleaning media. The duration of each cleaning programme is fixed. Each control valve in the line is monitored using positive feedback. In the event of a failure the system is designed to safe shut down.

The circuit diagram of automated CIP system is given in the Figure 32.1

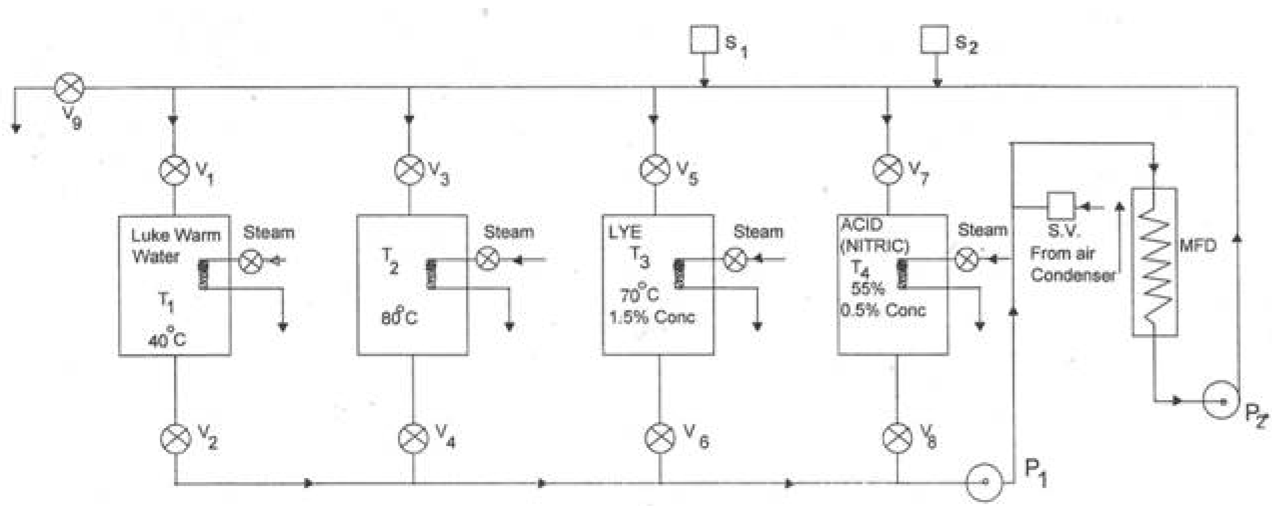
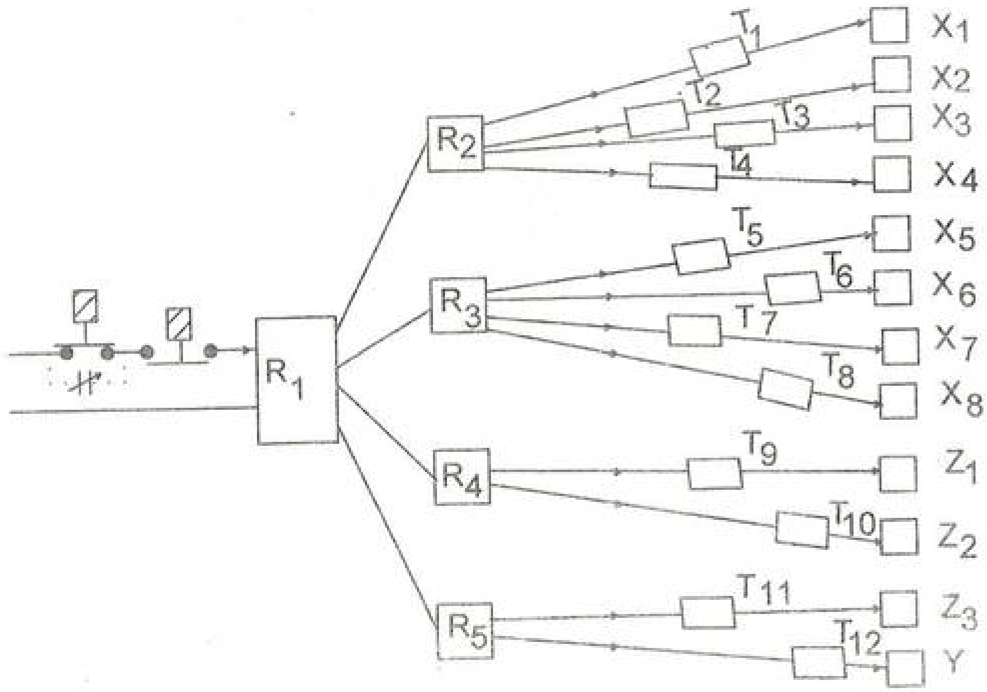


Fig. 32.1 CIP system automation

In the figure the T_1, T_2, T_3, and T_4 are the Tanks for luke warm water, hot water, alkali (sodium hydroxide) and nitric acid solutions. The heating is done by steam and the temperature in the tanks is controlled by steam thermostat. The milk flow path is denoted by MFP and all the milk contact surfaces of the equipments such as separator, homogenizers, plate heat exchangers, pasteurizers are connected series. The valves V_1 to V_9 are the air operated heavy duty valves which are operated by pilot valves. The valve V_9 is the drain valve. P_1 and P2 are the forward and the return flow pumps respectively. SV represents the solenoid valve for compressed air flow. S_1 and S_2 are the Solution Analyzers to control the concentration of Lye and Acid solutions respectively. The Wheatstone Bridge type circuit is used where the conductivity (electrical conductivity) of the solutions are compared to operate and control solution valves for injecting on to CIP lines. The operation of the CIP system is illustrated in Figure 32.2.



To start the system the start button ST is switched on. This in turn switches on the Electromagnetic Switching Relays R_1 to R_5. Now the power is ready for all the valves. The various valves in the CIP system include; X_1 and X_2 which are the air operated pilot valve for the Rinse Water, X_3 and X_4 for Lye Solution, X_5 and X_6 for Hot Water flow, X_7 and X_8 for Acid solution, Z_1 is the compressed air solenoid valve, Z_2 CIP drain valve and Z_3, Y are the solution analyzers valves. The power supply is controlled by electronic timers T_1 to T_{12}, which switches on / off at different times set for various valves for flow of cleaning solutions.

32.5 Automatic Chlorinator

A simple automatic chlorinator using venturi flow meter is shown in figure 32.3. It consists of a balloon of a flexible material which contains the chlorine solution. The flexible balloon is placed in a fixed metallic or PVC drum. A venture tube is placed in the water supply line. Pressures across the venturi tube are sensed and this pressure differential drives the flow if chlorine solution (i) to the water line. The quantity of chlorine solution injected is proportional to the pressure differential (P1-P2) which in turn is proportional to the flow of water. Hence chlorine is injected at the constant rate to the water line. The system is designed for 50 ppm of free chlorine.

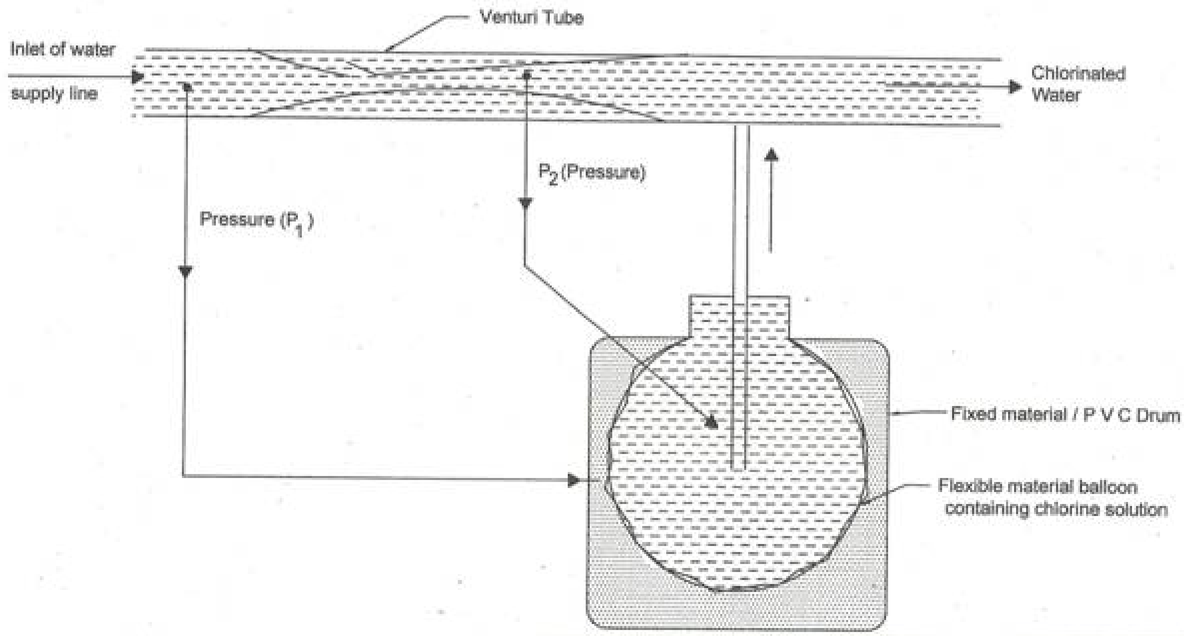


Fig. 32.2 Automatic chlorinator

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